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CLIMATE CHANGE IMPACT ON HYDROLOGICAL EXTREMES ALONG RIVERS IN FLANDERS

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بسْمِ اللّهِ الرَّحْمَنِ الرَّحِيمِ

إِنَّ اللّهَ لاَ يَغْفِرُ أَن يُشْرَكَ بِهِ وَيَغْفِرُ مَا دُونَ ذَلِكَ لِمَن
يَشَاء وَمَن يُشْرِكْ بِاللّهِ فَقَدْ ضَلَّ ضَلاَلاً بَعِيدًا

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Summary

The consequences of changes in climate for the society and the environment are referred to as the Impacts of Climate Change. This PhD thesis focuses on the impacts of climate change on rainfall (including extreme rainfall) and potential evapo(transpi)ration, and how this affects the hydrology of river basins in Flanders. Because these impacts are most significant as a result of extreme fluctuations in the climate, such as the extreme heat and dry conditions in the summer or exceptional rainfall events, the PhD study has given particular focus to these hydrological extremes. Extreme dry summer periods may lead to low flow problems along rivers. Such as problems in drinking water supply, navigation, water quality, etc. High rainfall events may lead to flooding.

The compilation of several scientific results, mainly based on the work of IPCC, states that the impacts are already occurring as a result of past changes in the climate and more especially as a consequence of human induced climate change through the release of extra greenhouse gases into the atmosphere. Today, the scientific community considers global warming a reality for which there is no more room for doubt but an increasing number of studies and analyses of potential impacts and possibilities for adapting to them. Their findings state that an increase in temperature should result in changes in the hydrological regimes and for instance the hydrological extremes in terms of floods and droughts. These changes can be assessed by means of hydrological models.

Because impacts vary from place to place, and because the vulnerability to these potential impacts depends on variations in the capabilities to adapt to the changes, the most informative impact studies have focused on particular regions. For this reason, the materials presented in this PhD study mainly focus on the Flanders part of the Scheldt River Basin District in Belgium, where climate data have been initially gathered at a continental scale (large scale), and then more finely at sub-regions, and sub-catchment scale.

The more specific focus of this study is to answer the following questions regarding the possible future hydrological conditions in the Flanders area of the Scheldt River Basin District. Has climate change possible impact on the hydrological extremes in the area? If yes, can we assess the size of the impact? Do both the frequency and the intensity of the hydrological extremes change? How large are the uncertainties in this impact change? Would this impact have possible economical consequences? From a methodological viewpoint, what method should be used to quantify the change in the hydrological extremes caused by climate change in the study area and the related uncertainty?

This PhD study answers the above questions through setting a methodology leading to the assessment of the impacts of climate change on the hydrological extremes in Flanders. A set of modelling techniques have been applied to provide numerical assessment of the key variables of the hydrological system (e.g., runoff peaks, low flow values, overland flow and potential/actual evapo(transpi)ration) on a sub-catchment scale for the study area.

While this study presents in itself a first step to combining several scientific fields (climatology, hydrology, modelling sciences, statistics...), it is to be noted that several assumptions are taken (and further discussed) that strongly influence the results upon which the reader should have a critical view. Below is a summarized description of the settled methodology and the main findings of the results for the Flanders' Scheldt River Basin District sub-catchments.

Methodology for climate change impact assessment on the hydrological extremes in Flanders

Obviously, the development of a methodology that analyzes potential climate change impacts on hydrological extremes along rivers in Flanders leads us to deal with the science of climatology from one side and with hydrology from another side. These two science fields together with their investigations form the two major basic points of our methodology. The transfer of the data from the climate system, which outputs act as a driver to the hydrological

system, forms in itself the third major basic point of our methodology. This transfer involves reducing the time and space scale representations of the climate data to accommodate with hydrological investigations requirements. This third major point is referred to hereunder as downscaling.

More clearly, the developed methodology of this study relies on 3 points:

- The climate system investigation: through the analysis of simulation results from climate models;
- The downscaling of the climate data acting as drivers of the hydrological system;
- The hydrological system investigation of the impact of rainfall and ETo changes on river high flows and low flows by means of rainfall-runoff models.

Investigations could be done by either empirical trend analysis on historical series or by means of physically-based simulation models. Indeed, detecting possible changes (trends) in climate variables or hydrological variables (high flows/low flow) can be made by means of empirical methods on a sample of climatological or/and hydrological data collected throughout several Belgian meteorological stations. Although this study used an empirical analysis for validation of the models, this method remains limited to historical periods. For future predictions, models are required to approach the complex systems as the climate through climate models and the hydrology through hydrological models.

Although models, in both systems, reached high reliability level, they still incorporate major assumptions to simplify the representations of major complex processes happening separately in different space and time scales in nature. Chapter 1 and 2 give a literature review overview of the different available methodologies on assessing climate change impact on hydrological extremes.

We will go below through a scientific explanation for each of the above points.

The climate system investigation

Global warming and accompanied climate change are most likely caused by human greenhouse-gas emissions, mainly the CO_2 emissions. The UN and the World Meteorological Society's Intergovernmental Panel on Climate Change (IPCC) are unequivocal on science behind climate change. Hence, climate change is studied and simulated using the modelling science through climate models. Powerful computer softwares link different components of the climate system together with the joined natural processes in different space and time scales. Climate models are numerous and different in concepts as in spatial and temporal resolutions and in the integrated processes. The chapter 3 of this study presents a literature overview on the climate system modelling concepts through a physical description of climate change and its drivers.

The climate system investigation in chapter 3 lead us to go through the historical improvement of climate models from General Climate Models (GCMs) first generation, where the ocean-land interface was poorly incorporated into the physics of the model; to GCMs second generation, where the representation of the ocean land-interface showed significant improvements together with better time and space resolutions although they were still keeping operating on continental scale (~300km). Since then, enhancing the resolution keeps going on to end up lately to regional representation of the climate system through the Regional Climate Models (RCMs). GCMs act as boundary conditions for the RCMs, while these last present only an increased time and space resolutions of GCMs. This study benefits of RCMs outputs ranging from 50km to 12km in space and from seasonally to daily climate data in time. The outputs of the climate model are used as forcing inputs for the hydrological models.

So far, the question of investigating how climate models would help us understanding climate change remains unanswered. In fact, chapter 3 of this study made clear that climate models are the best tool for predicting climate change through the concept of greenhouse gases emission scenarios. Indeed, the climate system is very sensitive and its components are very much related to the level that any changes in one of the components results into change in the total climate behaviour. Accordingly, the changes in the atmospheric composition of greenhouse gases, mainly CO_2, would lead to several changes in the natural regimes as the hydrological cycle. In this way, and in spite of the strong assumptions taken upon the physics of the climate models while the climate is in process of changes (will be discussed below), they still are our best tool to provide the possibility of predicting climate change.

Thus, in climate change studies, the models are forced by different emissions of greenhouse gases to produce different possible pictures of future climate accounting for many sources of uncertainty. Most of the impact studies are based on a set of 4 groups of emission scenarios provided by IPCC. As for this PhD study, the impact assessment is limited to the set of climate models that have been forced with 2 groups of emissions scenarios, largely known by A2 and B2 emissions scenarios. These last assume consistent future situations coming from studies on the possible changes in the world population growth, in the technological development and in the use of energy sources. However, uncertainty regarding the emissions scenarios remains very high as the IPCC stated that no probability can be assigned to any of them.

During this study, a main task was to find an efficient source of GCM/RCM simulation results for current and future conditions (after greenhouse gases emission scenarios) and covering the Flanders area with space and time resolutions compatible with the hydrological requirements. This source has been identified to be the European climate project PRUDENCE: Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects. Indeed, PRUDENCE provides a large database of result coming from more than 20 simulations of 10 different RCMs with A2 and B2 emission scenarios and different time and space resolutions and covering the Flanders Area. The climate results take the period of (1961-1990) as a baseline period presenting the current conditions (referred to in the manuscript as the “control period”) and 2071-2100 as the simulated targeted period (referred to in the manuscript as the “simulated period”).

The PRUDENCE results have been processed by the Royal Meteorological Institute of Belgium (RMI) (P. Baguis, E. Roulin) as a task of the CCI-HYDR project of the Belgian Science Policy Office. The PRUDENCE results have been extracted in the closest grid model point to the main meteo-station of Belgium at Uccle. Once provided by RMI, the data of precipitation and potential evapo(transpi)ration have been statistically processed to create climate scenarios for Flanders and to prepare the hydrological models inputs.

The reader might wonder why this study choose to work with such a large set of climate model simulations, while it would have been easier to select one or two models from the PRUDENCE list to work with. The reason behind this is the very strong difference in climate change impacts between the different climate model simulations. This is due to uncertainties in the physical representation of the climate processes; same for the included processes and the assumption on the stationarity of the physical processes representations inside the models while the climate is changing. Climatologist and climate modellers claim lack of knowledge and base their assumptions on the fact that models physics as they chose, provide good results for the long term past data. But they disregard the reality that all human historical record had never seen such high fluctuations of greenhouse gases in the atmosphere. Other uncertainties are related to the time resolution and to the emissions scenarios. In this respect, no probability is assigned to the suggested emission scenarios of IPCC. Large uncertainty remains on the trend of the world’s economical development and use of energy sources especially that many nations have already started implementing non-polluting energy sources. Geologists also overlook the possible changes in volcano’s activities which release very large amounts of greenhouse gases.

Moreover, the increased resolutions from GCMs to RCMs do not include any regional/local processes that might largely influence the hydrological response to climate change (land use, soil acidification…). This so-called dynamical downscaling relies only on improvement of computer power.

All these uncertainties make clear differences in the simulated results whether for the control or simulation periods. In this respect, voting for this or that climate model to be a good model for the Flanders’ conditions would not be scientifically proved. Thus, this study decided to process all the PRUDENCE model results while covering the extent of possible differences in climate change impact.

Another important point generally underestimated in climate impact studies is the fact that most of climate models chose the period 1961-1990 as a baseline simulation, which meets closely with European economical development period after World War II. In this period, society, landscape and human practices have been severally changing in Europe which induced also changes into natural systems like the hydrological regimes. The distinction between the hydrological regime changes caused by climate change and the ones caused by urbanization is not clear yet. Many studies are currently investigating this issue. This is to say that climate change impact is sometimes being overrated.

The downscaling method and creation of climate scenarios

The downscaling forms a critical part in this study. It takes the role of the bridge transferring information at the scale on which climate models act to the scale of hydrological models. Chapter 4 and 5 deal with the statistical processing of the GCM/RCM PRUDENCE climate model simulations, the creation of climate change scenarios for Belgium and the transfer of changes (called perturbations) to the hydrological model inputs.

As starting basis for the development of the climate change scenarios, the daily precipitation and potential evapo(transpi)ration data of every climate model simulation are compared between control and scenario simulations. The comparison is done for the daily values having the same empirical return period (or the same rank number after sorting the daily values in both the control and the scenario periods). Perturbation factors were calculated as the ratio between the scenario and control periods or rank numbers. The derived perturbation factors are averaged above a certain return period chosen to be for extreme events higher than 0.1 year.

This procedure has been applied for data coming from different time aggregations ranging from daily to weekly, monthly and seasonal data, aiming to investigate whether climate change acts differently depending on time aggregations.

We had then to answer the question of which models' results are most valuable for impact analysis in Flanders. In this study, a methodology was created to select the climate models most representative of the Flanders condition in order to create climate scenarios.

An empirical selection procedure was followed. The procedure aims to reject the climate models presenting very high or very low perturbation factors which are acting as outliers comparing to other models' factors. This procedure is further sustained by a consistency check of the outlier models control simulations with the historical record (Uccle station data) to confirm the rejection. Based on the accepted models, potential climate change scenarios were developed for Flanders based on sequences of low, mean and high variation factors of the variables of precipitation and potential evapo(transpi)ration.

While the mean scenario, which corresponds to an average value of the climate models' factors, might provide the best estimate for the future conditions, the low and high scenarios present extreme future conditions accounting for the climate models differences in physics, resolutions and emission scenarios.

The future Flanders climate scenarios suggest a slight increase in winter precipitation for the mean scenario, while the high scenario gives a strong increase and the low scenario an almost unchanged climate. As for potential evapo(transpi)ration, increases are predicted in all the scenarios.

The scenarios appeared different between winter and summer and are, for summer precipitation, time scale dependent. The latter is explained by changes in the number of events in summer. The perturbation factors derived in this study combines both changes in the intensity and frequency of the events.

The perturbation factors are, further on in the study, applied to change the rainfall and ETo inputs of the rainfall-runoff models. Because they were – except for summer rainfall – independent on the time scale, assumption was made that they could be applied to any time scales, including time steps of the rainfall-runoff model inputs smaller than 1 day (e.g., 1 hour in this study). This process is called "statistical downscaling" and combines with the dynamical downscaling through the use of RCMs instead of GCMs.

In this study, due to the small fluctuation of the perturbation factors in time, a constant factor was used for all aggregations. However careful temporal downscaling should be taken while going towards very short time scales (10min, 1 min…).

The hydrological system investigation and impact analysis

Similarly to the climate system, the hydrological system has been approached through modelling science, using this time the lumped conceptual NAM model of DHI. It is a model with simple hydrological cycle description based on a set of 4 storages (snow, surface storage, soil storage and groundwater storage) where the flow between them depends on time variable average soil moisture levels. The NAM model requires only precipitation and potential evapo(transpi)ration as input files. These last are perturbed in this study with respect to the generated climate change scenario factors.

Hence, the climate change impact analysis is based on a simulation approach where the hydrological system behaviour of the main rivers in the Scheldt River Basin District is modeled for an observed historical period and for a future change from the control period (1961-1990) to the predicted period (2071-2100) under forcing of a modified (predicted) climate. In chapter 6, this study assessed the impact on hydrological extremes by comparing the key variables of the hydrological system for the two periods (e.g., runoff peaks, low flow values, overland flow and potential evapo(transpi)ration).

To perform this assessment, several statistical tools were used. Indeed, the WETSPRO tool was applied where a Peak Over Threshold (POT) selection followed by an extreme value analysis aimed to extract the extreme events (high runoff peaks and low flows) and to estimate their probability of occurrence through the graphical QQR technique (chapter 6). The calibrated extreme value distributions were statistically transferred to assess possible changes into the composite hydrographs of every sub-catchment in the Flanders area. This work has been done for the generated low, mean and high scenarios separately considering the current conditions taken as a baseline condition to compare with.

The modelling procedure results state that the predicted climate evolution induces a significant reduction of the low flows due to a considerable hydrological regime modification. As for high flows (flood risk), the results range from increasing to decreasing depending on the climate change scenario and thus counting for a large uncertainty. Overland flow follows similar patterns as for the high flows while evapo(transpi)ration shows systematic increases as a result of regional warming.

This study made clear that considerable uncertainties remain in estimating the size of the impacts of climate change. It is, however, unlikely to set the limitations to the overall uncertainties in the resulted impact as the hydrological model itself adds a set of important assumptions like the stationarity of hydrological processes while climate is changing.

Although, it is true that the size of the impact remains highly uncertain, the trends of the impact look to be beyond doubts. Flood risks might increase or decrease depending on the climate scenario, but drought risk increases in all cases. This result is perfectly seen all over the Flanders area where local characteristics (land use, soil type and topographical slope) do not seem to strongly influence the results neither to explain the regional differences in the hydrological response to climate change. The latter could be explained by the hydrological model uncertainties, e.g. due to the inconsistent calibrations done for the different sub-catchments in the Flanders area.

This study was proceed thereafter to the simulation of the hydraulic behaviour of the Flanders' rivers using the perturbed rainfall-runoff results as inputs in hydrodynamic models (MIKE11 of DHI), which are in turn linked to models for topographical information (DEM: Digital Elevation Models) to create finally flood maps for the three climate change scenarios for every river basin and for several return periods. The flood extent showed to be dependent of the generated climate scenarios where in most of the cases for the high scenario, an applied risk calculation model results into considerable damage.

Being critical to this study results, we would say that understanding the "science" of climate change impacts on the hydrological extremes is important but is not in itself enough to enable efficient actions or adaptation. This is because it will never be feasible to base decisions on a set of future climate scenarios. This is a result of incomplete knowledge in climate and hydrological systems physics but also because of inherent uncertainty in future emissions of greenhouse gases and downscaling. Therefore, water managers need to deal with a range of scenarios. Correspondingly, researchers must focus largely on appropriate analytical and management tools to cope with uncertainty. Such an uncertainty is far to be quantified, although the chapter 8 of this manuscript assessed the degree of sensitivity of the hydrological response to the created climate change scenarios.

Sensitivity analysis

While confirming our thoughts of criticizing the important weight of the overall uncertainties, especially those brought through the climate models; this study implemented, in chapter 8, a statistical method to assess the hydrological response sensitivity to changes induced by the created climate scenarios and by natural variability. The idea was to set a statistical selection procedure based on ensemble modelling of the regional climate model simulations and on Monte Carlo simulations to account for the effect natural variability (randomness) when comparing the climate model results with historical data (Uccle data corrected by means of areal reduction factors). This procedure assisted in creating new statistical low, mean and high scenarios for precipitation and potential evapo(transpi)ration, which, in turn, are compared to the original ones.

The degree of sensitivity of the scenarios to the scenario generation procedure is then transferred to the hydrological model where the results appear to be highly sensitive, which raises significant implications difficulties for future water-resource planning and management.

Despite the different uncertainties in the impact results of this study, the findings show that climate change is going to alter water availability and supply, flood risks and the performance and sustainability of the rivers in the study region. Coordinated regional action is indeed recommended, both at the political level in order to control CO_2 emissions and at the regional level to investigate adaptation measures in order to compensate for the negative effect.

Nederlandstalige samenvatting

Voorliggend doctoraatsonderzoek behandelt de ontwikkeling van een methodologie voor impactanalyse van klimaatverandering op hydrologische extremen langs Vlaamse rivieren in België.

De studie onderzocht vooreerst de mogelijkheid om via de combinatie van klimaatmodellering en hydrologische modellering de impact in te schatten van klimaatverandering op rivierhydrologie en hydrodynamica. Er werd een methode uitgewerkt gebaseerd op continue lange-termijn simulaties. Gecombineerde hydrologische en hydrodynamische modellen werden voor alle deelbekkens van het stroomgebiedsdistrict van de Schelde doorgerekend voor zowel een referentieperiode in het verleden (de zogenaamde controleperiode 1961-1990) als voor een periode in de toekomst (de scenarioperiode 2071-2100). De hydrologische en hydrodynamische modellen werden in vorige studies opgebouwd door het Laboratorium voor Hydraulica van de K.U.Leuven en door het Waterbouwkundig Laboratorium van de Vlaamse Overheid. De invloed van de klimaatverandering (van de controle- tot de scenarioperiode) werd ingerekend voor zowel de neerslag als de potentiële evapotranspiratie (ETo). Neerslag en ETo zijn immers de voornaamste invoervariabelen in de hydrologische modellen. Voor beide variabelen werden klimaatveranderingsscenario's opgebouwd. Ze zijn gebaseerd op de A2 en B2 scenario's van de IPCC intergouvernementele werkgroep voor klimaatverandering m.b.t. de toekomstige uitstoot aan broeikasgassen. De impact van deze toekomstige uitstoot op neerslag en ETo werd ingeschat op basis van bestaande simulaties met regionale klimaatmodellen voor Europa. 24 simulaties met dergelijke klimaatmodellen werden bekomen via het Europese PRUDENCE project, en in samenwerking met het Koninklijk Meteorologisch Instituut van België verwerkt voor Ukkel (d.i. de locatie van het voornaamste meteorologisch meetstation in België). Na statistische analyse van deze klimaatmodelsimulaties werden seizoensafhankelijke kwantielperturbatiefactoren afgeleid (factoren verandering in neerslag- en ETo-kwantielen van de controle- tot de scenarioperiode). Voor de uitbijters in deze factoren werd voor de controleperiode een consistentiecontrole uitgevoerd van de neerslag- en ETo-kwantielen afgeleid van de klimaatmodelsimulaties met de historische neerslag te Ukkel. De inconsistente factoren werden verwijderd. Op basis van de consistente factoren werden drie scenario's weerhouden: laag, midden en hoog scenario, en dit voor zowel de gemiddelde seizoenscondities als voor de uitzonderlijke gebeurtenissen (de extremen). Ook werd de afhankelijkheid van deze scenario's met de tijdschaal onderzocht (dag-, week-, maand- en seizoensschaal) en geëxtrapoleerd naar de uurlijkse tijdschaal. De neerslag- en ETo invoertijdreeksen van de hydrologische modellen werden overeenkomstig geperturbeerd, doorgerekend in de modellen, en de impact geanalyseerd voor uurlijkse piekdebieten (representatief voor overstromingskansen en –risico's), uurlijkse laagwaterdebieten (representatief voor de problematiek van watertekorten), cumulatieve neerslagafstromingsvolumes, oppervlakteafstromingsvolumes en evapotranspiratievolumes. Ook werd de invloed op uurlijkse piekdebieten verder doorgerekend naar overstromingskaarten en overstromingsrisicokaarten. Voor dit laatste werden de hydrologische en hydrodynamische riviermodellen verder uitgebreid met modellen voor de overstromingsgebieden, met digitale hoogte-informatie, en met modellen die overstromingskansen en -schades combineren tot overstromingsrisico's.

Resultaten geven aan dat toekomstige klimaatverandering zal leiden tot een stijging van de watertekorten, maar dat de invloed op overstromingskansen en -risico's minder duidelijk is. Verder zullen verdampingsvolumes toenemen en neerslagafstromingsvolumes afnemen. De onzekerheid op de impactresultaten blijkt hierbij zeer groot, en is het gevolg van vooral de onzekerheid in impactresultaten van de klimaatmodellen op (extreme) neerslag en ETo.

List of symbols

AOGCMs	Atmospheric-Ocean General Climate Models.
ARFs	Areal Reduction Factors.
Clcov	Cloud covering.
DEM	Digital Elevation Models.
DTM	Digital Terrain Models.
ETo	Potential Evapo(transpi)ration.
ETa	Actual Evapo(transpi)ration.
EVT	Extreme Value Theory.
FAR	First Assessment Report of IPCC.
FOAR	FOurth Assessment Report of IPCC.
GCMs	General Climate Models.
GEV	Generalized Extreme Value.
GHG	GreenHouse Gases.
GPD	General Pareto Distribution.
H	Humidity.
IDF	Intensity, Duration, Frequency relationships.
SIRBD	The Scheldt International River Basin District.
ML	Maximum Likelihood Techniques.
MSE	Mean Square Error.
MSLP	Mean Sea Level Pressure.
NAM	Hydrological model of the Danish Hydraulic Institute, Water & Environment.
P	Precipitation.
POT	Peak Over Threshold.
PRPM	The Poisson Rectangular Pulses Model.
PRUDENCE	Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects.
QDF	Runoff, Duration, Frequency relationships.
Q-Q plot	Quantile-Quantile plot.
RCMs	Regional Climate Models.
SAR	Second Assessment Report of IPCC.
SWdown	Total radiation balance.
SRES	Special Report on Emission Scenarios.
TAR	Third Assessment Report of IPCC.
T2m	2-meter temperature.
W-10m	10- meter wind.
WETSPRO	Water Engineering Time Series PROcessing tool.

List of Acronyms

BELSPO	The BELgian Science Policy Office.
CCCma	Canadian Centre for Climate modelling and analysis.
CCSR	Centre for Climate System Research.
CSIRO	The Commonwealth Scientific and Industrial Research Organization.
DHI	The Danish Hydraulic Institute, Water & Environment.
DMI	The Danish Meteorological Institute.
DKRZ	The Service Centre for Climate Modelling in Germany.
EEA	The European Environmental Agency.
HYDRAM	Hydrology and Land Improvement Laboratory of the Swiss Federal Institute of Lausanne, Switzerland.
IPCC	Intergovernmental Panel on Climate Change.
KNMI	Het Koninklijk Nederlands Meteorologisch Instituut, The Royal Netherlands Meteorological Institute.
K.U. Leuven	Katholieke Universiteit Leuven.
NCAR	The National Centre for Atmospheric Research in America.
NCEP	The National Center for Environmental Prediction.
RMI	Royal Meteorological Institute of Belgium.
UKMO	Met Office and Hadley Centre for Climate prediction and research.
UNEP	United Nations Environment Program.
UNFCCC	United Nations Framework Convention on Climate Change.
WL	Waterbouwkundig Laboratorium of the Flemish government.
WMO	World Meteorological Organization.

Table of Contents

Chapter 1

Introduction

1.1 Research introduction

Climate changes are induced by the internal variability within the climate system and external factors that are either natural or anthropogenic. Recent climate change researches confirm that global warming is induced by anthropogenic forcing (IPCC, FOAR 2007).

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change – the most up-to-date scientific assessment of past, present and potential future climates (IPCC, FOAR 2007) - resumes the current findings of the scientific community as follows: "*There is very high confidence that the globally averaged net effect of human activities since 1750 has been one of warming, with a radiative forcing of +1.6 [+0.6 to +2.4] W/m*^{2}" (IPCC, FOAR 2007).

The global average Earth surface temperature has increased by about 0.6°C over the 20th century (Folland, 2001). This temperature increase is likely to have been the largest of any century during the past 1000 years and is unlikely to be either due to the internal variability alone or entirely natural in origin (Folland, 2001).

The observed concentrations of atmospheric greenhouse gases (GHG) have increased as a result of human activities. The IPCC (FOAR, 2007) stated that: "*Most of the observed increase in globally-averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations*" (IPCC, FOAR 2007). This is an advance since the Third Assessment Report (TAR, 2001) conclusion that "*Most of the observed warming over* *the last 50 years is likely to have been due to the increase in GHG concentrations*" (IPCC, TAR 2001).

The concentration of carbon dioxide (CO_2) has increased by 31% since 1750 and the present CO_2 concentration has not been exceeded during the past 420'000 years (Prentice et al., 2001). This increase in greenhouse gas concentrations is likely to have induced most of the observed warming over the last 50 years (Mitchell et al., 2001).

Today's scientific community concern is whether we can model and predict natural processes variations along with their interactions to human activities, due to their interactions with the climate and the resulting climate evolution. The main question to answer is: what is the impact of climate change on human activities and on life on Earth in general? Especially that the IPCC (FOAR, 2007) stated: "*Anthropogenic warming over the last three decades has likely had a discernible influence at the global and regional scales on observed changes in many physical and biological systems*" (IPCC, FOAR 2007).

The modelling of the climate system requires complex physically based models and a large amount of input data to define initial and limiting conditions. Despite this highly complex task, "*Confidence in the ability of models to project future climate has increased*" (IPCC, 2001). Regardless of this fundamental question whether actual scientific knowledge enables us to predict the climate evolution; it is logic that any modification of the climate will indeed have an important impact on the natural systems. But are we able to predict this impact? Can we predict these climate change induced impacts on water resources systems and how certain are these predictions? These essential questions have motivated the research of the present PhD thesis.

The climate system is closely related with the water cycle. Any climate perturbation will result to temporal or permanent modification of the hydrological cycle and have an impact on water resources and related water uses.

A major concern is currently focused on climate change induced hydrological extremes (floods and low flows). A modification of the hydrological state has potentially a major impact, especially on economy and on human life. These problems are potentially enhanced by a climate change induced modification of the frequency and intensity of heavy rainfall events as well as periods with low rainfall volumes.

In the present PhD research, we focus on climate change impacts on the hydrological extremes (floods and low flows) along rivers in the Scheldt River Basin District (limited to the Flanders region of Belgium). This area embraces the major river systems in Belgium and one of the important international river basins in Europe.

The Scheldt River Basin District is likely to be sensitive to potential climate change impacts. The hydrological regime of such environments is strongly influenced by water accumulation variation throughout the different sub-basins. A modification of the prevalent climate and especially of the precipitation and potential evapo(transpi)ration can therefore considerably affect the hydrological regime and induce important impacts on the water management (Burlando et al., 2002; Jasper et al., 2004). This could have a significant impact on water uses highly dependent on the hydrological regime, such as navigation or irrigation, but also increase water related risks such as floods and low flows (Willis and Bonvin, 1995; Loukas et al., 2002). The prediction of climate change impacts has consequently an evident socio-economical interest.

The simulation of current observed climate conditions is being a complex task while the simulation of hypothetic future climate conditions becomes a challenge in an area like the Scheldt River Basin District situated between the elevations of the Ardennes and the influence of the North Sea. Such a challenge has been overcome through the emergence of climate models (refer to chapter 3 - "Review on the climate physics") and hydrological and hydraulic models that account for the main hydrological and river hydrodynamic processes involved. However, other difficulties show up by the classical scale incompatibility problem between future climate predictions and local scale hydrological models: The climate predictions are the result of climate models that have typically coarse resolutions for global climate models (GCMs) and of ~50 km for regional climate models (RCMs). This resolution is generally far too coarse for a direct use of the model outputs, namely precipitation and potential evapo(transpi)ration, in hydrological models (Hay et al., 2002; Wood et al., 2004), especially in the present context where the studied sub-catchments (the uniform hydrological response units) are smaller than 200 km^2. For a further discussion of this problem, refer to chapter 4 - “The downscaling methods”.

A modification of the climate system potentially affects the hydrological regime but also the frequency and intensity of extreme events in the Scheldt River Basin District. In the present study, climate change scenarios for the variables of precipitation and potential evapo(transpi)ration have been developed for Belgium (refer to chapter 5 - “Climate change scenarios for Belgium”) with a focus on the prediction of hydrological extremes (refer to chapter 6 - “Climate change impact analysis: the Dender case” and chapter 7 – “Regional differences analysis for entire Scheldt River Basin District”).

In this thesis, a special emphasis is given to the climate change uncertainties and their effect on the hydrological impact results. Their quantification is currently one of the key issues in hydrological research (Kuczera and Parent, 1998; Beven and Freer, 2001; Vrugt et al., 2003). This quantification is essential to assess whether the system modification is induced by climate change or by model errors.

While the simulation results are destined to be used in management or planning decisions, the estimation of the precision and the exactitude of the obtained results is fundamental for the decision maker. This study demonstrates the ability of quantifying the impact prediction uncertainty at certain modelling level (refer to chapter 8 – “Uncertainty analysis”).

1.2 Objectives of the doctoral research

Climate change impact on the risk of hydrological extremes along surface waters is studied for the local hydro-climatologic conditions in the Scheldt River Basin District. Both floods and low flows are considered. The study takes four main steps:

a. Study of climate change concept. This step includes a detailed review of climate change physics and scenarios relevant to the impact on hydrological extremes in the Flanders region of Belgium and neighbor countries.
b. Study of the downscaling methods most relevant to hydrological requirements and downscaling of recent climate model simulations, together with the creation of potential climate change scenarios for rainfall and potential evapo(transpi)ration at the relevant time scales for hydrological impact analysis for the Flanders region of Belgium.
c. Impact modelling towards flood risk and low flow risk along rivers, using hydrological and coupled hydrological–hydrodynamic river models developed for the different sub-catchments in the Flanders region of the Scheldt River Basin District.
d. Quantification of the climate scenarios uncertainty and its propagation into hydrological impact uncertainty.

The study will apply in (b) new analysis for spatial and temporal downscaling of the Global Circulation Model results to the scale required for hydrological investigations. These combine statistical methods with regional climate model results. The latter results are largely used in climatology, without allowing good description at the scale of hydrological processes, neither the influence on the extremes. Also in (b), the separate fields of statistical hydro-climatology and hydrology and physical climate modelling will be brought together to verify the climate model derived scenarios with the present and past climate. In tasks (c) and (d) the climate change scenarios will be processed in order to assess their effects on the Discharge-Duration-Frequency (QDF) relationships for the impact to river flow. The uncertainty in both the climate scenarios and the impact predictions will be taken into account through ensemble modelling and probabilistic simulations.

1.3 Overview of the study area: the Scheldt River Basin District

The Scheldt river basin will act as river basin case study, modeled at a small scale of sub-basins. All the cases will be selected based on data availability and existing hydrological and hydrodynamic tools, which are applied in the current water management practice of the Waterbouwkundig Laboratorium of the Flemish government.

The Scheldt river basin extends from northwestern France, via the western half of Belgium to the Netherlands. The total area of the district of the Scheldt is 36 416 km²: The Scheldt International River Basin District, as delineated for implementation of the European Water Framework Directive, is one of the most industrialized river basin districts in Europe with the densest population (12.8 million inhabitants). Other important river basins included in the Scheldt River Basin District are the Somme river basin (6548 km²) and the IJzer basin (1750 km²) (ISC, 2005). Figure 1.1 shows the location of the international Scheldt basin.

A big part of the Scheldt International River Basin District lays in Flanders which is considered as one of the densest populated area in Europe with 442 inhabitants per km^2 with a total population of 6.058.368 inhabitants (Figure 1.2).

Table 1.1 shows the distribution of the total Scheldt area over the different country regions where approximately half of the river basin district is located in the French territory and about one third in the Flemish territory, while only a small part lies in the Walloon Region, the Brussels capital region and in the Netherlands where the Scheldt estuary meets the North Sea (CIW, 2005).

From its source in Northern France to its mouth in the North Sea, the Scheldt river has a length of 355 km. Downstream of the sluices of Ghent, about 160 km from the sea, tidal influences are already noticeable. From the border between Flanders and the Netherlands the river widens considerably and becomes the brackish estuary, called the Western Scheldt. The Scheldt estuary region is both an important agricultural and industrial area (Figure 1.3). It is of a high ecological importance (ISC, 2005).

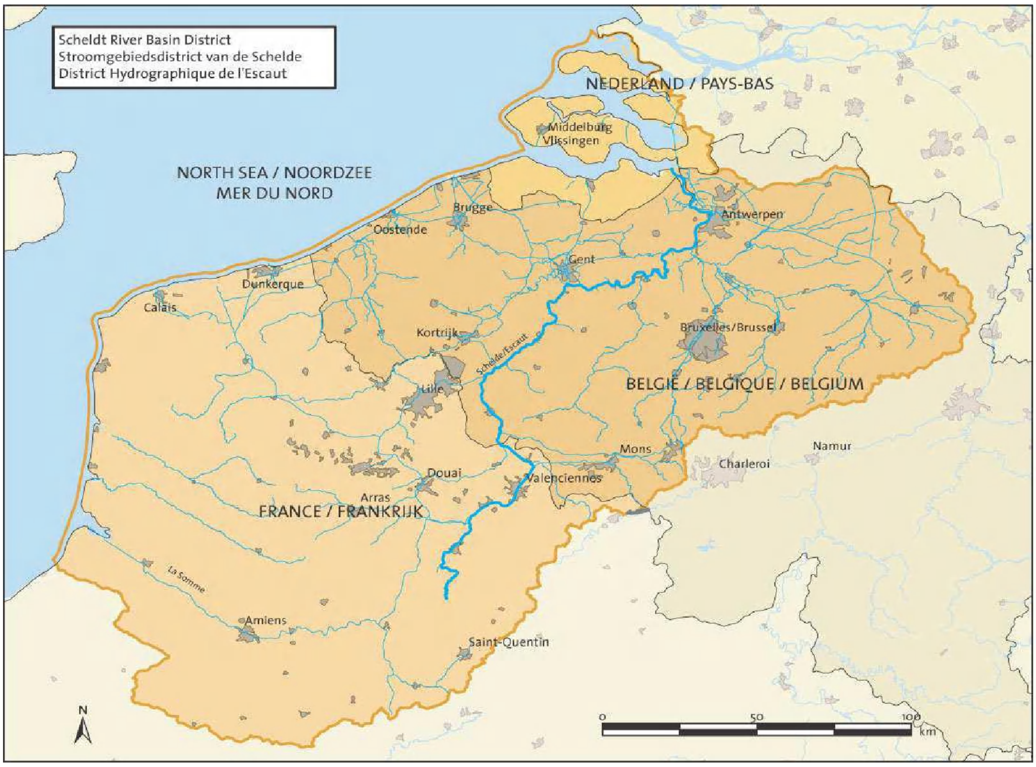


Figure 1.1 International Scheldt River Basin District (ISC, 2005).

	Area (km^2)
France	18,486
Walloon region	3,770
Brussels capital region	161
Flemish region	11,991
Netherlands	2,008
DISTRICT	**36,416**

Table 1.1 Area of the Scheldt per region (CIW, 2005).

Figure 1.2 Location of Flanders in Belgium.

Figure 1.3 The international Scheldt estuary (Verhallen et al., 2001).

The major part of the area of the Scheldt district lies in France and in the Flemish region (respectively 50% and 33%). The Walloon Region and the Netherlands cover 10% and 6%. The Brussels Capital Region comprises 0.44% of the Scheldt district (ISC, 2005).

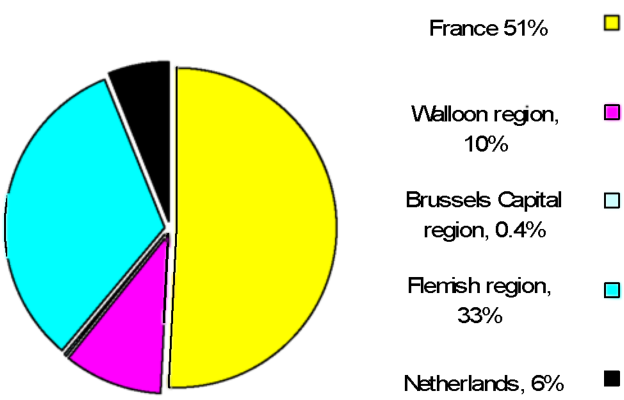


Figure 1.4 Area of the International Scheldt River Basin District per region (%) (ISC, 2005).

The total Scheldt district area is as well distributed over different river basins that are part of it, where beside the Scheldt river basin; the Somme basin covers a considerable part (Figure 1.5). A number of these river basins are further divided into hydrographical units; they form the basic units for water management. These hydrographical units are mainly delimited hydrographically, but they also take into account the national/regional boundaries (Table 1.2).

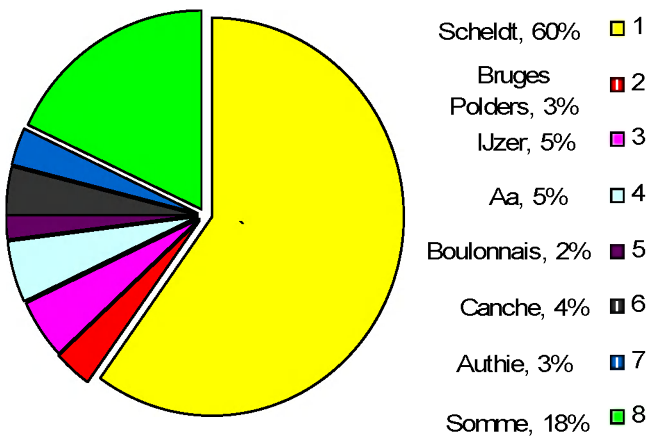


Figure 1.5 Area of the International Scheldt River Basin District per river basin (%) (ISC, 2005).

The Scheldt morphology is hilly. The rivers are mostly lowland watercourses, characterized by varying slopes. The Flemish part of the Scheldt is mainly flat. The highest altitude is 157m above sea level. The lowest altitudes are nearby the coast and the Scheldt region around the city of Antwerp. The Dutch part comprises primarily low-lying, flat polders. Differences in altitude are only a few meters in relation with sea level.

Agriculture dominates the land use in the Scheldt basin with 61% of total area, mainly livestock and arable farming, but the basin is also highly urbanized (13%) with on average 353 inhabitants/km^2. Main industrial areas include Lille-Roubaix-Tourcoing, Dunkerque, Brussels, ports of Ghent, Terneuzen, Antwerp and Vlissingen. In coastal areas tourism plays an import role. Less than 10 percent of the land is covered with forests. Part of the land used for transportation and communication is also shared with some water courses. The land use in Flanders has been developing quite slowly with the beginning of the new millennium (Table 1.3). Figure 1.6 shows the land use map for the Flanders area of the Scheldt River Basin District.

River basin	Hydrographical unit (HU) name	Region	HU nature
Scheldt	“Lys”	F	RP of SB
	“Scarpe amont”	F	RP of SB
	“Scarpe aval”	F	RP of SB
	“Peule et Marque”	F	RP of SB
	“Escaut”	F	RP of SB
	“Sensee”	F	RP of SB
	“Escaut lys”	W	RP of SB
	“Dendre”	W	RP of SB
	“Haine”	W	RP of SB
	“Senne”	W	RP of SB
	“Dyle-Gette”	W	RP of SB
	“Senne/Zenne”	BR	RP of SB
	“Leie”	VL	RP of SB
	“Bovenschelde”	VL	RP of SB
	“Dender”	VL	RP of SB
	“Zenne”	VL	RP of SB
	“Dijle”	VL	RP of SB
	“Demer”	VL	RP of SB
	“Gentse Kanalen”	VL	RP of SB
	“Benedenschelde”	VL	RP of SB
	“Nete”	VL	SB
	“Zeeland en Brabantsewall”	NL	RP of SB
IJzer	“Yser”	F	RP of SB
	“IJzer”	VL	RP of SB
Aa	“Audomarois”	F	SB
	“Delta de l’Aa”	F	SB
Somme	“Haute somme”	F	SB
	“Somme aval”	F	SB
Bruges Polders	“Brugse Polders”	VL	RB
Boulonnais	“Boulonnais”	F	RB
Canche	“Canche”	F	RB
Authie	“Authie”	F	RB

Table 1.2 Hydrographical units per river basin (where RB = river basin; SB = sub-basin; RP of SB = regional part of sub-basin; F= France region; W= Walloon region; BR = Brussels region; VL =Flemish region and NL= Netherlands region) (CIW, 2005).

In respect to the study subject, climate change related sea level rise and stronger waves are likely to increase the flood risk in the Netherlands region of the Scheldt River Basin District, but also further upstream in the Flemish region (area of the present study, see figure 1.7). High and /or long-lasting precipitation events in winter furthermore cause flood risks in the upper Flemish region of the Scheldt River Basin District. In that region the risk is ranging from high flood potential in winters to potential severe low flows in summers, a fact raising that environmental policy is a regional responsibility (VMM, 2006).

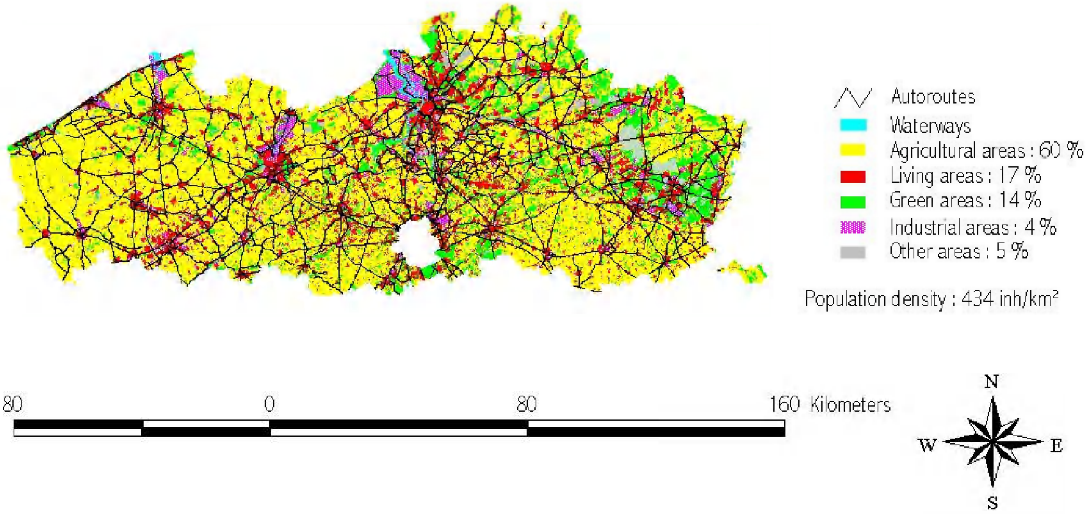


Figure 1.6 Land use map of the Flanders area of the International Scheldt River Basin District (ISC, 2005).

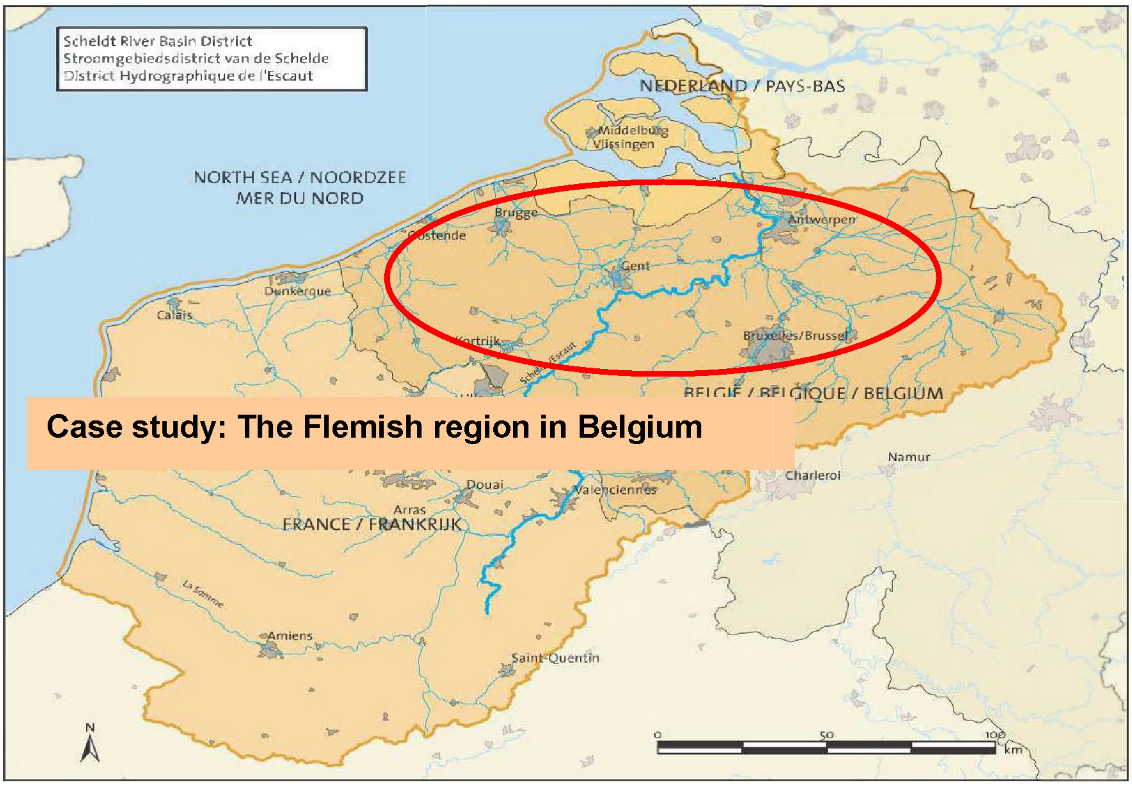


Figure 1.7 Study area: The Flemish region of the International Scheldt River Basin District (ISC, 2005).

Year	2000	2001	2002	2003	2004	2005
Total surface (km^2)	**13552**	**13552**	**13552**	**13552**	**13552**	**13552**
Agricultural area	8473	8444	8422	8392	8369	8346
Built area	3303	3335	3361	3391	3416	3439
Industrial area	347	353	357	359	362	364
Area used for mines, wells…etc	14	14	14	14	14	14
Commercial area	88	89	89	90	90	90
Public service area	121	121	121	122	123	124
Mixture use area	63	63	63	63	63	63
Communication & transportation area	1029	1032	1035	1041	1044	1046
Technical infrastructural area	15	16	16	16	16	17
Free spaces area	237	238	238	239	240	242
Residential area	1385	1407	1424	1444	1460	1476
Diverse	1744	1742	1737	1738	1736	1736

Table 1.3 Land use in Flanders (Economie, 2006).

Figure 1.8 presents the location of the different Flanders basins that will be subject of the present study.

Figure 1.8. Location of the Flanders basins subject of this study.

1.4 Overview of data availability

Data needed to estimate climate change impact on the hydrological extremes in Flanders (Belgium) have to be sought within a much wider area than that delimited by the Flemish water Authorities. This is because the impact of climate change is quite complicated and cannot be directly described by existing statistics or covered by easily organized additional data collection.

The necessary data for this study have been organized into two fields: the climate data necessary for the present and future investigations derived by the support climate study that should cover the studied area with different spatial resolutions and different aggregation time scales, and the hydrological data normally used by the water managers and local authorities in Flanders (Belgium).

These two data fields were fully provided for the present study as follows:

- The climatological data were fully provided by the European project PRUDENCE

PRUDENCE is an acronym for Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects. It is a project with many European partners, funded by the EU 5th Framework program for energy, environment and sustainable development 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 aimed to:

- Quantify the confidence and the uncertainties in predictions of future climate and its impacts over Europe;
- Interpret these results in relation to European policies for adapting to/or mitigating climate change.

To do so, PRUDENCE provides a series of high-resolution climate change scenarios for 2071-2100 for Europe. This is done through 10 different regional climate simulations with a high resolution coming up to 10 km in space and daily scale in time. PRUDENCE chooses the period of 1961-1990 as a baseline for climate simulations and provides the predicted change for 2071-2100, mostly using A2 greenhouse gases emission scenario. The project was completed in 2004; its results are satisfactory and easily accessible. Within the PRUDENCE project, different kind of impact analysis can be assessed with good resolutions which can be compatible with the hydrological studies that require high resolutions (DMI, 2004).

PRUDENCE simulation data from its participants are freely available in public domain of the project host http://prudence.dmi.dk. Due to the detailed and thorough data available, based on many climate models and covering the whole European continent, we will use the results of these simulations in the present study.

The objectives of the PRUDENCE project can be summarized as follows. (1) First carry out a series of 30-years long climate simulations for the present reference period (1961-1990) and the end of this century (2071-2100). The models used in this phase are coupled atmospheric-oceanic global circulation models (AOGCMs). The results of these simulations are then used to drive geographically more detailed, regional climate models (RCM)-based simulations. (2) Analysis of the response of each numerical experiment, in order to assess the uncertainty due to model formulation. (3) Analysis of hydrological impacts, for the study regions of the entire Baltic Sea drainage basin, the Lule River basin in Sweden and the Rhine River basin in Central Europe. (4) Evaluation of the impacts of detailed climate change scenarios on agriculture, forestry and ecosystems for selected regions in Southern and Northern Europe. (5) Assessing the risk from climate extremes over Europe, with primary focus on winter windstorms, heat and cold waves, hydropower, Mediterranean droughts and floods, and resource risk.

The PRUDENCE project provides the necessary data to run hydrological applications in different spatial and temporal resolutions. It provides the variables of precipitation, evapo(transpi)ration, mean seal level pressure, total radiation balance, cloud covering, 2-meter temperature, 10-m wind and humidity. PRUDENCE simulation outputs give as well the great opportunity to calculate some hydrological variables according to specified schemes. The example is given here for the variable of evapo(transpi)ration where it is calculated according to the Bultot equation which involves several parameters currently satisfied by PRUDENCE outputs.

The Royal Meteorological Institute of Belgium (RMI) assured the extraction and processing of the PRUDENCE simulation outputs, as a task of the CCI-HYDR project study under the authority of the BELgian Science Policy Office (BELSPO). The CCI-HYDR project is coordinated by the Hydraulics Laboratory of K.U. Leuven (by my supervisors P.Willems and J. Berlamont) and is running in close cooperation with RMI (E.Roulin, P.Baguis and G.Demarée). RMI fed this study with the daily precipitation and potential evapo(transpi)ration data for 24 climate scenario simulations corresponding to the different climate models used within the PRUDENCE project with their different physical concepts, different spatial resolutions and different emission scenarios. The data were provided for current conditions (calibrated models) corresponding to the period (1961-1990) and for future conditions (2071-2100) and were extracted at the closest model grid point to the main meteo-station of the Royal Meteorological Institute of Belgium at Uccle.

The hydrological data were fully provided through the dense climatological and hydro-meteorological network of RMI and the rain gauge network of the Waterbouwkundig Laboratorium (WL) of the Flemish government. In Belgium, rainfall data and most of the climatological variables are recorded by RMI. Rainfall data are collected through rain gauges in the hydro-meteorological network (rain gauges with 10 min temporal resolution) and the climatological network (rain gauges with daily rainfall). Other rain gauge data are collected by WL and by the water company Aquafin, at the city of Antwerp, etc. RMI benefits of a long rainfall series record at the main station of Uccle; it is a 10 min rainfall intensity of the period 1898-2005. These data are stored digitally since 1967. The older records were digitized from 1934 by RMI in a research project on sewer system ancillaries for the WL (coordinator Prof. J. Berlamont) from 1898. Coordinator of this extensive and unique digitalization work was Dr. G. Demarée from RMI.

All the necessary hydrological and hydrodynamic modelling tools were provided for this study through the Hydraulics Laboratory of K.U. Leuven that has carried out large number of hydrological and hydrodynamic modelling projects in the past for the Flemish area, and through the WL by financially supporting a research project on investigating regional differences for climate change impact on high and low flows along Flemish rivers.

Hence, this study benefits from a huge data base giving the possibility to deeply investigate climate change impact on the hydrological extremes for Belgium.

It is however clear that in order to approach such a complex topic of “climate change impact on hydrology”; we are using often simple representations of an extreme complex real nature. The reader should therefore keep in mind that some assumptions are taken in this study as in the climate science field and that these assumptions should be redressed in future studies.

Chapter 2

Methods for Climate Change Impact Analysis

2.1 Introduction: What is climate change?

Climate Change is the change in climate over a time period that ranges from decades to centuries. The term refers to both natural and human-induced changes. The term “climate variability” refers to shorter term (years to decades) fluctuations in climate. However, the United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as: “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods”. In other words, the UNFCCC uses the term Climate Change to mean only those changes induced by human activities.

But is climate change real? Does it exist already? How do we know?

2.2 Climate change facts

There is a growing consensus among scientific and political leaders that climate change is the biggest environmental threat modern society faces. According to the scientific opinion, there has been a sustained increase in global average temperatures that began to have an effect on the earth’s climate. The average temperature of the earth's surface has risen by 0.6°C since the late 1800s. It is expected to increase by another 1.4 to 5.8°C by the year 2100 (IPCC, TAR). Some investigators come to the conclusion that even if the minimum predicted increase takes place, it will be larger than any century-long trend in the last 10,000 years (IPCC, TAR 2001).

The growing concentration of greenhouse gases causes a gradual rise in temperature, and for many areas in the world, impacts on precipitation (rain and snow) patterns, and on the frequency of extreme events, such as extreme temperature, rain storms, droughts, and consequently also on the risk of flooding and low flow effects (IPCC, TAR 2001).

The average sea level rose by 10 to 20 cm during the 20th century (Wood et al., 2004), and an additional increase of 9 to 88 cm is expected by the year 2100 (IPCC, FOAR 2007). Freak weather conditions and changing ecosystems furthermore leave little room for doubt regarding the changing climate (IPCC, FOAR 2007).

Although many prediction uncertainties persist, the work of IPCC has led to a number of convincing conclusions in regard to human's impact on climate (Marbaix and van Ypersele, 2005). The FOAR confirmed with high confidence that observed warming is due to the increase in greenhouse gases concentrations in the atmosphere (IPCC, FOAR 2007). It is obvious that this increase is translated into changes in the hydrological cycle which will show different regimes totally depending on the climate behaviour.

The European Environment Agency (EEA) report indicates that climate change impacts in Europe are likely to be very significant (EEA, 2004). The report states that Europe, in particular, has been and will continue warming faster than the global average predicted by IPCC. As a result, Europe will experience increased impacts on the environment, human health, and various sectors of society, which includes (and is not limited to) an increase in heat waves, a rise in sea levels of two to four times, more frequent droughts, heavy rain and hail, economic and agricultural losses from droughts, floods, storms and heat waves, and substantial decreases in snow cover and glaciers (Hulme et al., 2002).

However, the challenges surrounding climate change open a range of quite important questions. For instance, what makes the climate changes?

2.3 Climate change forcing

Including the natural process of change, the emissions of various gases from industrial and other human activities are changing the world's atmosphere. These gases are commonly known as greenhouse gases (GHGs). The GHGs are minor gases in the atmosphere, although relatively transparent to sunlight, they absorb most of the infrared heat energy transmitted by the earth towards space. This phenomenon is called the "greenhouse effect" and the absorbing gases that cause it "greenhouse gases". Important GHGs include water vapor, carbon dioxide, methane, nitrous oxide, ozone, and halocarbons. Human activities have increased the amount of GHGs in the atmosphere, especially carbon dioxide and methane which in their increasing quantities, are rising the global temperature to high levels and altering the climate with returning back the infrared heat energy to earth. The 1990s appear to be the warmest decade of the last Millennium, and 1998 the warmest year. Figure 2.1 presents the greenhouse gas effects.

Carbon emissions are the key cause for climate change (CO_2 accounts for more than 80% of all greenhouse gas emission in Belgium), (Inventory of greenhouse gas emissions in Belgium, 1999). There is a growing scientific evidence of their causal effect on the climate and it is now apparent that the release of carbon emissions needs to be controlled. Several attempts were focusing on the issue of reducing the emissions. Governments across the world are deeply interested in the matter. The first step was in 1988 when the Intergovernmental Panel on Climate Change (IPCC) was established to help understand the scientific issues and impacts of climate change. In 1992, the UNFCCC took place which is supposed to be an international convention establishing non-legally binding targets towards emission reductions. Then the Kyoto protocol was adopted under the UNFCCC in 1997 which came into force in Feb 2005, containing legal binding targets for each country to reduce greenhouse gas emission by 2008-2012. Belgium, as a part of the European Union's target is supposed to reduce the emissions by 7.5% (Gail, 2006).

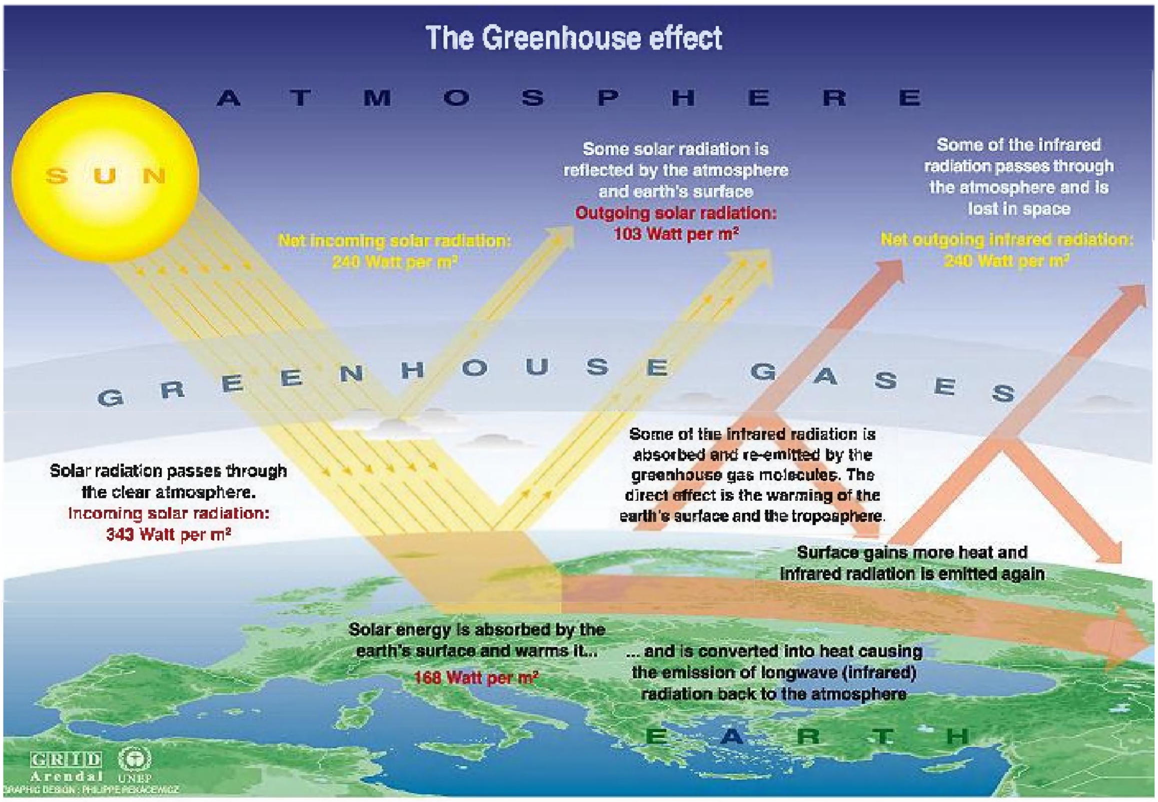


Figure 2.1 The greenhouse gases effect (IPCC, TAR 2001).

The overwhelming majority of experts worldwide now accept the science behind climate change. Studying climate science, its fluctuations and its possible impacts on natural systems (e.g., the hydrological system) is then with a high priority. The ongoing daily debates regarding the future of energy, agriculture, health, environment, etc. take their origins from the possible approaches of studying climate change impacts.

In the next paragraph, we will state the methods of approaching the complex problem of assessing climate change impacts on the hydrological system.

2.4 Methods for climate change impact analysis

The climate system is a physically based (all components have physical meaning) complex system. Scientists regroup its components into five major parts: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere. Each component regroups an unknown number of factors and processes. Our knowledge of the climate system is still limited.

The climate system changes its behaviour constantly at small temporal and space scales. A lot of interactions are taken place between the different factors and components which makes understanding it difficult and predicting its changes more difficult. The climate system behaves like an adiabatic enclosure forced or influenced by various external and internal forcing mechanisms. The effect of human activities on climate system is considered as an external forcing.

By changing one factor in one component of the climate system, and giving the complex interactions between the different factors and components, you are changing a total behaviour of the climate system on a range of different space and time scales. This point explains the total threat that climate change is causing, because actually we are not in the measure of surely expecting the climate answers to changes of the atmospheric composition due to greenhouse gases emissions and therefore the impact on the hydrological system. Although, many scientists link the recent floods disasters, hurricanes and droughts to the increased emissions of greenhouse gases, researches are still investigating this fact.

The climate as it is known, manages the totality of life on earth: the biodiversity, the ecosystem, the vegetations and animals types of a specific area are totally adapted and dependent on the climate. The hydrological cycle or system, which is also a physically based system, is dependent on the climate. Precipitation, for example as a climate variable, represents the major driving factor for the hydrological system. Temperature, humidity, solar radiation, wind speed and other variables are as well driving factors for several natural systems. It is therefore important to study the link between the climate and the different natural systems (Figure 2.2).

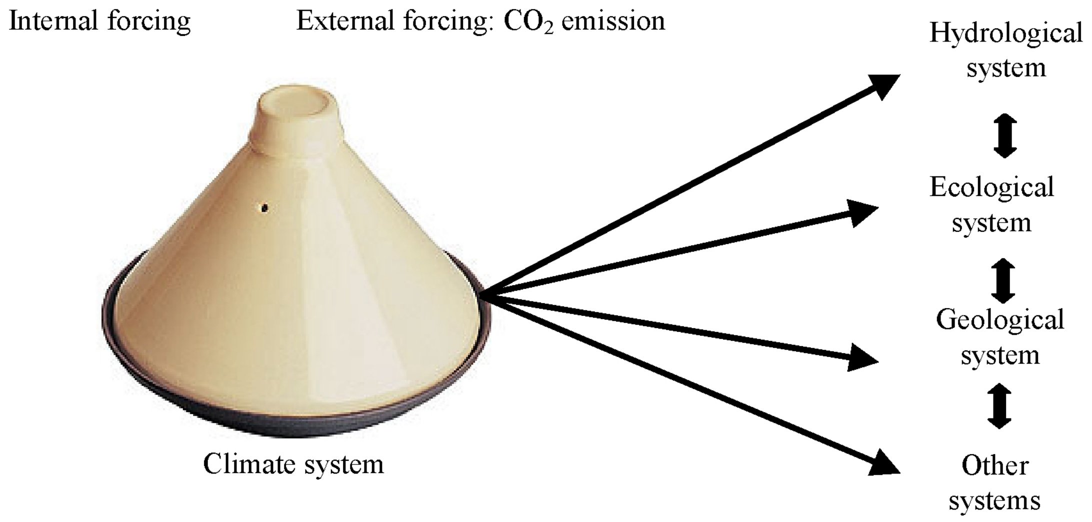


Figure 2.2 The interactions between the climate and natural systems.

As for the specific interaction between the climate system and the hydrological system, if we simulate the climate system to a manufacture, then the output products of this manufacture (climate variables e.g., precipitation, humidity, temperature…) will be acting as inputs for the hydrological system which products will be the hydrological variables (runoff…). The outputs of the climate system are very sensitive to the external and internal forcing acting on it, and therefore the outputs of the hydrological system will be totally influenced (Figure 2.3).

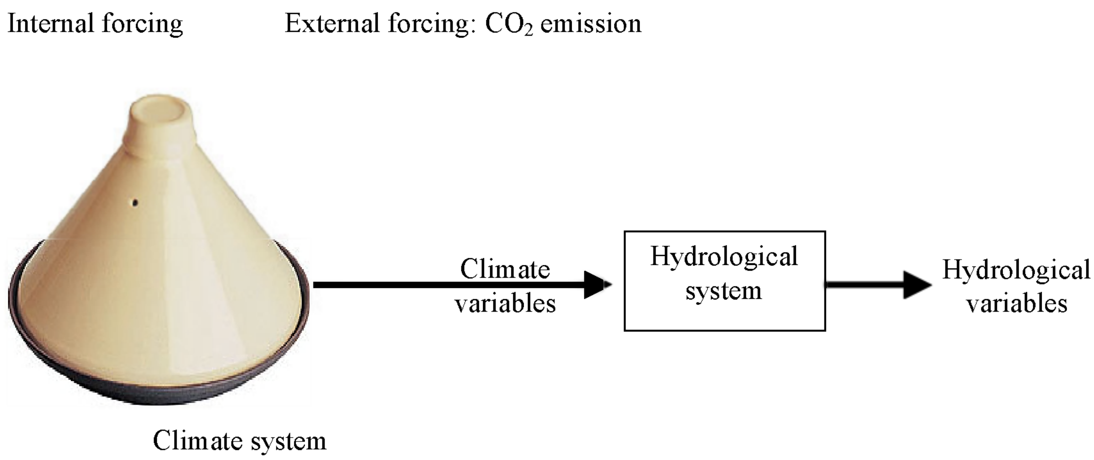


Figure 2.3 The interaction between the climate system and the hydrological system.

To make scientific progress in the field of investigating the link between the two systems, we need to explore mechanisms and test theories by carrying out experiments. However, it is not feasible to experiment on the climate system itself, nor is it possible to reproduce its full complexity in laboratories. That's why modalities for approaching the link are done through two major methods:

- Physically based methods;
- Empirical methods.

2.4.1 *The physically based methods*

These methods are totally based on the modelling science through climate models. Climate models are powerful computer programs designed to simulate earth's climate, they are based on mathematical equations that describe the behaviour of the climate derived from the laws of physics. Many equations describe how temperature, pressure, wind and other variables vary over the time. Other equations deal with the chemical and biological aspects of the climate. In a model, the climate variables are represented on a three dimensional grid covering the atmosphere and the oceans. The space between the points differs from model to model in a tentative of enhancing the resolution (Figure 2.4).

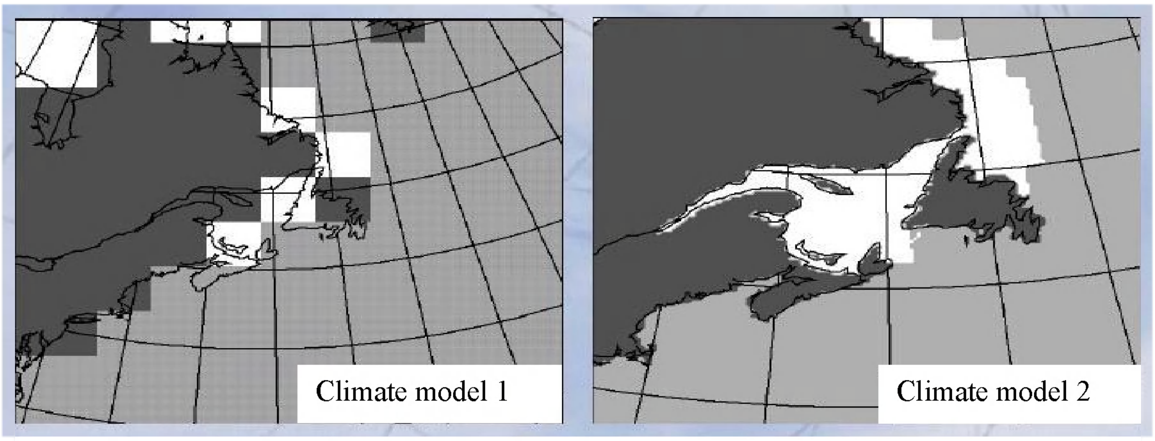


Figure 2.4 Climate models - Different resolutions (Goldstein et al., 2004).

The climate models are numerous and variables. They differ in their main concepts as in their resolutions and the integrated processes. By changing some parameters in the model equations, it is possible to see the answer of the whole climate system giving the different interactions between the components. The climate models are continually evaluated against datasets of real observations. Actual results show that the models can reproduce many aspects of the present and past climate. As for short-mid term forecasting, it has been shown that climate models can successfully forecast the climate and even major climate phenomena such as the Southern Atlantic Oscillation El-Niño.

Thus climate models offer us the best possible alternative to approach the issue of climate change impact. They are the only scientifically credible tool for making predictions about climate on global and regional scales. Nonetheless, although climate models sometimes disagree, they are still mathematical approximations of the climate system and not the system itself, their results must be taken with caution.

This research presents and illustrates with a study case the whole concept of the physically based methods in assessing climate change impacts on hydrology. We will present a detailed overview on the climate models, the differences between them, their advantages and disadvantages (chapter 3). The transition step between the climate system and the hydrological system, referred here as "Downscaling" will also be fully presented and discussed (chapter 4). Then we will end up to create future potential climate scenarios for Belgium (chapter 5) to be introduced into the hydrological system (hydrological model) (chapter 6) to assess the impact of climate change on the hydrological extremes along rivers in Flanders.

2.4.2 *The empirical methods*

In these methods we are making an eye on the climate system, with a special statistical focus on the climate outputs records which are inputs for the hydrological system (e.g., precipitation, temperature…). To both understand the present climate and predict the future climate change, it is necessary to have a look on the past. How the climate data varied across time provides a quantitative and qualitative measure of climate change. For that purpose, the climate data corrected for in-homogeneities (Generally caused by measurement instruments) needs to be analyzed. The statistical analysis of the climate data involves the calculation of averages and variances of the data and the identification, using various statistical techniques, of periodic variations, persistence and trends in the time series (Mitchell, 1966; Barry and Perry, 1973).

The aim of the statistical analysis is to identify systematic behaviour in the data and hence improve understanding the processes that drive such behaviour. Statistical analysis is a search for a signal in the data that can be distinguished from the background noise (Climate varies on all time scales in response to random and periodic forcing factors (Mitchell, 1976). Across all time periods from a few years to hundreds of millions of years there is a white (background) noise of random variations of the climate, caused by internal processes and associated feedback mechanisms, often referred to as stochastic or random mechanisms (Goodess et al., 1992). Such randomness accounts for much of the climate variation, and owes its existence to the complex behaviour of the climate system in responding to forcing (Lorenz, 1991; Nicolis et al., 1984; Palmer, 1989). That's why considering different time scales when investigating climate change is very important. In climate change research the searched signal will be a periodic variation, a quasi-periodic variation, a trend, persistence or extreme events in the climate variable. Figure 2.5 shows an example of typical periodicity and trend after statistical analysis of a climate variable (Conrad and Pollak, 1962).

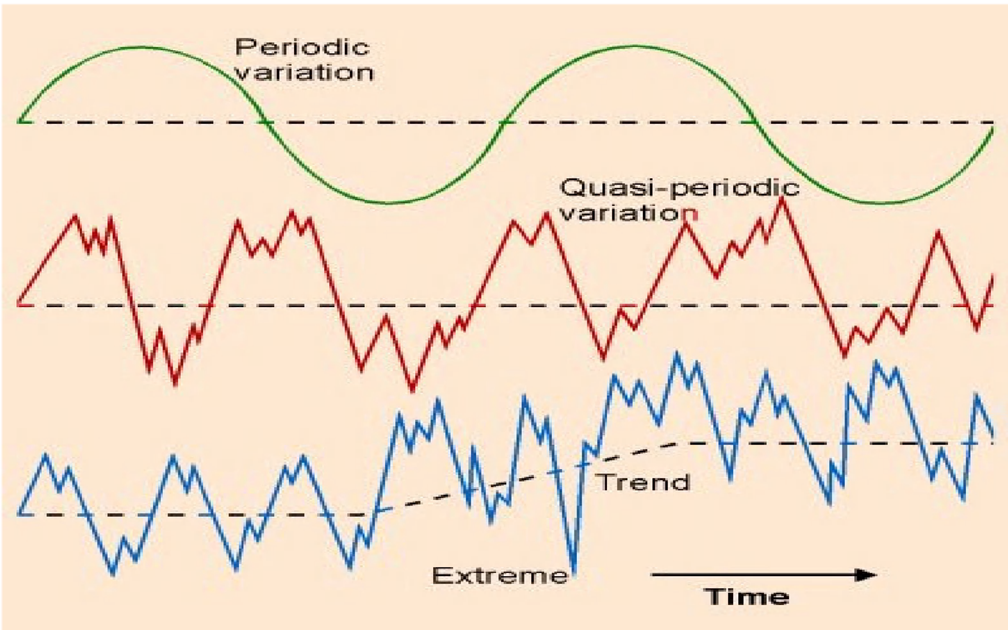


Figure 2.5 Example of periodic variation and trend in climate variable analysis (Conard and Pollak, 1962).

Actually, the statistical analysis of a climate record to investigate climate change should follow specific steps in order to achieve the goals. In a first step, descriptive and investigative analysis should be applied.

2.4.2.1 *Descriptive analysis*

It sets particular aspects of the variations present in the data set. Many statistical indices will be calculated and will include the mean and variance (or standard deviation). The occurrence of extreme events, cycles and trends will also be noted (Gibbs et al., 1978). Significance testing is important in this analysis. Significance testing establishes whether or not the variation of the data is different from what one would expect to arise in a random time series.

2.4.2.2 Investigative analysis

Investigative analysis is set to test a hypothesis. A hypothesis could be: “Does the times series contain an El Niño cycle?” (Mitchell, 1966).

In the second step, we are facing the choice of the most appropriate climate variable to set the empirical analysis on. For instance, precipitation from Uccle station (Belgium) is a good variable to use as it is representative of the most relevant physical climate processes taking place in the area, and it is sufficient in quantity and quality to support the statistical method. Uccle benefits of a 100-year precipitation data.

The next step consists on the choice of the appropriate technique to conduct the statistical analysis. Often it will be clear as to which statistical method of analysis is required. The nature of the data may determine whether or not a particular technique is valid (or, at least the way in which the technique is applied). Barry and Perry (1973) offer a detailed introduction of the mathematical aspects of statistical analysis, with many useful examples.

The statistical analysis of climate data serves to compliment and support theories developed to explain the causes (and effects) of climate change. It does not prove cause and effect because it is totally based upon the laws of probability. So when analyzing and interpreting climate data from a statistical point of view, for the effort to aid understanding the causes of climate change, it is necessary to set attentive conclusions.

2.5 Conclusion: Methods for climate change impact analysis

Assessing climate change impact on the hydrological field would lead to deal with two complex physically based systems: the climate system and the hydrological system. Both of the systems as for the interactions between them can be understood empirically and also through the modelling science. Climate system is represented by climate models and the hydrological system is represented by hydrological models. The models differ in concept, in natural processes included and in temporal and spatial resolutions. It is obvious then that the “better” resolute climate model looks to represent the natural processes happening in small spatial and temporal scales. This would have significant impact on the choice of the hydrological model.

From the other side, the climate models are forced by different emissions of greenhouse gases to produce different possible pictures of future climate. The outputs of the climate model simulations are used as forcing inputs of the hydrological models. Therefore the interaction or link between the two systems is taken place through some climate variables that will be used as drivers for the hydrological cycle (e.g., precipitation, temperature…). This link between the two systems is a very important interface and has to be studied in a careful way because it allows the right transfer of information between the two systems. This will be fully discussed in the “Downscaling Methods” chapter (chapter 4).

It is, however, important to mention that during the downscaling process, and while empirically analyzing the climate outputs that are valuable for hydrological studies; some climate models results would not be consistent with real observations and, therefore, cannot be valuable for impact analysis. This procedure allows a feedback from the interface between the two systems to the climate system and helps choosing the climate models the most representative of the real Belgian (Flanders) situation.

As for the empirical methods for assessing climate change impact on the hydrological field, they can be applied at both levels of climate system outputs and the hydrological system outputs.

It is to be mentioned that climatologists as well as hydrologists assume stationarity of physical phenomena representations in the climate models and in the hydrological models, while the climate is changing.

Figure 2.6 gives an overall summary on what has been explained above regarding the different methods of assessing climate change impact on hydrology.

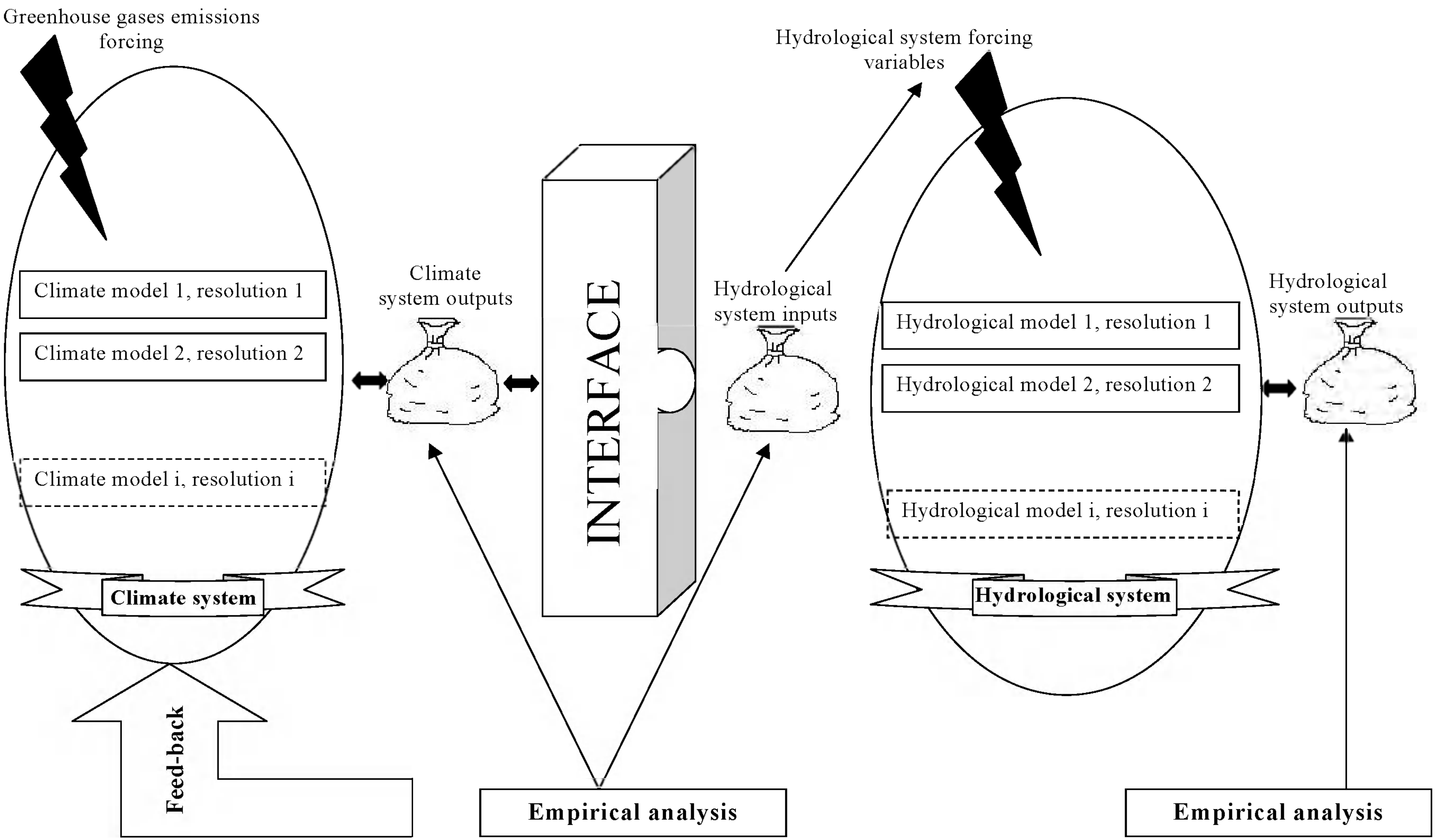


Figure 2.6 Different methods to assess climate change impact on hydrology.

Chapter 3

Description of Climate Change Physics

3.1 Introduction

Weather and climate have a deep influence on life on earth. They are part of the daily experiences of human being and are essential for health, food production and well-being. If one wishes to understand, detect and eventually predict the human influence on climate, one needs to understand the system that determines the climate of the earth and the processes that lead to climate change. Actually human activities occur on a scale that interferes with natural systems such as the global climate.

Climate change ultimately affects us all. Last year was the second hottest on record in Belgium (RMI, 2006). Many areas in the world experienced devastating droughts and bushfires. Indonesia saw weeks of incessant rain and the worst flooding in decades. In India, 1,000 people died in a heat wave. Rivers burst their banks and crashed through Germany, Russia and the Czech Republic. As temperature rose in Antarctica, 3,250 km^2 of the Larsen ice shelf collapsed (IPCC, TAR 2100). Scientists found that the global ice-melt rate had doubled since 1988 and predicted the sea could rise by 27 cm by 2100 (IPCC, TAR 2100).

However, our capacity to withstand climate change consequences can come down to economics and to standards of life. This is why “working/researching” on the climate change topic is with prior importance. Policymakers need an objective source of information about the causes of climate change, its potential environmental and socio-economical impacts, and possible response options.

Recognizing this, the Intergovernmental Panel on Climate Change (IPCC) was established by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) in 1988, with a basic role of assessing the best scientific technical information on climate change around the world. IPCC is open to all members of the UN and WMO and it regroups scientists and experts who base their assessments on reviewed literature related to the climate issue plus a set of assumptions (scenarios) to the evolution of the factors strongly interfering in climate change, mainly the future emission of greenhouse gases. The IPCC consists of three working groups; respectively the first group of assessment of scientific aspect of climate system and climate change, the second group addresses the vulnerability of socio-economical and natural system to climate change and the third group works on options for limiting greenhouse gas emissions and otherwise mitigating climate change.

The IPCC has completed four assessment reports, the first (FAR), second (SAR), the third (TAR) and the fourth assessment report (FOAR) respectively in 1990, 1995, 2001 and 2007 that developed methodology guidelines for national greenhouse gas inventories. IPCC published as well some special reports and technical papers. These assessment reports provide comprehensive scientific, technical and socio-economical information on climate change which have become standard works of reference, widely used by policymakers, scientists and researchers.

This chapter presents a summary on the main definitions of the climate system, the climate models, the expected changes, and how to predict them.

3.2 The climate system and climate models

3.2.1 Weather / climate definition

In common languages, the notions of “weather” and “climate” are cloudy defined. “Weather” is the fluctuating state of the atmosphere around us, characterized by the temperature, wind, precipitation, clouds and other weather elements. This weather is the result of rapidly developing and decaying weather systems such as mid-latitude low and high pressure systems with their associated frontal zones, showers and tropical cyclones. Weather has only limited predictability. Mesoscale convective systems are predictable over a period of hours only; synoptic scale cyclones may be predictable over a period of several days to a week. Beyond a week or two, individual weather systems are unpredictable.

“Climate” refers to the average weather in terms of the mean and its variability over a certain time-span in a certain area. Classical climatology provides classifications and descriptions of the various climate regimes found on earth. Climate varies from place to place, depending on latitude, distance to the sea, vegetation, presence or absence of mountains and other geographical factors. Climate varies also in time; from season to season, year to year, decade to decade or on much longer time-scales, such as the Ice ages. Statistically, significant variations of the mean state of the climate or of its variability are referred to as “climate change” (IPCC, TAR 2001).

Climate variations and changes, caused by external forcing, may be partly predictable, particularly on the larger continental and global spatial scales. Because human activities, such as the emission of greenhouse gases or land-use change, do result in external forcing, it is believed that the large-scale aspects of human-induced climate change are also partly predictable.

3.2.2 Climate variables

The traditional knowledge of weather and climate focuses on variables that affect daily life most directly: average, maximum and minimum temperature, wind speed and direction near the surface of the earth, precipitation in its various forms, humidity, cloud type and solar radiation. These are the variables observed hourly by a large number of weather stations around the globe. However the growth movement and decay of weather systems depend also on the vertical structure of the atmosphere, the influence of the underlying land, sea and many other factors not directly experienced by human beings (IPCC, SAR 1998). To understand the climate of our planet, its variations and then possibly predict the changes brought by human activities, there should not be any ignorance of these many factors and components.

3.2.3 The climate system

3.2.3.1 Climate components

The climate is an interactive system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere, forced or influenced by various external forcing mechanisms, the most important is the sun (Figure 3.1). The direct effect of human activities on the climate system is considered as an external forcing. The atmosphere is the most unstable and rapidly changing part of the system. Its composition, which has changed with the evolution of the earth, is of central importance. The earth's dry atmosphere is composed mainly of nitrogen (N_2, 78.1% volume mixing ratio), oxygen (O_2, 20.9% volume mixing ratio), and argon (Ar, 0.93% volume mixing ratio). However there are numbers of trace gases, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3), which do absorb and emit infrared radiation. These so-called greenhouse gases, with a total volume mixing ratio in dry air of less than 0.1%, play an essential role in the earth's energy budget (BBC planetary science, 2001). Moreover the atmosphere contains water vapour (H_2O), which is also a natural greenhouse gas. Those last absorb the infrared radiation emitted by the earth and emit an infrared radiation up and downward, they tend to raise the temperature near the earth's surface (IPCC, TAR 2001). The ozone layer in the lower part of the atmosphere, the troposphere and lower stratosphere, acts as a greenhouse gas.

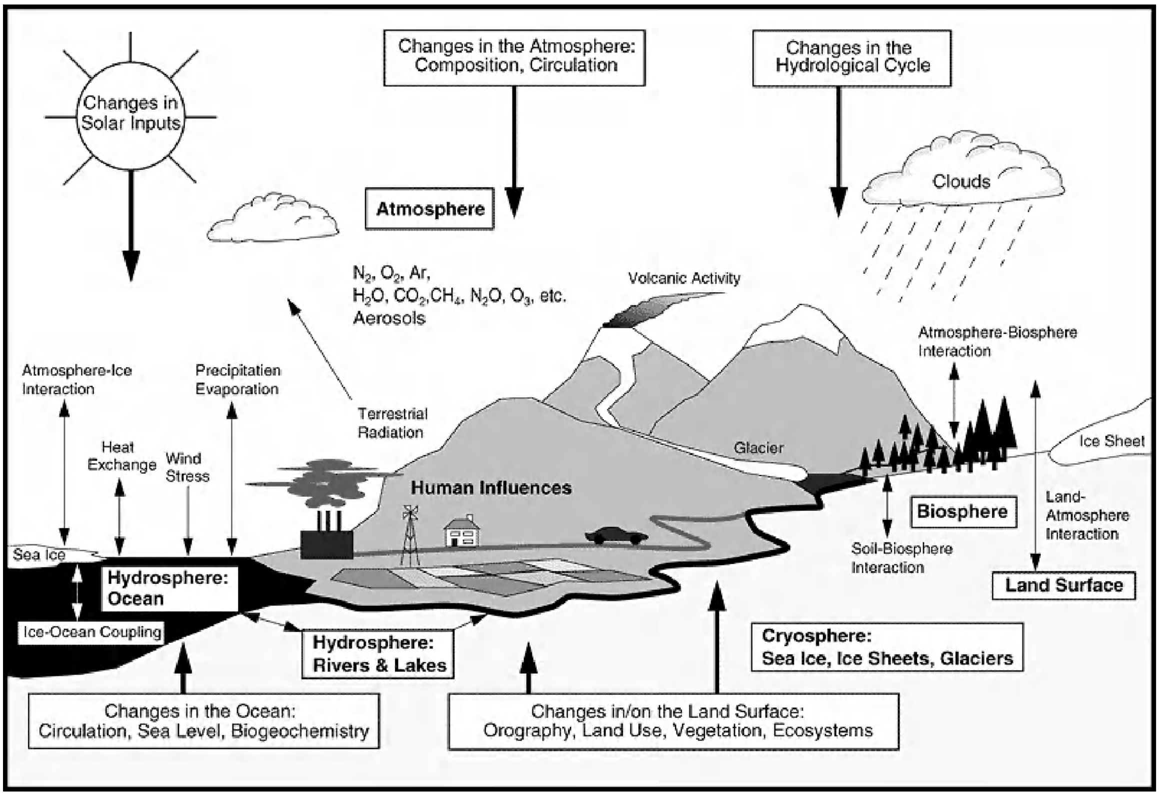


Figure 3.1. Schematic view of the global climate system components (bold), their processes and interactions (thin arrows) and some aspects that may change (bold arrows) (IPCC TAR, 2001).

The important component of the atmosphere is water in its various phases such as vapour, cloud droplets, and ice crystals. Water vapour is the strongest greenhouse gas (IPCC TAR, 2001). Due to these reasons and giving that the transition between the various phases absorbs and releases much energy, water vapour is central to the climate, to its variability and change.

The hydrosphere is the component comprising all surface liquids and subterranean water, both fresh water, including rivers, lakes, aquifers, saline water of the oceans and seas. The oceans cover approximately 70% of the earth's surface, they store and transport large amount of energy, dissolve and store great quantities of carbon dioxide. Their circulation, driven by the wind and density contrasts caused by salinity and thermal gradients (known as: thermohaline circulation), is much slower than the atmospheric circulation (WMO, 2002).

3.2.3.2 Interactions among the components

Many physical, chemical and biological interaction processes occur among the various components of the climate system on a wide range of space and time scales, making the system extremely complex. Although the components of the climate system are very different in their compositions, physical and chemical properties, structure and behaviour, they are all linked by fluxes of mass, heat and momentum: all sub-systems are open (IPCC, TAR 2001). The atmosphere and the hydrosphere are strongly coupled; this relation leads to condensation, cloud formation, precipitation, runoff, and supplies energy to weather systems. On the other hand, precipitation has an influence on salinity, its distribution and the thermohaline circulation (IPCC, TAR 2001).

3.3 The General Circulation Models: GCMs

3.3.1 General description of GCMs

With the enormous growth in computer power that has occurred over the past three decades, researches in both the physical and social sciences have turned increasingly on mathematical modelling as a way of exploring complex phenomena. Mathematical models link to the various equations that describe the key relationships and the processes within a system to simulate its behaviour. By changing the value of certain variables, scientists can study how the system responds to both external and internal changes. Although system processes can never be understood perfectly, models are trying to simplify the reality. The models result must thus be used with caution.

However, models in many areas have now reached such a degree of reliability that they are used routinely for operational purposes as well as for research. The models are particularly important in climate change research. Indeed, understanding the climate system and how it is likely to respond to increasing concentrations of greenhouse gases in the atmosphere would be impossible without the existence of what are known as global climate models or general circulation models (GCMs) e.g., powerful computer programs that simulate the function of the global climate system in three spatial dimensions and in time (Climate Change Digest Canada, 2000).

Present concerns about climate change arise from two basic facts. The first is that greenhouse gases, such as carbon dioxide and methane, retard the rate at which the earth loses heat to space and thus help to the warming of the earth's atmosphere. The second is that concentrations of these greenhouse gases are increasing as a result of human activities. This increase, which is already quite substantial and which will continue until greenhouse gases emissions are reduced, is expected to lead to a warming of the planet's lower atmosphere and surface. We cannot be certain how much it will warm, however nor can we immediately determine how other aspects of climate might be affected, because the earth climate system is very complex. It is the result not only of processes within the atmosphere itself but also interactions involving the world's oceans, land surfaces, life matter, and polar ice masses. A significant change in anyone of these elements can introduce important changes in the others. These in turn may cause a variety of feedback effects that further modify the original changes, in some cases offsetting or moderating it, in others, enhancing it (Hengeveld, 2000).

To determine the likely effects of a change such as an increase in greenhouse gases concentrations on the climate system, it is necessary to look at how the system as a whole unit responds. To do this, climate models are essential, because they integrate the main processes that occur within the climate system and calculate the adjustments of its various elements as they respond to the original changes.

The first models that could perform such tasks appeared in the late 1970s. They simulate the working of the earth atmosphere in three dimensions, representing the operation of climatic processes not only at the earth's surface but also in various levels above it. Because of the limited computer power available at the time, their simulations of the climate system were simplistic. Oceans that play a major role in transporting heat from one part of the globe to the other were described in a highly simplified way and their interactions with the atmosphere were represented only in a general way. Clouds, whose effects on the heating of the atmosphere vary with their structures; altitude and coverage of the sky (as well as with the time of the day) were also poorly represented and could not respond to changes in other atmospheric conditions. The representation of the water cycle, which has important implications for clouds, precipitation, soil moisture, and greenhouse warming, was equally crude. In addition, early models suffered from coarse resolution; in fact, they could only represent variations in the simulated climate variables at scales of about 800 km or larger. As a result, the precision with which they could represent many climatic processes was limited (Hengeveld, 2000).

By the late 1980s, advances in modelling techniques, understanding of climatic processes, and computer power made possible the development of a second generation of GCMs. Although these models still use highly simplified oceans, their representation of interactions between the upper ocean and the atmosphere was much improved. In addition spatial resolution had been enhanced, the description of the water cycle had become more detailed, sea ice and clouds respond to change in the model. With these models researchers, were able to explore the changes in climate that would result after the climate system has stabilized in response to a given climate change (usually a doubling in greenhouses gases concentrations). These models gave valuable insight into a sensitivity of the climate system to higher concentration of greenhouse gases, but they still could not simulate well what is known as transient climate change, that is the behaviour of the climate system while changing rather than it has changed. The ability to model transient change is very important because it gives close approximation to how we observe the climate system from year to year, decade to decade and hence allows more rigorous test of how well the model approximates the behaviour of the real system (Climate Change Digest Canada, 2000).

By early 1990s various modelling groups had began to meet these requirements, and a much more sophisticated third generation of climate models began to emerge. Known as coupled atmospheric-ocean general circulation models (AOGCMs) or more simply as coupled climate models, they include an atmospheric GCM that is fully coupled to a detailed three-dimensional model of the ocean. This feature, in combination with other refinements, gives them the ability to model climate much more realistically.

At the present time, there are more than 20 such models in use or under development around the world (Hengeveld, 2000). The use of GCMs in climate change predictions, however, often needs adjustments. This need of adjustments is a reminder that models are simplified approximations of a very complex reality, and that their results must be interpreted with caution. Evaluating the models reliability is with a major importance. Such evaluation not only indicates whether the model's performance is acceptable but also helps investigating experimental results and refines the model's components.

The performance of a model can be evaluated in a variety of ways. A basic test is its ability to reproduce the principal characteristics of the present climate. From the other side, investigating the model's ability to simulate past climatic changes is necessary. An inter-comparison in relation to other climate models is also an important step.

3.3.2 Types of simulations with GCMs

GCMs have been tested to see if they could realistically simulate changes in the world's climate over the past century. To do so, a series of experiments were run with the models. The first of these was a control run in which greenhouse gas concentrations and other external forces of change were held constant. The purpose of this experiment was to provide a reference or baseline (control or baseline scenario) against which the results of the other experiments could be compared. A second experiment considers only increases in greenhouse gas concentrations, converted to an equivalent or "effective" concentration of carbon dioxide. Finally, a set of experiments look at the effects of greenhouse gases and additional factors e.g., the direct effect of sulphate aerosols.

3.3.3 Most known GCMs

Currently, around 20 general climate models are in use or under development around the world. Table 3.1 presents some of the most known GCMs developed by the Canadian Center for Climate modelling and analysis (CCCma), the Center for Climate System Research (CCSR), the Commonwealth Scientific and Industrial Research Organization (CSIRO), the Service Center for Climate Researchers in Germany (DKRZ), the National Center for Atmospheric Research (NCAR) in America and the UK Met Office plus the Hadley Center for Climate Prediction and Research (UKMO). For each model, a scenario is setup generally depending on the increase of the concentration of greenhouse gases in air. Most GCMs take the period of 1960-1990 as a reference period, and build their scenarios based on an increase of CO_2 concentration (e.g., 1% a year), or by a factor increase in CO_2 concentration in the air (e.g., doubling of CO_2 concentration) which is supposed to happen around the year 2050.

Centre	Model	Reference	Scenario	Prediction of increase in temperature due to doubling CO_2 concentration T_{2*CO2} (°C)
CCCma	CCC	Mc Farlane et al., 1992	$2*CO_2$	3.5
	GCM1	Boer et al., 2001	1% $year^{-1}$	3.6
CCSR	CCSR 98	Emori et al., 1999	1% $year^{-1}$	3.5
CSIRO	CSIRO	Watterson et al., 1997	$2*CO_2$	4.3
	CSIRO-Mk2	Gordon and O'Farell, 1997	1% $year^{-1}$	3.7
DKRZ	ECHAM1	Cubasch et al., 1992	IPCC90A	2.6
	ECHAM3	Cubasch et al., 1996	IPCC90A	2.2
	ECHAM4	Roeckner et al., 1996	IPCC90A	2.6
NCAR	NCAR	Washington and Meehl, 1984	$2*CO_2$	4.0
	NCAR1	Washington and Meehl, 1996	1% $year^{-1}$	4.6
UKMO	UKMO	Wilson and Mitchell, 1987	$2*CO_2$	5.2
	UKH1	Haarsama et al., 1993	$2*CO_2$	3.5
	UKTR	Murphy et al., 1998	1% $year^{-1}$	2.7
	HadCM2	Mitchell and Johns, 1997	1% $year^{-1}$	2.5
	HadCM3	Gordon et al., 2000	1% $year^{-1}$	3.0

Table 3.1 Most known general climate models (DMI, 2004).

3.4 GCM scenarios

3.4.1 The role of scenarios

A scenario is a coherent, internally consistent, and plausible description of a possible future state of the world (IPCC, TAR 2100). Scenarios are required in climate change impact assessments to provide alternative views of future conditions considered likely to influence a given system or activity. A distinction is made between climate scenarios which describe the forcing factor of interest, and non-climatic scenarios which provide socioeconomic and environmental "context" within the climate forcing.

3.4.2 *Types of scenarios*

Most of the scenarios are based on emissions of greenhouse gases and aerosols due to human activities. Changes in climate occur as a result of internal natural variability of the climate system and external factors (as a result of human activities). Future emissions of greenhouse gases and aerosols are determined by driving forces such as population, socio-economical developments, and technological changes. Scenarios are alternative images of how the future might unfold and are an appropriate tool with which we can analyze how driving forces may influence future emission outcomes.

The IS92 series scenario consists of an assumption of increasing the CO_2 concentration due to human activities by 1% a year. This would lead to a doubling of the carbon dioxide concentration by 2050 and the triple by the year 2100. This picture has been used in many experiments as in the IPCC work reports I and II (1998, 2001).

In the year 2000, the IPCC published a very special report which they called “Special Report for Emission Scenarios” (SRES) that provides new concepts of emission assumptions. The SRES scenarios, developed to update the IS92 series, consist of six scenario groups, based on narrative storylines, which span a wide range of these driving forces (Figure 3.2). They are all plausible and internally consistent, and no probabilities of occurrence are assigned. They encompass four combinations of demographic change, social and economic development, and broad technological developments (A1B, A2, B1, B2). These emissions cause changes in the concentrations of greenhouse gases and aerosols in the atmosphere. As with the IS92 scenarios, all combinations of emissions of greenhouse gases and aerosols in the SRES scenarios result in increased radiative forcing (IPCC, TAR 2001).

- **A1.** The A1 storyline describes a fast growing economy, the introduction of new and efficient technologies and a population that peaks at around mid-century and declines thereafter. The storyline is further subdivided in three groups according to changes in the energy system: fossil-intensive (A1FI), non-fossil energy sources (A1T) and balanced use of all sources (A1B).
- **A2.** The A2 storyline describes a heterogeneous world, where the local identities are preserved and the population grows continuously. Economic growth and technological progress are more fragmented and slower than in other storylines.
- **B1.** In the B1 storyline, the global population evolves as in the A1 storyline, but the economic structures change rapidly towards a services and information model, while new clean and resource efficient technologies are developed.
- **B2.** The B2 storyline describes a world with global population evolving as in the A2 storyline but more slowly, and where emphasis is given on local solutions to sustainability. Intermediate economic development is expected while the technology would have a more diverse evolution than in the A1 and B1 storylines.

It might be important to mention that many specialists and researchers in the climate assessment impact believe that the A2 emission scenario is very severe comparing to the other scenarios and to the reality of human development. Although, most of the regional climate models simulations are done using the A2 scenario.

Generally, scenarios are built based on many factors. The approaches employed to construct them vary according to the purpose of the assessment. For instance, scenarios may be required for illustrating climate change, communicating potential consequences of climate change or for strategic planning for policymakers. In the following, we will mention some of the important factors that have direct impact on climate in regional as well as on global scale. Figure 3.3 shows the possible inter-connections between the purposes of assessments in a matter of constructing a scenario.

- Socio-economical scenarios: They have been used more extensively to project greenhouse gas emissions. Most socio-economical scenarios identify several different topics or domains, such as population or economic activity, as well as background factors such as the structure of governance, social values, and patterns of technological change. Most of these scenarios assume a continuous slow increase in world population with better use of energy towards comfortable technology;

- Land-use and land-cover scenarios: Most of these scenarios focus on food and life security issues due to climate change. Food security and carbon cycling are of most interest. However, large improvements have been made since the second assessment report (SAR) of IPCC (1995) in defining current and historic land-use and land-cover patterns, as well as in estimating future scenarios (IPCC, TAR 2001);

- Environmental scenarios: They focus on changes in environmental factors other than climate factors. Changes could have an important role in modifying the impacts of future climate change, such as atmospheric composition (e.g., carbon dioxide (CO_2), tropospheric ozone (O_3), water availability, water quality and marine pollution). The environmental scenarios assumptions consist mainly on an increasing amount of greenhouse gases as well as an increase of urbanization;

- Climate scenarios: One of the three following assumptions is used for the climate scenarios: incremental scenarios, analogue scenarios, or model-based climate scenarios. Mostly these scenarios are constructed by adjusting a baseline climate (typically based on regional observations of climate over a reference period such as 1961-1990) to different changes between the simulated present and future climates (IPCC, TAR 2001);

- Sea-level rise scenarios: These scenarios are built for security reasons especially for the low land and coastal areas. Relative sea-level scenarios tide gauge and wave height records of 50 years or more are required, along with information on severe weather and coastal processes, to establish baseline levels or trends. The simple method of obtaining scenarios is to apply global mean estimates from simple models. However, some new studies are taking the problem of sea level rise from a probabilistic side especially in assessing the occurrence of severe events (IPCC, TAR 2001).

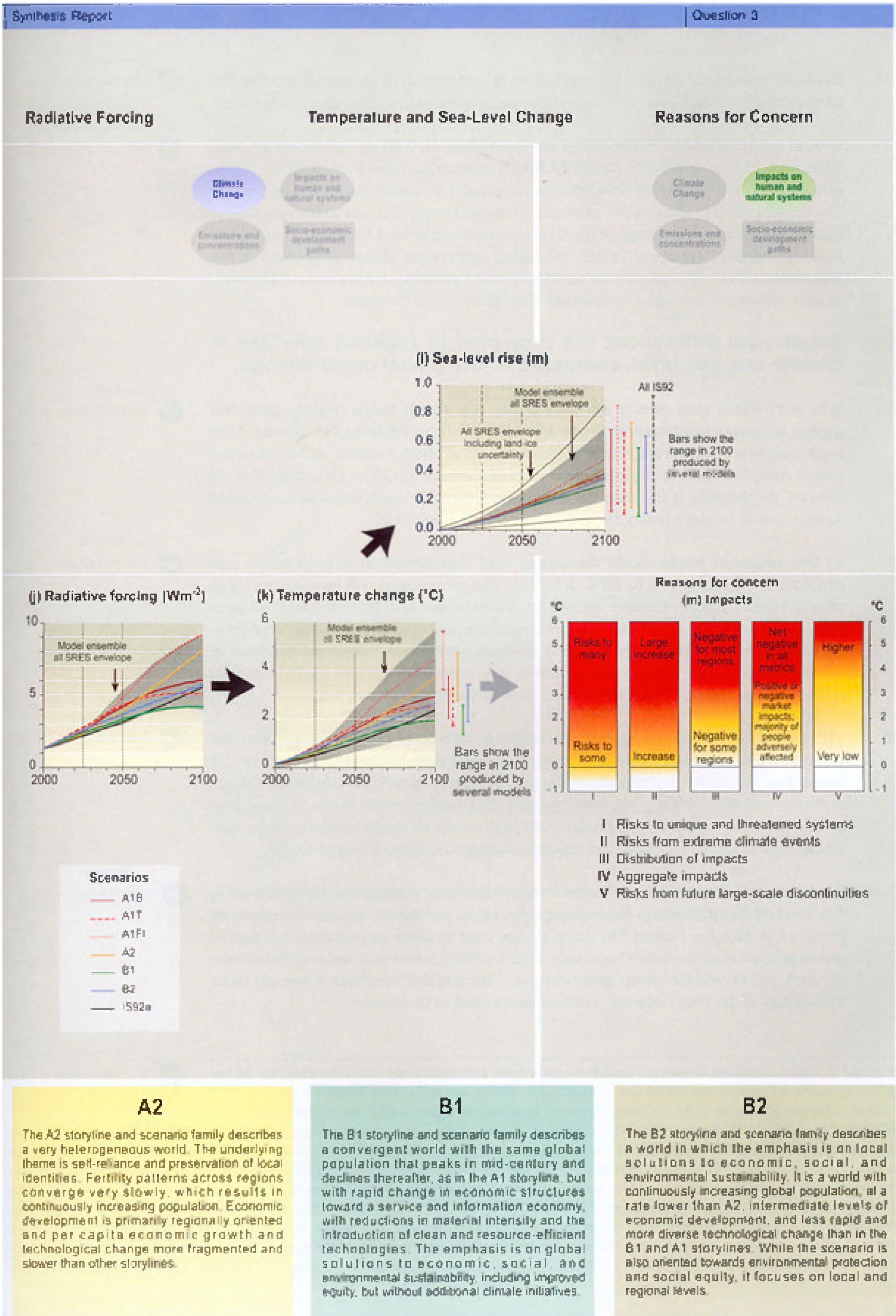


Figure 3.2 The SRES scenarios (IPCC TAR, 2001).

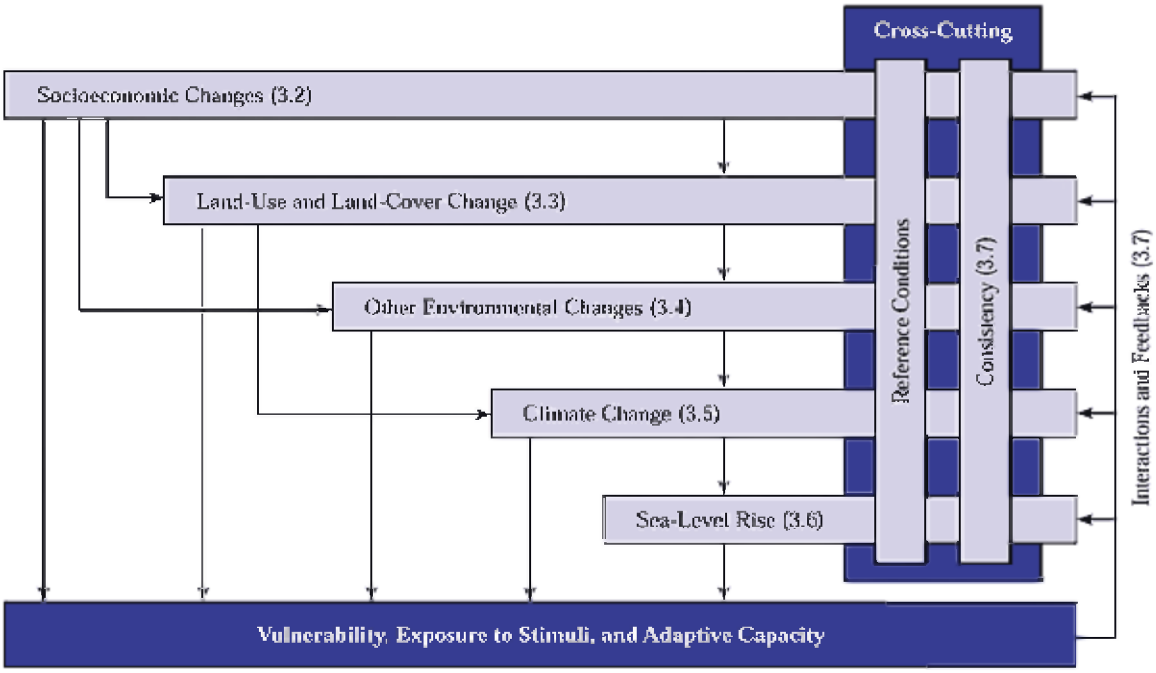


Figure 3.3 Types of scenarios required for climate impact, adaptation, and vulnerability assessment and their interactions (IPCC, TAR 2001).

3.5 Necessity of downscaling

Many impact studies have constructed their concepts and results on the basis of GCM outputs. It is therefore impossible to investigate the impact on smaller scales or on regional details, due to the wide resolution of the GCMs. In fact, one should know that these models have a very large spatial resolution (several hundred kilometers) which presents a fundamental barrier to progress in studies of atmosphere-hydrosphere interface (Figure 3.1), as the research community wants to develop an understanding issue of the impact of changes on smaller scales. Spatial and temporal scales used in the atmospheric studies considerably differ from those of hydrology for example. In order to match these discrepant scales, it is necessary to downscale climate outputs.

3.5.1 Method for GCM downscaling

Regional details are obtained from the coarse-scale outputs of GCMs by using three main methods: simple interpolation, statistical downscaling, and high-resolution dynamical modelling also known as Regional Climate Models (RCMs). Figure 3.4 states a simplified concept of downscaling.

The simple method of interpolation, which reproduces the GCM pattern of change, is the most widely applied in impact studies. As for the statistical method, it presents the major disadvantage of assuming that the statistical relationship made in between large and small scales would remain the same under changed climate. From the other side, modelling approaches in downscaling or RCMs are used as a mean to downscale from global scale of GCM simulations to regional scales. In this sense, the GCMs are used to provide a consistent representation of the large-scale global circulation, while the RCMs are used to introduce more details to the climate simulations due to regional features such as topography and inland seas (Rummukainen et al., 2001). In both cases, simulations are produced for a control climate representing present-day climate conditions and for future climates representing various greenhouse gas emission scenarios.

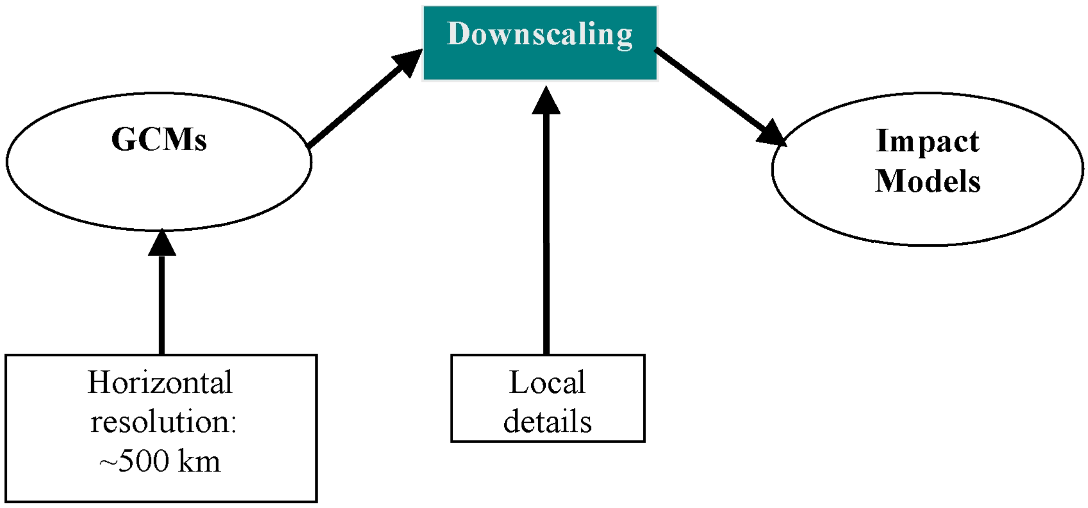


Figure 3.4 Introduction to downscaling.

Regional climate models (RCMs) are then climate simulation models with high resolution (horizontal resolution around 50 km) submitted to the GCM initial conditions as well as to their boundaries (Figure 3.5). For most of the cases, 30-year control climate simulations of present climate representing the period 1961-1990 are normally compared to future climate simulations representing the period 2071-2100.

Within the development of the variable resolution for general climate models, a new approach has enhanced the horizontal resolution through the stretched-grid GCM simulation. A finite-difference based atmospheric model, or dynamical core using variable resolution, or stretched grids, is developed and used for medium-term and long-term integrations. In fact, the stretched-grid approach is a good tool for representing regional to global scale interactions. It is an alternative to the widely used nested-grid approach introduced over a decade ago and allows one to allocate the area of interest with uniform fine-horizontal (latitude by longitude) resolution over any part of the globe. Outside the region of interest, grid intervals increase or stretch, with latitude and longitude. It has been shown that a significant downscaling is the one taking place over the area of interest, due to better-resolved regional fields and boundary forcing.

Some of the new generations of RCMs have shown up with an extra resolution of 25 km and even with 12 km. This is the case for the models HIRHAM1, 2 and PROMES (The PRUDENCE project, DMI 2004). Their output results can be directly introduced in impact models.

The European climate change impact project PRUDENCE used several high resolute regional climate models (10 different RCMs), ranging from 50km to 12km of spatial resolution and providing results of seasonal, monthly and daily prediction of the major climate parameters e.g., temperature, precipitation, cloud cover, evaporation, snow, soil moisture, surface pressure, mean sea level pressure, etc (DMI, 2004).

One should know that a special vote for a downscaling method is accompanied with several assumptions that present in some cases many disadvantages for the impact study. Table 3.2 provides the main advantages and disadvantages for every type of the climate models output associated to their downscaling methods. More details on different downscaling methods will be given in chapter 4.

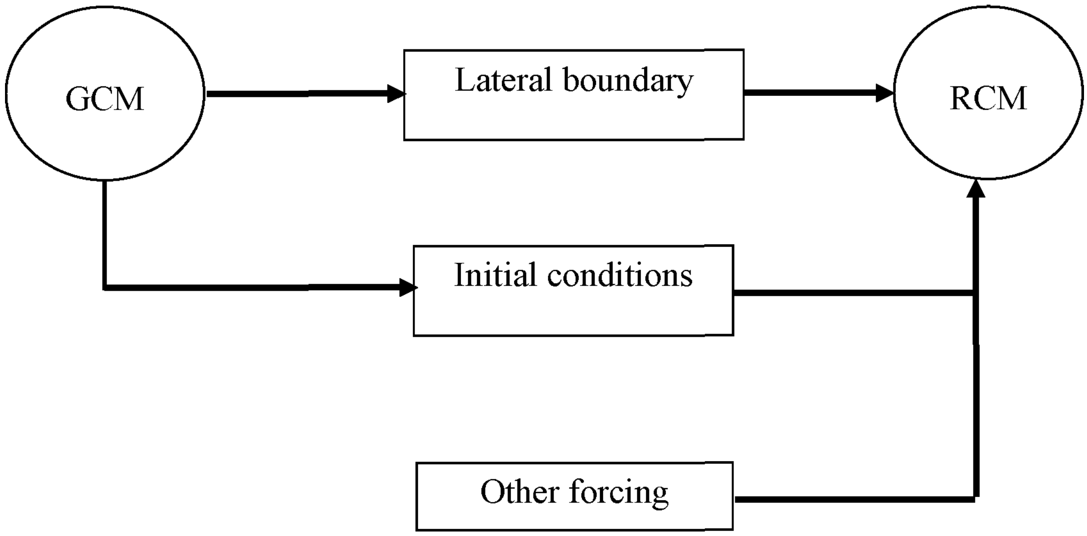


Figure 3.5 Downscaling with RCMs.

Model	Description	Advantages	Disadvantages
Coupled atmospheric ocean circulation models (AOGCMs)	• Starting point for most climate scenarios • Large scale response to anthropogenic forcing	• Information derived from the most comprehensive physically based models • Long integrations • Data readily available • Many variables	• Spatial information poorly resolved • Daily characteristics may be unrealistic except for very large regions • Computationally very expensive to derive many scenarios • Large control run biases may be a concern for use
Stretched Grid model AGCM	• Provides high resolution information at global continental scales	• Provides highly resolved information • Variables are globally consistent	• Computationally very expensive to derive many scenarios • Depending on inputs from AOGCMs
Climate model based + statistical downscaling	• Provides high spatial resolution information	• Can generate information on high resolution grids • Potential for some techniques to address a range of variables • Variables are internally consistent • Computationally cheap • Suitable for locations with limited computational resources • Rapid application to different GCMs	• Assumes constancy of empirical relationships in future • Demands access to daily observational surface and/or upper air data that span range of variability • Not many variables produced for some techniques • Depending on inputs from driving AOGCMs

Regional climate models (RCMs)	• Provides high spatial/temporal resolution information	• Provides very high resolved information in space and time • Information derived from physically based models • Many variables • Better representation of some weather extremes than in GCMs	• Computationally very expensive • Depending on inputs from driving AOGCMs

Table 3.2 Advantages and disadvantages of the different GCMs based downscaling methods.

3.5.2 Most known RCMs

The most known RCMs are:

- ARPEGE: a global operational forecast model in use at ECMWF and at the French meteorological service with different physical parameterizations. A third version with new parameters is in run for climate simulation having a range of 50 km resolution in the center of the Mediterranean Sea to 450 km in the southern Pacific Ocean. It has 31 vertical levels (Déqué et al., 1998).
- CHRM: the limited area mode CHRM derives from the operational weather forecast model HRM of the German and Swiss meteorological services. The model's computational grid is a regular latitude /longitude grid (81*91 grid points) with a rotated pole, a resolution of about 55 km and 20 vertical levels. This model is a full package of physical parameterizations including a mass-flux scheme for moist convection (Vidale et al., 2002).
- HadRM: this is the most recent Hadley Centre regional climate model HadRM3H. It is a limited area high resolution version of the AGCM HadAM3H which itself is an improved version of HadAM3, the atmospheric component of the latest Hadley centre coupled AOGCM HadCM3. Different relevant changes have been introduced in this model either in a fully physical parameterizations or empirical way. Large scale precipitation is derived from an explicit could water variable of the cloud scheme (Hudson and Jones, 2002).
- HIRHAM: it is an updated version of HIRHAM4 that uses the physical parameterization package of the general circulation model ECHAM4 developed by Roeckner et al (1996). These parameterizations include radiation, land surface processes, sea, surface sea ice processes, planetary boundary layer, etc. The adopted computational grid is a rotated regular latitude/longitude grid (110*104 grid points) with a rotated south pole at (27° E, 37°S), a resolution of about 50 km and 19 vertical level (Christensen et al., 2001).
- REMO: it is a regional climate model used as a combination of the dynamical core of the EUROPA model and the physical parameterization scheme of the ECHAM4 global climate model of the Max-Planck institute of Hamburg. REMO provides a resolution of about 55 km with 19 vertical levels. The integration domain covers whole of Europe and a part of the Atlantic Ocean. REMO has the same dynamical core like CHRM and shares the same physical parameterization schemes like those in HIRHAM (Hagemann et al., 1999).
- PROMESS: It is a regional climate model used in the European project PRUDENCE. It is in fact the climate version of the PROMES model of Castro et al (1993). The radiation in this model is considered from Anthes et al (1978). Explicit clouds formation and associated precipitation follows Hsie et al (1984). Soil-vegetation atmosphere exchanges are parameterized using the land-surface scheme SECHIBA (DMI, 2004).

Understanding the concept of the different climate models is with a basic importance. Each of them is trying to account the totality of the physically based phenomena occurring within the complex climate system. For instance, clouds play an important role, they significantly modify the distribution of the shortwave and long wave radiation absorbed and emitted by the earth in terms of affecting the temperature and humidity. The process of radiation interchanges within the different components of the system is taken into account in different climate models through different representations (equations). These last consider the upwelling and down-welling radiative transfer through different atmospheric layers. This is a more accurate representation giving the chemical composition change in the different layers of the atmosphere (troposphere, stratosphere…). RCMs therefore divide the atmosphere into a number of vertical levels varying between 19 to 31 levels. Table 3.3 makes a comparison of the main properties of some regional climate models (used in the PRUDENCE project).

Model	Resolution	Level number	Convection	Micro-physics	Land	Radiation
ARPEGE	50 km	31	Mass flux with moisture convergence closure (Bougeault, 1985).	-	-	-
CHRM	55 km	20	Mass flux (Tiedtke, 1989).	Kessler type (Lin et al., 1983).	4 thermal and 3 moisture layers (Dickinson, 1984).	(Ritter and Geleyyn, 1992).
CLM	56 km	20	Mass flux (Tiedekte, 1989; Nordeng, 1996).	Moist convection scheme	-	-
HadRM	50 km	19	Mass flux (Gregory and Rowntree, 1990).	(Smith, 1990, Jones et al., 2000).	4 thermal and 3 moisture layers (Cox et al., 1999).	-
HIRHAM	50 km	19	Mass flux (Tiedekte, 1989; Nordeng, 1996).	(Sundqvist, 1988).	5 thermal layers, 1 moisture bucket (Dumenil and Todini, 1992).	(Morcrette, 1991; Giorgetta and Wild,1996).
PROMESS	50 km	28	-	-	-	-
RACMOR	50 km	31	Semi-Langarian dynamical core (DMI, 2004)	-	-	-
RCAO	10-70 km	24-60	Bryan-Cox-Semtner (DMI, 2004)	-	-	-
REMO	55 km	19	Mass flux (Tiedtke, 1989).		5 thermal layers, 1 moisture bucket (Dumenil and Tidoni, 1992).	
RegCM	50 km	19	-	-	-	

Table 3.3 *Regional climate models characteristics (PRUDENCE website: http://prudence.dmi.dk).*

The “Convection” defined as a property in table 3.3, means the transfer of heat by currents within a fluid. It may arise from temperature differences either within the fluid or between the fluid and its boundary, which would affect density. Convection occurs in atmosphere and oceans continuously. Microphysics is meant for comprehensive cloud microphysics, which are a representation of the precipitation processes and cloud-aerosol interactions within clouds. Because cloud-radiation feedbacks depend strongly on cloud microphysics, they are critical for modelling both global climate sensitivity and regional climate change.

The land surface component is represented in the RCMs by changes in vegetation, changes in land use and in the total ecosystem taking account of the interaction occurring constantly between its different layers.

3.6 Review on climate change projects

This section gives an overview of recent and ongoing climate change projects based on climate modelling at regional and international scales, their goals and some of their results. The below description of the climate projects is classified following this scheme: the global scale projects investigating the reasons of climate change and climate change impacts will be presented first including the used GCMs. In a second step, we will present the impact analysis projects that developed high resolute regional climate models for climate prediction goals and used different downscaling methods. In the end, we will focus on the current climate projects and results of the Belgian neighbor countries. Comparing their climate project results to the Belgian results is with high importance as some of the countries share the same range of climate classification.

3.6.1 Large scale climate and climate change impact projects

- GPCP: Global Precipitation Climatology Project.

The Global Precipitation Climatology Project (GPCP) is a project element of the Global Energy and Water Cycle EXperiment (GEWEX) of the World Climate Research Program (WCRP). It was established by the WCRP in 1986 with the initial goal of providing monthly mean precipitation data. Monthly mean precipitation estimates were produced starting from 1979 and planned till 2005. The project used satellite data as a new way of estimation. The project is currently under work and the results are widely published. They based most of their calculations on general climate models (Moustafa et al., 2002).

- Abrupt Climate Change

Abrupt climate changes of the magnitude seen in the past would have far-reaching implications for human society and ecosystems, including major impacts on water supply demands. This project tried to estimate the likelihood of abrupt climate change, as to look for the potential social consequences of such a change. Abrupt Climate Change with its “Inevitable Surprises” branch looked at the current scientific evidence and theoretical understanding to describe what is currently known about abrupt climate, including patterns and magnitudes, mechanisms, and probability of occurrence. Abrupt climate change has highly focused on the collapse of the Gulf Stream; this is why this project used several GCMs where atmospheric circulation and ocean circulations are both linked. Abrupt was completed by 2002. It was funded by the National Oceanic and Atmospheric Administration (NOAA). The project results and publications are public (Alley et al., 2002).

- AIACC Project on Climate Change: Assessments of Impacts and Adaptations to Climate Change

This project enhances capabilities in the developing world for responding to climate change by building scientific and technical capacity, advancing scientific knowledge, and linking scientific and policy communities. These activities are supporting the work of the United Nations

Framework Convention on Climate Change (UNFCCC) by adding the knowledge and expertise that are needed for communications.

Twenty-four regional assessments have been conducted under AIACC in Africa, Asia, Latin America and small island states. The regional assessments include investigations of climate change risks and adaptation options for agriculture, water resources, ecological systems, biodiversity conservation, coastal settlements, food security, and human health.

The regional assessments were executed over the period 2002-2005. AIACC is a project proposed by the Global Environment Facility (GEF); it is implemented by the United Nations Environment Program (UNEP) and it is managed by the Global Change SysTem for Analysis, Research and Training (START) and the Academy of Sciences for the developing world (TWAS). AIACC received funds from several international environmental institutions. The assessment results are public in AIACC working papers and also reviewed online (Niel et al., 2005; Leary et al., 2005).

- WRINCLE: Water Resources, Influence of CLimate change in Europe

It is a European project funded by the European Union Environment and Climate Program for the purpose of studying the European water resources variability due to climate change. The project investigated the changes in most of the hydrological variables (precipitation, evaporation, river runoff...) at different temporal and space scales. As a specific task, WRINCLE investigated the environmental effects of water management measures. Hydrological changes within a catchment supply zone due to water demand management measures were identified and transferred into environmental benefit. Generic guidelines to aid policy-maker's decisions and deployment of water company resources were also produced.

Thus, WRINCLE allowed:

- Using the latest atmospheric model outputs to generate climate change scenarios;
- Improving downscaling methods to produce precipitation fields from model outputs, at hydrological important space-time scales. This has been done through dynamical and statistical downscaling methods;
- Introduction of new hydrological modelling tools and assessment of the extreme events.

This project was completed in 1999 and was very valuable in the step of improving the information resulted from climate models (Kilsby, 2000).

3.6.2 Regional scale climate and climate change impact projects

- BIOCLIM: modelling sequential BIOsphere systems under CLIMate change for radioactive waste disposal

The aim of BIOCLIM was to summarize what was known about the causes of climate change. Using different approaches, present day biosphere system descriptions were provided for the European areas that formed the focus for the climate change work (eastern France, central England, central/southern Spain, Czech Republic and Germany). As a second step, the project developed a hierarchical strategy for representing sequential climate changes to the geosphere-biosphere system.

Different GCMs models were used in this project: an earth model of intermediate complexity (EMIC-LLN-2D-NH model) to provide the long-term evolution of the climate for the Northern Hemisphere; and second model (IPSL_CM4_D) to provide a more detailed global view of the climate; and a regional climate model (RCM) (MAR model) to provide an even more detailed view at the regional scale.

The project provided therefore long term climatic scenarios for future changes with simplified physically based models. As for the downscaling approach used in this project, the methodology requested different steps summarized below:

- Development of regional climatic sequences and indices for the last climatic cycle;
- Identification of relationships between climate states and historical record;
- Identification of appropriate analogue situation to describe actual climate;
- Selection of appropriate variables for downscaling;
- Evaluation of the rule-based downscaling methodology for the last climatic data.

Thus, the project used mainly statistical downscaling with the re-sampling method in order to identify similar previous situation. BIOCLIM was completed by 2003. It was funded by the European Union. The project results and publications are public (Calvez, 2003).

- MONARCH: MOdelling NAtural Resource responses to climate CHange.

In April 2000, the MONARCH was born and concerned the areas of England and Ireland. This project is an investigation of the impacts of climate change on the natural conservation resources of the UK and Ireland. MONARCH investigated the impacts of climate change on the nature conservation resources of Britain and Ireland using regional climate models. Such results helped in developing methodologies for specifying changes incorporating additional factors, such as land use/cover and dispersal capability. It is also exploring the consequences of such changes for ecosystem functioning (including plants, birds and amphibians).

MONARCH project is an application of dynamical downscaling through several regional climate models with different spatial resolutions. MONARCH was completed in 2005. It was funded by English Nature (Berry et al., 2005).

- REGIS: REGional climate change Impact and response Studies in East-Anglia and North-West England
    - The REGIS project was set to achieve a better understanding of climate change impacts. It focused on different small scales of the UK region. Several modelling tools were used ranging from ecosystem environmental models to hydrological models. All of them were taken at regional scales beneficing from dynamical and several statistical downscaling techniques. The project aimed mainly to:
    - Assess the impacts of future climate change on the agriculture, biodiversity, hydrology and coasts of East Anglia and the North West of England;
    - Adapt, calibrate and validate existing models of agriculture, water resources, biodiversity and coastal zones for East Anglia and the North West, which can be used to assess the impacts of climate change;
    - Explore the impacts for the 2050s;
    - Involve regional experts, decision-makers in the design of the assessment;
    - Produce a methodology that can be used by other stakeholders or similar interest groups to address the same kinds of questions elsewhere in the UK.

REGIS provided a template for further assessments and studies by government departments and local authorities. It was completed in 2001 and funded by the Department for Environment, Food and Rural affairs DEFRA (Holman and Loveland, 2001).

- ASCCUE: Adaptation Strategies for Climate Change in the Urban Environment

The ASCCUE project concerns the vulnerability of towns and cities to climate change, and the development of adaptation strategies. For urban settlements in developed economies there is strong research evidence for moderate/high climate change impacts on buildings and infrastructure. People are threatened by flooding, landslides, sea level rise, heat/cold waves, water shortage, hail/windstorm, air pollution and intensification of high temperature. The key issues for UK towns and cities are considered to be the flooding, subsidence, wind and storm damage, and the impacts of warmer summers on thermal comfort. The research will address these problems by developing and testing tools for vulnerability assessment, followed by planned adaptation to change through strategic planning and urban design. The work will focus on the consequences for buildings, urban green space, human comfort and the interaction between them.

This project uses both general and regional climate models specified for each purpose. The project started in 2003, it is still under application and is funded by the Centre for Urban and Regional Ecology, UK (Daryn, 2003).

- ESPACE: European Spatial Planning Adapting to Climate Events

Funded by INTERREG North West Europe and the deputy office of UK prime minister, the ESPACE project is a promising step for spatial policy guidance on adaptation to climate change. It is a four-year project using different kinds of models and downscaling techniques for the purpose of:

  - Raising awareness and understanding of climate change and the need for adaptation;
  - Developing and reviewing spatial planning policies which take account of climate change;
  - Developing of a sound information and knowledge base (definitions, scientific data, risks, spatial planning regimes).

EEPACE works to ensure that the need for adaptation to climate change is recognized and to recommend that it is incorporated within spatial planning mechanisms at local, regional, national and European levels. The first adaptations and communication tentatives are promising and the goals of the project are being reached. Monthly project activities are released and can be found under the ESPACE work paper (Chitra, 2005).

- PRUDENCE: Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects. This project was previously described in chapter 1, ‘section 1.4’

Table 3.4 summarizes all the information presented above regarding the international and regional climate projects and impact project analysis.

Project	Funding agency	Covering region	Period	Type of Climate model	Impact analysis (yes/no)
GPCP Global Precipitation Climatology Project	World Climate Research program (WCRP)	World scale	1986-2005	Different kind of climate models	No
Abrupt Climate Change	National Research Council. USA	The totality of the Globe	Completed in 2002	GCMs	No
AIACC Assessments of Impacts and Adaptations to Climate Change	UNEP/WMO The Global Environment Facility	Southern and West Africa 46 developing countries. Especially Gambia and South Africa	2002- Till now	Regional climate models (specific to each region climate classes)	Yes. Impact analysis. Vulnerability and adaptation capacity
WRINCLE Water Resources: Influence of Climate change in Europe	EU Environment and Climate program	EUROPE	Completed in 1999	Different kind of climate models	Yes. Assess the variability on the European water resources due to climate change
BIOCLIM (2000) Modelling Sequential Biosphere Systems under Climate Change for Radioactive Waste Disposal	European union	Eastern France, central England, central/southern Spain, plus Czech Republic and Germany	2000-2003	General climate model GCM (IPSL_CM4_D) to provide a more detailed global view of the climate Regional climate model RCM (MAR model) to provide an even more detailed view at the regional scale	Yes. The project developed recommendations on how the effects of climate change on the biosphere

<u>MONARCH</u> Modelling Natural Resource Responses to Climate Change	English Nature	England, Ireland	2003- Till now	Different regional climate models	Yes. Consequences of climate changes for ecosystem functioning (including plants, birds and amphibians)
<u>REGIS</u> Regional Climate Change Impact and Response Studies in East Anglia and North West England	Department of Environment Food & Rural Affairs. England	England	1998-2001	Both general and regional climate models associated to the specific impact models (hydrological models, agriculture models, water quality models...)	Yes. Assess the impacts of future climate change on the agriculture, biodiversity, hydrology and coasts of East Anglia and the North West of England
<u>ASCCUE</u> Adaptation Strategies for Climate Change in the Urban Environment	Centre for Urban and Regional Ecology. UK	England, big cities	2003- Till now	Small scale models	Yes. The vulnerability of towns and cities to climate change, and the development of adaptation strategies
<u>ESPACE</u> European Spatial Planning Adapting to Climate Events	INTERREG North West Europe and the UK office of first minister	North-West Europe	2004-Till now	Different kind of climate models	No
<u>PRUDENCE</u> Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects	EU Environment and Climate program	Europe	2001-2005 Completed	More than 10 regional climate models with high temporal and spatial resolution	• Assess the *<u>uncertainty</u>* in European regional climate scenarios; • Quantitatively assess the *<u>risks</u>* rising from changes in regional weather and climate over all of Europe, and estimate future changes in *<u>extreme events</u>*

Table 3.4 Generalities about international and regional climate projects.

3.6.3 Climate impact projects in European neighboring countries

European economical organizations and industries as well as the general public need detailed information on future climate. Projections of future climate change already exist, but are deficient both in terms of the characterization of their uncertainties and in terms of their regional details. The GCM coarse resolution precludes the simulation of realistic extreme events and the detailed spatial structure of variables like temperature and precipitation over heterogeneous surfaces e.g., the Alps, the Mediterranean or Scandinavia.

European governments took this issue in a very serious way; lots of laboratories and research centers are working on increasing the resolution and information from the GCMs, the urgent need for improved numerical models and scenarios becomes particularly apparent when considering extreme events. The importance of extreme events for Europe economy and environment has dramatically been demonstrated during the last few years with a number of serious events affecting the continent. Improving the GCMs resolutions and regional climate information as well as working on the downscaling techniques towards smaller scales and extreme events predictions are then in higher priorities.

It is interessant to see what is done inside each European country especially those in Belgian (Flanders) neighbors. Some of the Belgian neighbor countries share the same range of climate classification, thus comparing their climate change impact results to Belgian climate project results is very valuable.

In Germany: András Bárdossy (Universität Stuttgart) applied classification approaches on different climate regions including Germany and Greece. The main aim is to quantify possible impact of climate change on water balance and occurrence of extreme events at a medium time scale. The results show that the origin of the largest uncertainties is the GCM modelling (Bardossy, 2002).

In the Netherlands: In June 2006, the KNMI released the official climate change scenarios for the Netherlands covering 5 hydro-climatological variables. Temperature, precipitation, potential evaporation and wind are predicted for the year 2050. Sea level rise is predicted for the years 2050 and 2100. Climate change is represented by changes in many climate indices related to the means and extremes on different temporal and spatial scales, that's why the scenarios have been constructed based of different sources and techniques and user consultation involving individuals and institutions working on future planning for the Netherlands in the areas of water, agriculture, energy, ecosystem, transport and infrastructure. GCMs simulations prepared for the upcoming fourth assessment report (FOAR) of IPCC, were an important useful source for the Netherlands climate change scenarios.

The KNMI concluded that the majority of variable changes could be related to predicted changes in global mean temperature and changes in air circulation patterns. Thus, based on prediction results from the GCMs for 2050, two temperature scenarios were constructed and are refined by two anticipated circulation regime scenarios. The four scenarios are (Table 3.5):

- A "moderate" increase in temperature: +1°C in 2050;
- A "strong" increase in temperature: +2°C in 2050;
- A "weak" change in air circulation (W);
- A "strong" change in air circulation which includes warmer and moister seasons and increasing the likelihood of dry summertime (W+).

The circulation parameter appears to have great impact on the number of precipitation days, the seasonal means and the extreme intensities exceeded once in 10 years. This issue was therefore used to evaluate the performance of a group of GCMs simulated by FOAR for present day climate conditions. Five models with adequate skills were selected among eight GCMs and were used for the construction of the temperature, precipitation and wind scenarios. The three removed models present low resolution versions and systematic biases that cause errors in the surface pressure and circulation patterns. The five selected models are presented in table 3.6.

Scenario	Global temperature increase	Changes of atmospheric circulation
G	+1°C	Weak
G+	+1°C	Strong
W	+2°C	Weak
W+	+2°C	Strong

Table 3.5 The four KNMI climate scenarios (G: moderate, W: Warm, +: strong changes in circulation) (Van den hurk et al., 2006).

GCM	Reference
ECHAM$_5$	Jungclaus et al, 2005
CCC6$_3$	Flato, 2005
GFDL $_{2.1}$	Delworth et al, 2006
HadGEM	Johns et al, 2004
MIROCH$_I$	K-$_I$ model developers, 2004

Table 3.6 Selected general climate models based on the circulation parameter

(Van den hurk et al., 2006).

The KNMI scenarios assess climate changes in the whole region as the Netherlands comprises a relatively small area. The results remain consistent with the total western European area where high summer temperature and dry weather condition are expected. Different quantile and statistical techniques were used to derive the predictions for mean temperature, warmest days, wettest days, extreme precipitation… (See table 3.7). For the actual time, it is still impossible to assign probabilities for the predicted events. Probability density functions for future global temperature based on ensemble GCM simulations are gaining attentions (Murphy et al., 2004; Stott et al., 2004), but large uncertainties in atmospheric circulation response, in models concept, in emission scenarios are still fundamental barriers for decreasing the prediction uncertainties. The KNMI scenarios present a step to eliminate prediction errors when following the series of variables from temperature via sea level rise, precipitation and wind. The mean changes seem to be more certain than changes in the extremes; this is due to the complexity of the physical processes.

Variables	G	G+	W	W+
Summertime values				
Mean temperature (k)	0.9	1.4	1.7	2.8
Yearly warmest day (k)	1	1.9	2.1	3.8
Mean precipitation (%)	2.8	-9.5	5.5	-19
Wet day frequency (%)	-1,6	-9.6	-3.3	-19.3
Precipitation on wet day (%)	4.6	0.1	9.1	0.3
10 year return level daily precipitation sum (%)	13	5	27	10
Potential evaporation (%)	3.4	7.6	6.8	15.2

Wintertime values				
Mean temperature (k)	0.9	1.1	1.8	2.3
Yearly coldest day (k)	1	1.5	2.1	2.9
Mean precipitation (%)	3.6	7	7.3	14.2
Wet day frequency (%)	0.1	0.9	0.2	1.9
Precipitation on wet day (%)	3.6	6	7.1	12.1
10 year return level daily precipitation sum (%)	4	6	8	12

Table 3.7 KNMI climate change scenario for 2050 relative to 1990 (Van den hurk et al., 2006).

Complementary to this KNMI research, de Wit et al. (2001) and de Wit et al. (2007) have conducted several climate impact projects on the hydrology of the Meuse river basin. They have proceeded within the modelling technique in assessing climate change impact in the Meuse by introducing the direct outputs of 9 GCMs (instead of RCMs) into the hydrological models. de Wit et al. (2001) suggested two different GCM runs, where the first takes changes derived only from the HadCM2Gsa1 global circulation model and the second represents a mixture of other GCM runs, both using an average range of emission scenario. They extract therefore the average monthly relative change of the variables of interest (temperature, precipitation, cloud cover, wind speed, relative humidity) to be directly applied to the hydrological models. The results show that climate change may result in a decrease of average precipitation during the summer which may lead to low flow problems especially during the autumn mainly due to the increase of summer temperature. The increase of winter precipitation might lead to an increase of the discharge regime of the Meuse (de Wit et al., 2001; de Wit et al., 2007).

In Switzerland: The laboratory of hydrology and land improvement at the Swiss Federal Institute of Technology, Lausanne (HYDRAM, EPFL), Hingary et al (2005) developed probability distributions of surface temperature and precipitation for regional climate change. It combines a probability distribution for global mean temperature increase with the probability distributions for the appropriate scaling variables, e.g., the changes in regional temperature/precipitation per degree global mean warming. The distribution of each scaling variable is assumed to be normal. The uncertainty of the scaling relationship arises from systematic differences between the regional changes from global and regional climate model simulations and from natural variability.

Five case regions were considered: N-W England, the Rhine basin, Iberia, Jura lakes (Switzerland) and Mauvoisin dam (Switzerland). The resulting regional climate changes for 2070-2100 vary significantly between seasons, and between meteorological variables. A notable point is that for all the regions, the expected warming in summer is higher than the expected warming for the other seasons. The summer warming is accompanied by a large decrease in precipitation. The uncertainty of the scaling ratios for temperature and precipitation is relatively large in summer due to the differences between regional climate models (Hingary et al., 2005).

In Denmark: The Danish hydraulic Institute (DHI) with collaboration with The Danish meteorological Institute (DMI) are working on investigating the climate change impact and extreme events occurrence in Denmark. Giving the relatively long coastline and the North Sea meeting the Baltic Sea, also with the high natural variability, a dynamical downscaling method is being adopted actually using the regional climate model: HIRHAM. This model is a 12 km resolution model (DMI, 2004).

In UK: The project "UK Climate Impacts Program (UKCIP)" is the leading project over the Britain area. In the UKCIP98 and UKCIP02 projects, general climate models and regional climate models were considered with 300 km - 50 km grid resolutions, 15 climate variables, 4 emission scenarios and 3 predicted time slices: 2020s, 2050s, 2080s. The results have become a standard reference for impact assessment in UK. It was concluded that the monthly, seasonally and annually mean precipitation will be largely influenced by the emission scenarios for the future climate. Summer precipitation mean volumes will have a decrease of about -60% comparing to the actual time and an increase in winter volumes by +45% in winters of the 2080s. UKCIP02 results talk about hotter drier summers, wetter winters, and frequent extremes precipitation. These results confirm the large result tendency for most of European countries (CIWEM, 2006).

The project also suggests new approaches that are actually emerging into researches that will try to give "probabilistic" forecast for climate variables, since the climate modellers are actually UNABLE to quantify the climate models uncertainties. Although the uncertainties are still far to be perfectly accounted, the probabilistic forecasting, testing non-stabilization emission scenarios vs. stabilizations emission scenarios, is still a very promising field and as it matures better advances in climate researches could drive policy (CIWEM, 2006).

As a specific application on south-east England, HR Wallingford was working on potential impact of climate change on rainfall and drought. His results concluded that the river flows show positive and negative impact respectively in winter and in summer. The magnitude of river flow variation depends essentially on the emission scenario and reaches in summer time a reduction of almost -40% for south-eastern UK catchments. The range of variations for the hydrological variables is different from model to model and from scenario to scenario, although most of them agree about wetter winters and drier summers (CIWEM, 2006).

In Belgium itself, previous studies were made by Vaes, Willems and Berlamont (Hydraulics Laboratory, K.U.Leuven) who investigated the possibility of trends on the 100 years Uccle rainfall record (Vaes et al., 2002). Blanckaert and Willems have made further investigations on the cyclic behaviour of Uccle rainfall (Blanckaert and Willems, 2006). From his side, Gellens and colleagues (e.g., E. Roulin) (RMI) applied the IRMB model (Integrated Runoff Model) to eight Belgian Catchments to assess the stream flow response to IPCC scenarios. They found that all the catchments present an increase in flood frequency during winter months (Gellens and Roulin, 1998).

3.7 Additional climate change effects

Climate change obviously impacts on several natural fields in different ways. The scientific literature is very rich with studies about climate change effects on soil reaction (pH), fertility, microbial decomposition of organic matter…but also several studies focused on climate change induced effects on crop response to increase of CO_2 and to productivity. Parry (1990) sketches a broad picture of the effects of climate change on crop production; he stated that the effects of CO_2 enrichment, without associated changes in climate, would probably be beneficial for agriculture. Higher temperatures, however, could increase the rate of microbial decomposition of organic matter, adversely affecting soil fertility in the long term.

Most researchers believe that higher temperatures and droughts caused by climate change will depress crop yields in the coming decades. But a recent consensus has emerged that rising atmospheric concentrations of CO_2 could come to the rescue (Easterling et al., 1993). The gas thought to be behind global warming could also speed up photosynthesis. Some modelling studies used scenarios that do not include the physiological effects of CO_2 predict a decrease in estimated crop production, but including the physiological effects of CO_2 mitigates the negative effects (Bowman and Strain, 1987).

The analysis of biophysical impact of climate changes associated with global warming showed that higher temperatures generally threaten plant maturity, thus shortening the growth stages of crop plants. Global estimates of agricultural impacts have been fairly rough to date, because of lack of a consistent methodology and uncertainty about the physiological effects of CO_2.

According to Easterling et al (1993), climate change could have possible variations in forcing variables through:

- A gradual, continuing rise in atmospheric CO_2 concentration entailing increased photosynthetic rates and water-use efficiencies of vegetation and crops, hence increases in organic matter supplies to soils;

- Minor to moderate increases in soil temperatures during extended periods in which soils warm enough for microbial activity could return to an increase in crop production depending on changes in air temperatures and vegetation zones;
- Increases in evapo(transpi)ration in high latitudes caused by temperature increase could return to an extension of the growing period;
- A gradual sea-level rise leads to encroachment of vegetation that accumulates pyrite in soils near the coast.

3.7.1 Possible effects of higher CO_2 on soil fertility

A condensed CO_2 atmosphere increases growth rates and water-use efficiency of crops and natural vegetation as pre-discussed; whilst higher temperature optima of some plants under increased CO_2 would tend to have opposite effects such as increasing night respiration. Higher temperatures, particularly in arid conditions, entail a higher evaporative demand. Inadequate land or farm water management, drainage or irrigation scheduling could result in soil salinization. Conversely, recent experiments by the Salinity Laboratory, Riverside, California, point to increased salt tolerance of crops under high atmospheric CO_2 conditions (Bowman and Strain, 1987).

3.7.2 Possible effects on soil reaction (pH)

Several studies show that most soils would not be subject to rapid pH changes resulting from climate change, although exposure to increasingly long dry seasons could affect potential acid sulphate soils extensive in some coastal plains and estuaries. Note that it is possible to observe relatively rapid soil acidification in an accelerated climate change, but after a shorter latent period, in some soils in Europe subjected to acid rain for several decades.

3.7.3 Possible effects of a rising sea level on soils in coastal areas

The probable effects on soil characteristics of a gradual rise in sea level vary by location depending on several factors (Brammer and Brinkman, 1990). In principle, a rising sea level would tend to erode and move back existing coastlines. However, the effect will depend on the elevation, the resistance of local coastal materials, the degree to which they are defended by sediments provided by river flow, the strength of riverbed currents and storm waves, and on human interventions which might prevent or accelerate erosion (Warrick and Farmer, 1990).

3.7.4 Possible effects on evapo(transpi)ration

Obviously, the temperature increase expected as a result of climate change and the possible effects on soil fertility and crop production discussed above, would definitely affect the evapo(transpi)ration process. Factors as radiation, air temperature, humidity and wind speed which are largely varying under climate change processes together with the crop factor (crop type, variety and development stage should be considered when assessing the evapo(transpi)ration) are changing the stomata reaction to the increase of atmospheric CO_2 (stomata are the port for plant transpiration). In this respect, the effect might impact on several levels:

- Possible effect of stomata density: The stomata density depends upon plant species, and can be related to the plant-ecotype (Rowland-Bamford et al., 1990; Woodward, 1987; Kimball et al., 1986)). Woodward (1987) correlated the decrease in the stomata density over time, observed in leaves collected over the last centuries, with the rising CO_2 concentrations and concluded from the shift in ^{13}C (Woodward, 1993) that the water-use efficiency has improved. Experimentally, an increase in CO_2 up to 310 ml/l decreased the stomata density, but sometimes no effect is found (Woodward and Bazzaz, 1988). This point is still under discussion (Körner, 1988; Woodward, 1993) although such a correlation has also been confirmed in some studies (Van der Burgh et al., 1993). Among species large differences in response of stomata density to elevated CO_2 seem to exist;

- Possible effect of stomata functioning: The stomata are the major resistance for gas transport between the leaf and the surrounding air. A change in gas exchange resistance of the stomata affects the exchange of CO_2 and water vapour. The opening status of the stomata is a compromise between water loss and absorbance of CO_2 from ambient air (Farquhar et al., 1980; Mott, 1990; Wolfe, 1994). In fact, stomata response to elevated concentrations of CO_2 is reflected generally in partial stomata closure; where the closure mechanism is still not clear (Mott, 1990; Wolfe, 1994).

3.7.5 Conclusion about the additional climate change effects

No firm statement can be made up to date concerning the wideness of possible climate change impacts. Indeed the impacts are spread largely and would effect as for future situation with respect to water-limited agricultural production. In many studies the impact of climate change on crop growth is analyzed using crop simulation models (Van Keulen and Seligman, 1987; Kenny *et al.,* 1993). Some major and widespread soil changes are expected; especially the gradual increases in soil fertility and physical qualities consequent on increased atmospheric CO_2. The scope of increasing productivity and water-use efficiency of crops and vegetation, and the generally similar or higher rainfall indicated by climate models, might lead to higher evapo(transpi)ration, which might lead to widespread increases in ground cover, and consequently better protection against runoff and erosion.

The expected soil changes might cause multiple reactions: soil structure degradation, decreased porosity, increased runoff and erosion on sloping sites. In certain fragile soils, the nature of the dominant soil-forming process may change for the worse with increased, decreased or more strongly seasonal rainfall.

In this study, the possible effects of climate change on soil acidity and fertility as well as on crop production are neglected while more focus is held on the possible effects of climate change on evapo(transpi)ration.

3.8 Conclusion: Climate change physics

This chapter showed that global climate is produced through a variety of processes and interactions that operate on a wide range of scales, including regional, continental and global. Changes in climate occur from physical interactions that take place on any or all of these scales. The changes, and the resulting weather patterns, can occur nearly instantaneously or they can take decades to develop.

Predicting the long term evolution of the climate system along with its major components and their complex interactions can be made through climate models. These latter are mathematical representations of the rules that drive the evolution of a given parameter according to other variables. These parameters will typically include mean temperature, mean precipitations… and their corresponding spatial patterns. Although the possible changes of the physics of the natural processes due to climate change are totally neglected in the GCMs, they are the best tool for predicting future climate changes.

Unfortunately, GCMs are limited to gross representations of the geographic, geologic and atmospheric details that they use to run climate simulations. Thus, many small-scale features, such as a temporary but significant shift in the prevailing winds or unusually dry surface conditions due to increased evaporation or laud use cannot be represented, even though they may significantly impact the local, regional, or even global climate. A fact that keeps raising the challenge of enhancing the spatial and temporal resolutions of the natural processes into climate models which gives emergence to RCMs. These developments have been made under several climate impact projects across Europe and the world.

Chapter 4

The Downscaling Methods

4.1 Introduction

Climate change will have an important impact on the hydrological cycle at a variety of temporal and spatial scales. The temporal scales may vary from very short intervals to annual balances. Spatially the effect may be local, regional or global. Water related projects often have life spans of 50 to 100 years. The design of these projects therefore needs to consider the possible effects of climate change for different periods.

General Circulation Models (GCMs) (principal tool for climate change research) have been recognized to be able to represent reasonably well the main features of the global atmospheric circulation, but are commonly far to provide observational error which is acceptable for given applications and so far could not reproduce well details of regional climate conditions at temporal and spatial scales of relevance to hydrological impact studies.

Consequently, there is a growing demand for regional scale scenarios, which in turn are reliant on techniques to downscale from GCMs. The necessity of downscaling then becomes an activity justified on the basis of needs as the research of possible impacts of climate change needs the description of regional and local climate details.

Of particular importance for the management of water resources systems are those tools dealing with the linkage of the large-scale climate variability to the historical observations of the surface parameters of interest (e.g., precipitation and temperature). If this linkage could be established, then the projected change of climate conditions given by a GCM could be used to predict the resulting change of the selected surface parameters. The required linkage could be developed using downscaling methods.

Downscaling techniques are tools to bridge the gap (scale mismatch) between what GCMs can provide and what is needed in impact studies

Modelling science has given a large opportunity to approach the impact of climate change on regional scale offered by the continuous growth in computer intelligence in a tentative of enhancing the climate models spatial and temporal resolutions.

This chapter presents the different techniques of downscaling, especially those relevant to hydrological studies, shows their advantages and shortcomings and finally illustrates the selected downscaling techniques to proceed within the present study.

4.2 Necessity of modelling

Generally, the modelling of the hydrologic impacts of climate change is a simple process: (a) define, calibrate and validate a model for the hydrological system using current climate data, (b) define climate change scenarios, (c) run the hydrological model under current and future conditions and (d) compare variables of interest. However, this process might not lead to useful results. The uncertainties of climate scenarios and GCMs outputs are large. The ability of GCMs to reproduce the present situation on a regional or catchment scale is low. The coarse spatial resolution of GCMs makes the outputs at catchment scale problematic.

The uncertainties of the hydrological predictions are also large. The main assumption in such models is that the set of hydrological model parameters is the same today and in the future under different climate scenarios, which is far from reality. In fact, crop production, land use and water managements, which obviously contribute strongly into the hydrological regime of a region, are assumed to be similar to the current condition under changed climate.

However, although the shortcomings, climate models represent the only possible way of understanding the behaviour of a system and its possible changes or variations due to parameters change. To determine the likely effects of a change such as an increase in greenhouse gases concentrations on the climate system, it is necessary to look at how the system as a whole responds. Therefore climate models are essential, because they integrate the main processes that occur within the climate system and calculate the adjustments of its various elements as they respond to the original changes.

4.3 Problem of scale

In recent years, the science of modelling reached, in many areas, a high reliability degree. In climate science too, it is perfectly known that general climate models (GCMs) are good tools to describe the effects of increasing concentrations of atmospheric CO_2. Unfortunately, these models have a very large spatial resolution (several hundred kilometers). Bardossy (2002) states in table 4.1 the temporal and spatial scales in GCMs and hydrological modelling. This fact presents in reality a fundamental barrier to progress in studies of atmosphere-hydrosphere interface, as we want to develop an understanding methodology of the impact of management changes on small scales. Spatial and temporal scales used in the atmospheric studies considerably differ from those in hydrology, where the basic unit, the catchment itself, embraces already quite a considerable range of scales. The difficulty in direct use of GCMs results in hydrological studies due to scale mismatch may become alleviated by different techniques of downscaling.

As an example, precipitation is the key input variable for the hydrological models due to its role as a forcing field. This variable is normally provided by GCMs outputs in climate change studies where its estimation is somewhat “crude”, although new techniques have been integrated. Here is a short historical look on rainfall estimations.

	GCM output / Climate data	Hydrological requirement
Time	Daily Monthly	For rivers: hourly For urban drainage systems: 10 min

	Seasonal	
Space	300 * 300 km 150 * 150 km	For rivers: 50 km^2 For urban drainage systems: 10 km^2 or the spatial scale of a sewer pipe

Table 4.1 Temporal and spatial scales in GCMs and in hydrological modelling (Bardossy, 2002).

4.3.1 Historical look

Historically, estimates of precipitation have been obtained largely by using a network of ground-based rain gauges. While these last remain the standard source of precipitation estimates, there are several problems and limitations associated with them. One of the primary problems is that they provide point measurements of a quantity that varies significantly in both space and time. Averaging techniques are often used to provide large-scale estimates. The errors in these estimates can increase in areas where the gauge network is sparse (Willems and Berlamont, 2002).

Another source of large-scale precipitation estimates is based on measurements using ground-based radar. As with rain gauges, limitations exist here too. A side from the lack of global distribution of radar stations, problems that are specific to radar include ground clutter, anomalous propagation, bright band, and range limitations. Therefore, as in the case of rain gauges, significant sampling errors exist within radar estimates of precipitation (Steven and Dara, 2001).

An important new data resource for hydrologists has appeared with the emergence of satellite remote sensing technologies. Satellites provide valuable data related to many of the atmospheric and land surface processes that are most relevant to hydrologists, including precipitation, net radiation and vegetation characteristics. The estimation of precipitation using remote sensing techniques solves some of the problems discussed above by augmenting current measurement capabilities. However, the current estimates provided by satellites are not without limitations as well.

While monthly precipitation is valuable for climatological studies, it is often necessary to have storm rainfall (as opposed to mean rainfall) on shorter time scales for hydrological studies. Many hydrological processes such as infiltration and evaporation are affected not only by the quantity of surface incident precipitation but also by the intermittent temporal structure (storm duration, inter-storm periods, rainfall intensity, etc.) involved in a storm sequence. Marani et al (1997) describe the important effects of the intermittent temporal structure of precipitation forcing on hydrological partitioning at the land surface. Their results show that due to the non-linear dependencies of surface hydrological processes on precipitation, the hydrological response of the surface varies considerably based on the temporal structure of the forcing.

Therefore, to make the climate model outputs useful for hydrological water balance studies, it is necessary to disaggregate the monthly precipitation estimates to shorter time scales so that they may be used in surface hydrology models. There have been many studies involving the disaggregation of rainfall (e.g., Hershenhorn and Woolhiser, 1987; Wilks, 1989; Bo et al., 1994; Salvucci and Song, 2000). They can be classified in two main approaches of downscaling. The next paragraph presents the downscaling approaches, discusses the differences between them and states the advantages and disadvantages of each approach.

4.4 Downscaling approaches

We can divide the downscaling approaches mainly to two different kinds:

- Dynamical downscaling;
- Statistical downscaling.

4.4.1 Dynamical downscaling

The dynamical downscaling uses regional climate models to simulate sub-grid scale features (Giorgi and Mearns, 1991). They simulate using the time varying atmospheric conditions obtained from the GCMs.

In this downscaling method modellers are working only on the physically based climate system modelling. They are therefore improving the hydro-meteorological information quality from the climate models by improving their resolution in time and in space. Space resolution has been enhanced from large scale to regional scale (medium scale), (400 km to 50 km to 25 km...) as for temporal resolution, we talk actually about weekly and daily instead of seasonally or monthly. Figure 4.1 illustrates the dynamical downscaling method indicating that the line of improving the resolution depends on the knowledge to have finer scale modelling (growth of computer power has great impact on enhancing space and temporal resolution) and on knowing additional local processes in comparison with global scales..

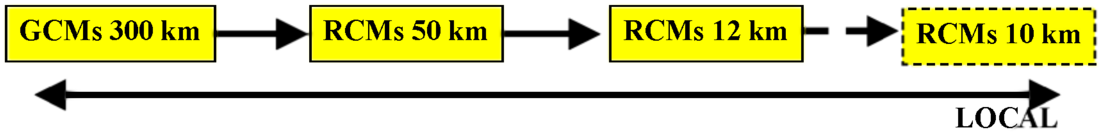


Figure 4.1 Dynamical downscaling procedure.

In recent years, high-resolution Regional Climate Models (RCMs) have been developing rapidly (Hudson and Jones, 2002; Giorgi et al., 2001). Much of these developments have been undertaken under some projects like PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects, Christensen, 2002) and in regional model inter-comparison projects like PIRCS (Project to Inter-compare Regional Climate Simulations). Computer performance has led to RCMs with typical resolutions of about 50 km, and in the near future resolutions of 10 km are foreseeable.

This issue opens new ways to estimate changes in river discharges by using the outputs of the RCMs directly to run the hydrological models. The approach is applicable within the medium scale and is known as the **direct forcing approach** (Figure 4.2).

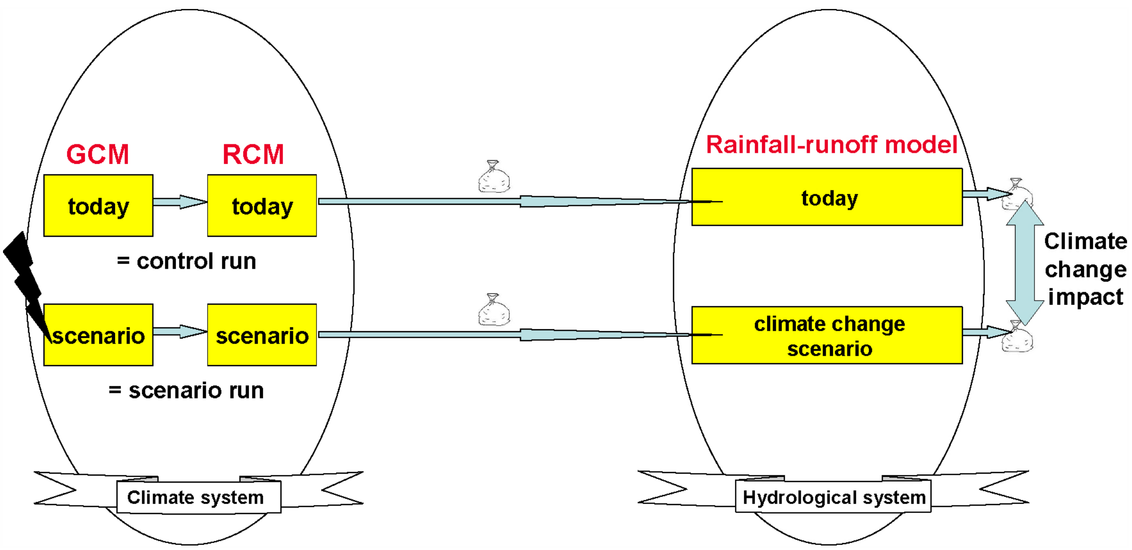


Figure 4.2 Schematic illustration of the direct forcing approach.

Generally, it is necessary to apply some bias corrections to RCM outputs based on historical records (e.g., historical rainfall series), before introducing them into the hydrological model. This ***adjusted direct forcing approach*** uses correction factors calibrated to the historical data and applied unchanged to the RCM climate change predictions (Figure 4.3).

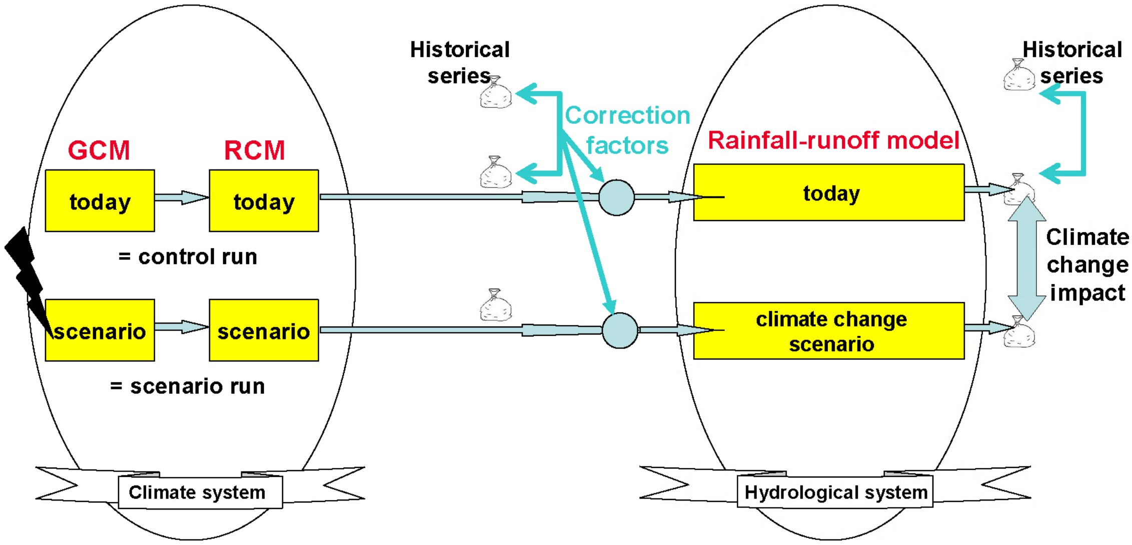


Figure 4.3 Schematic illustration of the direct forcing approach adjusted by means of the correction factors.

One of the main advantages of this method is that changes in the probability density functions of the input variables of the hydrological models are taken into account which might impact on the output of the hydrological model. However, this potential advantage might turn into disadvantages when the quality the RCM simulation is not "good"[1] enough. Another advantage is that it delivers meteorologically consistent downscaled variables. However, the uncertainty in this method and the non-uniqueness of the solution are generally not taken into account. It is also a computer intensive method.

4.4.2 Statistical downscaling

Statistical downscaling methods, also known as "**Empirical downscaling**" methods, are based on local observations that are used to estimate appropriate downscaling functions. In this downscaling method, modellers are working in two different levels: the physically based climate system level and the hydrological level including the past record and the present situation. In this method, links are to be built between these two levels in order to establish statistical relationships between one or several large-scale meteorological variables (atmospheric circulation) and local scale variables (hydrological variables). The assumption made is that the statistical relationships between the large-scale and the local-scale features remain the same even under a changing climate. This has given birth to the concept of "**predictors**" and "**predictants**".

The "predictors" are the large-scale meteorological variables (e.g., temperature, air moisture, etc) and are generally the GCM models outputs. In principal any kind of variable can be used as predictor as long as it is reasonable to expect a correlation with the predictants.

The "predictants" are the local scale variables to be downscaled which is commonly (most of the cases) the precipitation as it is the most important driving variable in hydrological modelling and analysis projects.

The statistical downscaling methods can also be used to evaluate statistical properties of the predictors and their correlation to the predictant.

Three different methods for empirical downscaling are used depending on the representation of the relationship between the two levels (climate modelling level and hydrological level):

[1] One uses the term "good" in a cloudy way, since not much is known about how to quantify "good" in relation to the output of the hydrological model (Lenderink et al, 2004).

- **Regression: statistical representation of the relationship**. This method makes use of observed empirical relationships or transfer functions between the predictants and the predictors. In this respect, generally an explicit function is used to describe the relationship between the large-scale and the local information. It is then up to the researcher to select the best choice of the predictor variables, in order to have high correlations between the predictor and predictant variables; and the best form of the transfer function in order to avoid numerical problems;
- **Conditional probability based methods: stochastic representation of the relationship**. Using **stochastic models**, with parameters dependent on the conditional probability, the probability distribution of the predictant is conditionally based on the predictor. This method is an extension of stochastic hydrology.

  Figure 4.4 shows the different links that might relate the two different levels of the physical system (the climate system and the hydrological system) while statistically downscaling.

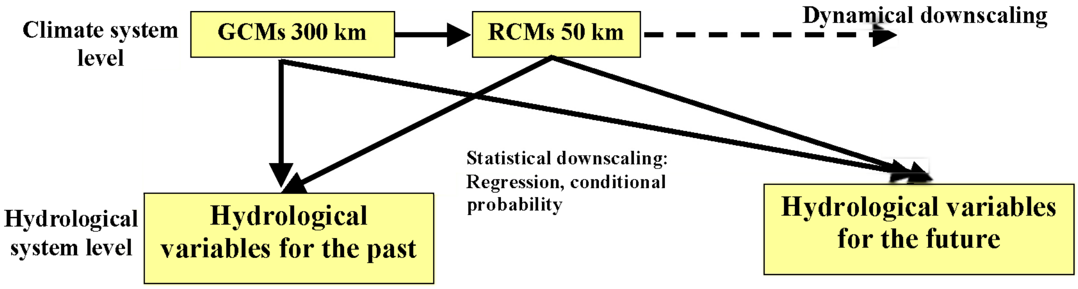


Figure 4.4 Statistical downscaling: regression and conditional probability methods.

- **Re-sampling methods**: also called “weather typing”, are based on historical reading of the data in the past trying to identify a similar situation. Predictions are based on observed historic patterns for observed climatic variables. Here the downscaling is made only focusing on the same hydrological level between the past situation and the future one with a time series representation (Figure 4.5).

Figure 4.5 Statistical downscaling: re-sampling methods.

4.4.2.1 Examples of statistical downscaling methods

The statistical methods in downscaling seem to be widely applied as they bring large windows of assumptions to hydrologists to build their statistical relationships. These approaches are becoming increasingly popular for gauging impacts of climate variability and changes at local and regional scales because of their relative simplicity and inexpensive computer requirement. We can state:

- statistical regression type:
  - linking large-scale predictors at monthly time resolution to regional statistics of daily precipitation which is purely a regression form;
  - transformation of point precipitation to areal precipitation by use of areal reduction factors (ARFs): it is an empirical regression based method taking place within the level of the hydrological system;

Gellens (2003) investigated the ARFs for areal precipitation extremes. He used data from the network of about 300 daily rain gauges managed by RMI, for aggregation levels of 24h and higher. He used kriging with seasonal variograms to integrate precipitation over squares centered on selected stations and with sizes increasing from 1 to 49 km (Figure 4.6). Gellens compared annual extremes of precipitation cumulated over k days and integrated over the squares, with the corresponding extremes at the stations. The ARFs are also computed for the whole year. It was concluded that generally speaking, the annual extremes of daily precipitation are progressively decreasing as the collecting area increases (Figure 4.7). The ARFs for precipitation over an area of 2400 km^2 are comprised within 0.8 - 0.9 depending on the location to the reference station. In that case, there is a good agreement between observations and theoretical approaches and it is possible to adapt IDF curves taking into account for ARFs. For longer aggregation times, ARFs are closer to unity but a difference is observed between the northern and the southern part of the country. In the northern part, precipitation is uniform enough over the spatial integration domain so that a decrease of ARFs while the collecting area increases is still observed. On the contrary, precipitation is by far less uniform in the southern part and the extremes of areal precipitation appear to be increasingly affected with orography. Empirical ARFs are therefore mainly site dependant.

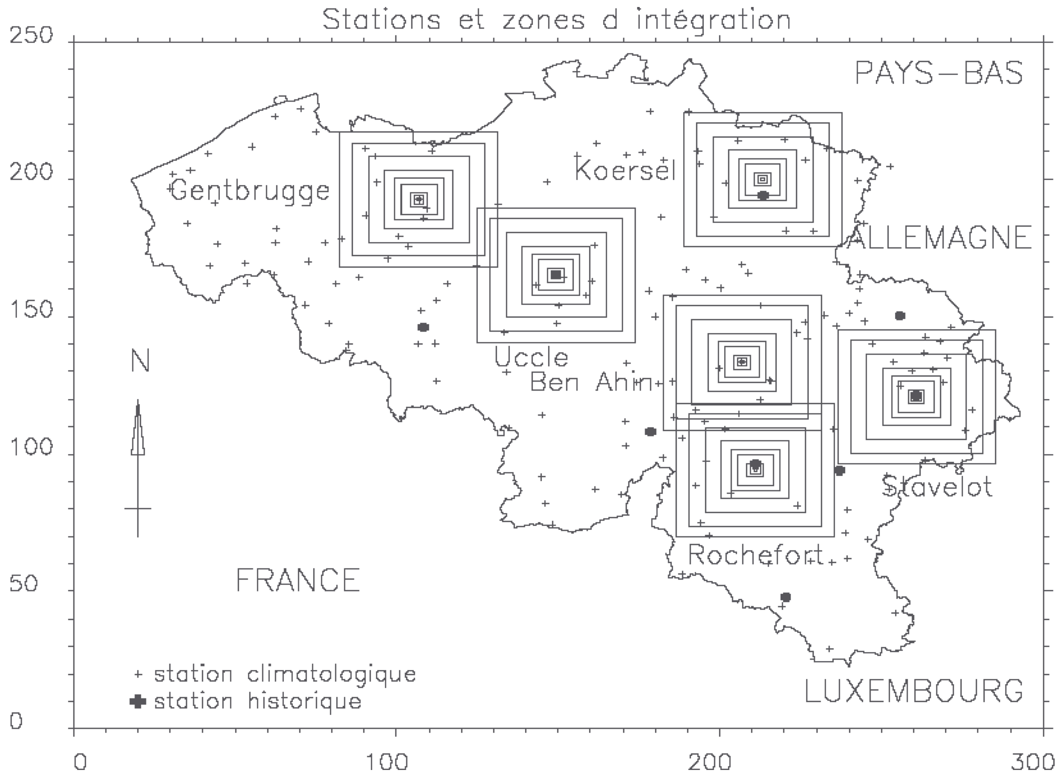


Figure 4.6 Map of Belgium with the stations and the surrounding squared areas where the areal reduction factors have been estimated (Gellens, 2003).

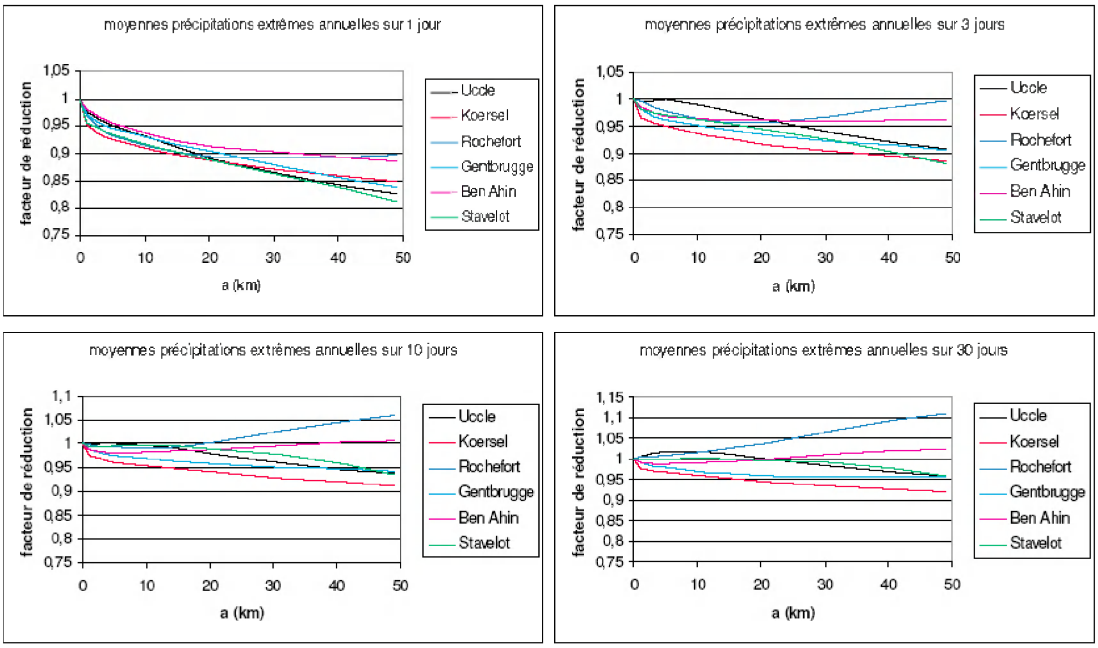


Figure 4.7 Areal reduction factors for annual extremes of precipitation cumulated over 1 to 30 days as a function of the size of the squared integration area (Gellens, 2003).

- re-sampling type:
  - Herschensohn and Woolhiser (1987) disaggregate daily rainfall amounts into storm events using the knowledge of total rainfall for that day and on the preceding and following days;
  - The analogue method: it is a translation of anomalies of the large-scale flow predictors (Climatological variables) into anomalies of some local hydrological variables;
  - The use of statistical analysis of the historical data to assess relationships with historical climate variables. In this way the modeller is using both regression and re-sampling forms of statistical downscaling;

4.4.2.2 Stochastic rainfall models

A stochastic rainfall model is a model that involves probability or randomness. In fact it is a mathematical model which takes into consideration the presence of some randomness in one or more of its parameters or variables. The predictions of the model therefore do not give a single point estimate but a probability distribution of possible estimates.

A distinction is made between the pure stochastic rainfall models that are totally related to the rainfall process and the stochastic rainfall models that are related to the climate variables commonly known as weather generators.

- Pure stochastic rainfall models: stochastic downscaling type (making use of conditional probability forms while downscaling). A pure stochastic model is typically used to generate rainfall at locations where observations are available to estimate the model parameters. The downscaling in this approach aims at the reconstruction of possible scenarios of the small scale structure of rainfall in either spatial or temporal domain (or both) by assuming that rainfall can be suitably interpreted as a random process. Some illustrations of this approach are given below:
  - disaggregation of long duration volumes to finite time scales based on a stochastic rainfall generator model, e.g. the modified Bartlett-Lewis rectangular pulses model, the Poisson storm arrival model (e.g., Salvucci and Song, 2000);

these methods require special focus on the historical record in order to investigate the storm arrival rates and storm structure characteristics (e.g., duration, intensity, inter-storm duration, etc.);

- conditional chain dependent process models (Wilks, 1989); parametric MARKOV models;
- The Poisson Rectangular Pulses Model (PRPM), as another example, is an application of the conditional probability form in statistical downscaling. In fact, The PRPM is an idealization of the rainfall process that represents rainfall events as independent rectangular pulses of duration *tr*, with constant intensity *ir*, and storm arrivals described by a Poisson process. The Poisson process which describes the occurrence of rainfall events can be characterized by the independent arrival rate 1/E[*tb*], where E[*tb*] is the mean inter-arrival time between storms. For the PRPM it is assumed that *tr* and *ir* follow independent exponential distributions with mean values of E[*tr*] and E[*ir*] (Rodriguez-Iturbe et al., 1984). Figure 4.8 illustrates the Poisson rectangular pulses model. The model is calibrated to preserve rainfall statistics e.g., the mean rainfall, variance, lag-1 autocorrelation, and probability of no rain. These statistics, which give a measure of the temporal structure of a given precipitation realization, are functions of the storm structure parameters E[*tb*], E[*tr*], E[*ir*].

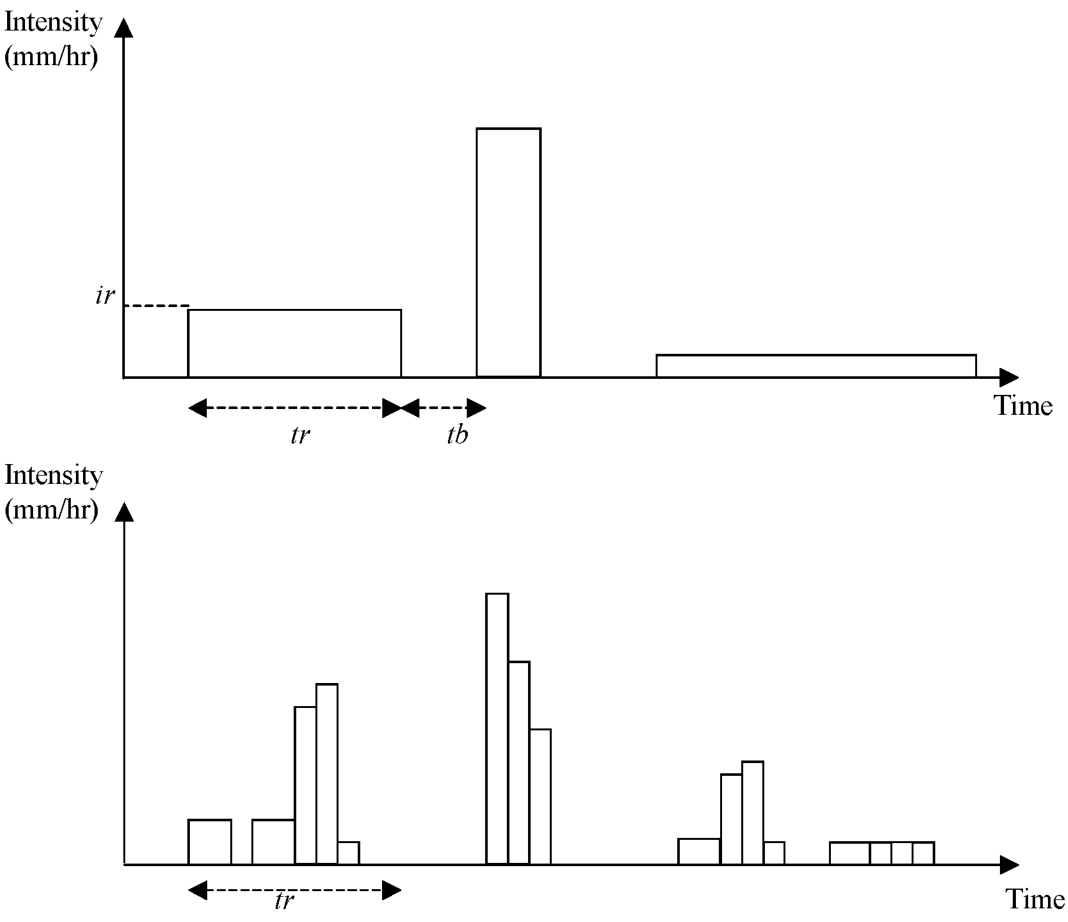


Figure 4.8 Schematic representation of the Poisson rectangular pulses model.

- For the region of Flanders, the use of Gaussian shaped rain cells (instead of rectangular pulses) has been demonstrated as a good approach to model both temporal and spatial rain storm structures in a stochastic way (Willems, 2001; Willems and Berlamont, 2002) (Figure 4.9). Hence, also this approach can be classified in the stochastic downscaling methods. This approach is based on a spatial rainfall model and it is mainly used for hydrological applications. The specificity of this generator is that it focuses on a microscopic spatial rainfall structure e.g., the rain cells, and on the small scale rain cell clusters.

The model investigates the rain cells structure on both ways: the spatial distribution of the rainfall intensities and the transport of the intensities. This is done through the bivariate Gaussian distribution which describes the rainfall intensities distribution in both spatial dimensions (*x, y*) and in time (*t*). The equation below describes the Gaussian distribution.

$$r(x,y,t) = r_{\max} \exp\left(-\frac{(x - x_0 - u(t - t_0))^2}{2S_x^{\;2}} - \frac{(y - y_0)^2}{2S_y^{\;2}} - \gamma(t - t_0)\right) \quad (4.1)$$

where $r(x,y,t)$ represents the rainfall intensity at spatial co-ordinates (x,y) and time t, r_{max} is the maximum rainfall intensity of the rain cell, S_x and S_y the standard deviation of the Gaussian distribution. U and γ are respectively the mean velocity and the decay velocity, as for (x_0, y_0, t_0) they represent the rain cell co-ordinates at initial time t_0.

The model was calibrated against storms observations at the city of Antwerp, where a dense network of rain gauges was used to derive the model description. The generated rainfall time series were compared to the Antwerp data and to a 27-year Uccle rainfall data in terms of IDF relationships. Results were found good for both rainfall frequency and large range of temporal scales (Willems, 2001).

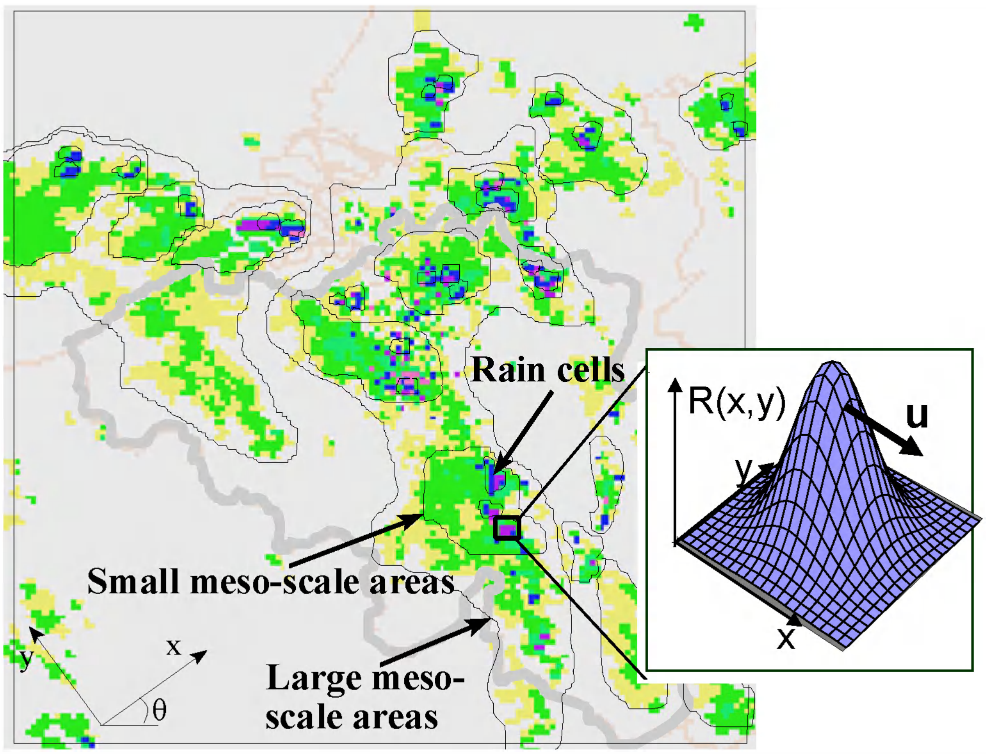


Figure 4.9 Stochastic spatial rainfall generation by means of Gaussian-shaped rain cell clusters (Willems, 2001).

4.4.3 The Perturbation Approach: A combined downscaling approach

Also known as the “Delta” change, the perturbation approach is the most common used method to transfer the signal of climate change from climate models to hydrological models (Vehviläinen and Huttunen, 1997; Lettenmaier et al., 1999; Middelkoop et al., 2001; Carlson et al., 2005). In this approach, only differences in the most relevant climatological variables to hydrology, typically precipitation, temperature and evapo(transpi)ration are extracted from the control and scenario simulations of the climate model, therefore the input series of the hydrological model is perturbed accordingly. The delta-perturbed database is thereafter used to make offline simulations with a hydrological model to provide a response to the future climate conditions. A schematic illustration of this modelling chain is shown in figure 4.10.

In the delta approach, one possibility consists on the perturbation of the baseline control climate time series (or observed times series) with estimated (mean) climate changes from the regional model simulations. As an example, for particular case of rainfall and temperature, the future time series are given by the additive coefficient of perturbation applied basically to the temperature and the relative perturbation factor which is best for precipitation.

$$T_{delta}(t) = T_{obs}(t) + (\overline{T}_{fut} - \overline{T}_{contr}) \quad (4.2)$$

$$P_{delta}(t) = P_{obs}(t) * (\frac{\overline{P}_{fut}}{\overline{P}_{contr}}) \quad (4.3)$$

$$T_{delta}(t) = T_{contr}(t) + (\overline{T}_{fut} - \overline{T}_{contr}) \quad (4.4)$$

$$P_{delta}(t) = P_{contr}(t) * (\frac{\overline{P}_{fut}}{\overline{P}_{contr}}) \quad (4.5)$$

where T_{delta} is the future temperature estimated with the delta scenario, $\overline{T_{fut}}$ is the mean temperature resulted from RCMs, $\overline{T_{contr}}$ presents the mean temperature for the control climate and T_{obs} is the observed temperature. As for precipitation, P_{delta} is the future precipitation estimated with the delta scenario, $\overline{P_{fut}}$ is the mean precipitation resulted from RCMs, $\overline{P_{contr}}$ presents the mean precipitation for the control climate and P_{obs} is the observed precipitation. Note that the method can be applied on the record (historical data) as well as on a control simulation taken as a reference climate after the bias correction. In this approach, both control and future climate share the same mean meteorological conditions, which makes the inter-comparison between the two methods as objective as possible. Therefore, in this method we assume that both the reference climate (control or baseline climate) and future climate preserve local spatial and temporal variability of the records.

By doing so, this method regroups both dynamical and statistical downscaling approaches. Dynamical downscaling, because we are extracting the climate signal from climate models (GCMs/RCMs) that are improving continuously in time and in space. This increase in climate resolution is actually beneficial for the hydrological water balance studies. Statistical downscaling, because we are applying the climate signal commonly to the observed data (past and present conditions).

- Advantages of the perturbation approach: As it uses observed climate as a baseline, this method is stable and always gives results that can be related to present conditions.
- Disadvantages of the perturbation approach: The use of observed climate as a baseline implies the assumption of no shift in the probability distribution of the hydrological variables other than due to climate change would occur. Also extremes are modified by the same factor as all other events.

Using the normal perturbation approach typically does not include changes in variability between RCM control and scenario simulations. In order to use more information from climate models while producing hydrological simulations for the present climate is with an adjusted perturbation approach. It implies an adjustment of specific variables to reduce systematic biases between the control simulation and the variable record (Carlson et al., 2005).

- Advantages of the adjusted perturbation approach: It provides more direct representation of RCM results and thus climate variability more consistent with the RCM simulations.

- Disadvantages of the adjusted perturbation approach: It is quite sensitive to the quality of the RCM used as input. It assumes a static bias correction that may not adequately represent future climate changes, such as changes in circulation.

Results from the delta approach provide an overall comparison of how the assessment of hydrological change is affected by using numerous different RCM configurations. It is a robust method making it possible to use output from climate models even if they do not produce a present climate with similar statistics to observations. The adjusted approach provides results on extremes that are more consistent with the RCMs; however it is best used with models that provide good representation of regional seasonality. Both of these methods make considerable modification to climate model results and implicitly assume that the systematic biases for the present climate will be the same for the future climate.

4.4.4 Selected perturbation approach

4.4.4.1 Perturbations depending on time scale and return period

The downscaling approach selected for this study is the combined dynamical – statistical downscaling method based on perturbations (Figure 4.10), because it is obvious from the above discussion that this method has clear advantages over the separate dynamical or statistical methods. In this study, the perturbations will however not be applied in a static way (mentioned above as one of the few drawbacks of the method). The perturbation factors (describing differences between current and future climate) will be analyzed for their dependency on the time scale and the intensity level or return period. For the rainfall variable, perturbations will furthermore be derived separately for the number or frequency of rainfall events (e.g., storm events) and the mean intensity per event. Both perturbations combined lead to perturbations in the mean intensity for a given aggregation level. Note that the perturbations present the difference between the control and scenario runs of the climate model and applied upon the inputs of the hydrological model for a current condition run and a future scenario run assuming the stationarity of the physical processes in the model (an assumption inducing careful interpretation of the hydrological model outputs).

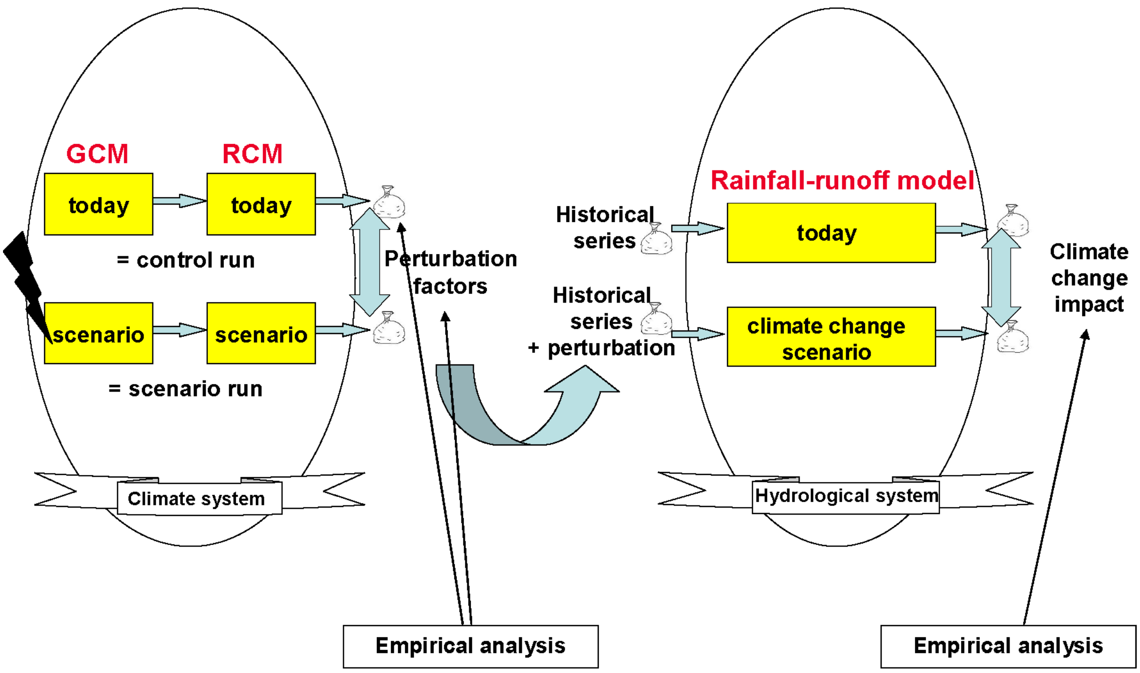


Figure 4.10 Selected downscaling approach: The frequency perturbation approach.

4.4.4.2 Frequency analysis approach

For the dependency on the return period, the frequency analysis method will be applied, comparing the frequency distribution between the RCM control period results and the historical results for the same period. The reason of applying such approach returns to the fact that when we compare hourly or daily times series between RCMs and historical data for different rainstorms (for example), we might compare a dry hour to a wet hour or a dry day to a wet day, and therefore the resulted perturbation factor would not be correct. A perturbation that is resulting from comparing day to day values is far from presenting climate change, as this last affects differently the extremes range and the normal range of each hydrological variable. Therefore, the frequency analysis approach has been adopted and it extracts the perturbation factors by comparing quantiles for given return periods. This can be done empirically or after calibration of extreme value distributions (see chapter 5).

Perturbations depending on time scale and frequency level or return period, also allow the perturbations to be defined as changes in the IDF and QDF relationships (see chapter 5).

For the case of rainfall, figure 4.11 gives a schematic overview of the variables for which perturbations will be defined and how they interrelate.

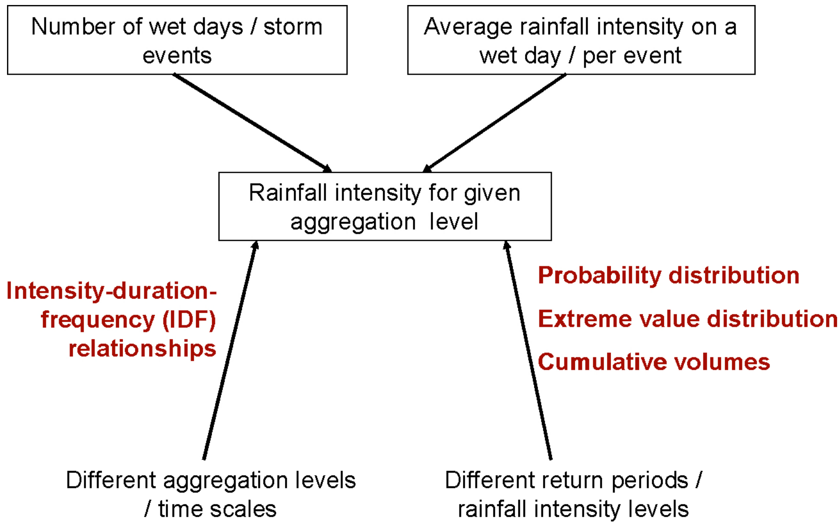


Figure 4.11: Rainfall related variables for which perturbations will be defined.

4.4.4.3 Consistency check with historical data (empirical analysis)

To overcome the disadvantage of the systemic deviations or biases between the climate models results and the present climate, an approach is applied here, referred as “consistency check with the historical data”, and consists of a comparison of the variable distribution of the observed climate and the historic modeled climate to remove model bias. So, the control GCM/RCM value are mapped to the record history (see chapter 5), then the climate models baselines that meet closely with the records are considered accurate for climate change study applications and will be used (accepted by statistical hypothesis testing). The others will be rejected. The statistical hypothesis testing will take into account the uncertainties in quantiles derived from the frequency analysis approach due to data limitation or randomness. This will require confidence intervals to be defined for the empirical frequency distributions or the calibrated extreme value distributions. The statistical hypothesis testing will be done for the different relevant time scales.

This returns to the fact that the RCMs used in this study cover all Europe and are calibrated and validated for a number of climatologic and rainfall stations spread over Europe, but maybe not specifically for Belgium. So there might be some results that are not presenting Belgium well. We need therefore to develop an approach to test the accuracy of the climate model results for our case study. With doing so, we are already deleting large part of the uncertainties that might be introduced into the hydrological simulation by less accurate climate results.

4.4.5 Advantages and disadvantages of the dynamical and statistical downscaling techniques

Using the statistical downscaling method makes it possible to assess the uncertainty of the prediction. Further local details which cannot be examined by the dynamical downscaling, can be considered in these models. Examination of the extremes is possible too. Compared to dynamical downscaling, statistical downscaling has the advantages of being computationally cheap and easily adjusted to new areas. This method requires few parameters which makes it attractive for many hydrological applications (Wilby et al., 2000). The statistical approach generates physically feasible spatial patterns of the surface variables. However, the application is restricted to the observed values. Other disadvantage is that it requires long and homogenous data series for establishment and validation of the statistical relationship.

Concerning dynamical downscaling, RCMs are used as a mean to dynamically downscale from the global scale of GCM simulations to regional scales. Dynamical downscaling ensures that the totality of climate parameters and processes are entwined while downscaling. However, it is still an expensive computationally tool accompanied with high uncertainty.

Table 4.2 summarizes the advantages and disadvantages of the different downscaling methods.

	Advantages	Disadvantages
Dynamical downscaling	• Consistent downscaled variables; • Physically based meaning; • Data readily available; • Changes in probability density functions; • Most of the climate variables.	• Spatial information poorly resolved; • High uncertainties; • Computer intensive calculation.
Statistical downscaling	• Generates information on high resolution; • Assess uncertainties; • Computer cheap ; • Possible extremes examination.	• Assumes consistency of empirical relationships in future; • Reduced number of variables.

Table 4.2 Advantages and disadvantages of the downscaling methods.

A remark can be made regarding the downscaling methods applied in some current climate change impact assessment studies where the climate signals (perturbation factors) are applied upon the control hydro-meteorological data (data calibrated by the regional climate model used for the climate simulation), instead of applying it on the observed data (Lenderink et al., 2004). This method is not applied in the present study as it presents several shortcomings. We list two here:

- Prediction uncertainties are high as the baseline data were provided by the calibrated model which presents systematic deviations with the historical data;
- Within climate simulations, uncertainty propagation might increase.

4.5 Downscaling approaches used in climate projects for European neighbor countries

<u>In Sweden</u>: The department of earth sciences at Uppsala University has generated a statistical precipitation downscaling method known as the analogue method. They applied it in south central Sweden. This method showed good similarity to other previous studies made on the

same region. Drier summers and wetter winters are predicted by the method with an increase in extreme events. Because of its simplicity and low subjectivity degree, the analogue method was taken as a benchmark method for downscaling precipitation in Scandinavia (Wetterhall et al., 2004).

In Germany: András Bárdossy (Universität Stuttgart) applied a stochastic downscaling method to come up with classification approaches on different climate regions including Germany and Greece. (Bárdossy, 2002).

In France, Germany and Switzerland, Geert Lendreink (Royal Netherlands Meteorological Institute, KNMI) estimated the future discharge of the river Rhine using two downscaling methods: The direct forcing approach (dynamical downscaling) versus the delta approach (combined downscaling). The Rhine has a big basin extends from Swiss Alps to Germany and France and ends to the Dutch coast where it discharges in the North Sea. It therefore has a large influence on water resources and economy of those countries. Geert concluded that the mean discharge, in both methods for the future climate, increases about 30% in winter and decreases by about 40% in summer. The severe response of the summer season is largely uncertain. It's mainly caused by the decrease of summer precipitation. As for the extremes, the direct forcing approach predicts an increase of 10% with a return period of 100 years, whereas the delta approach predicts an increase of 40% for the same return period (Lendreink et al., 2004).

From their side, Dubuisson et al (2006) were working on climatological variable series in order to look for temperature and precipitation extremes evolution during the last century. Dubuisson et al constructed daily reference series of the climate variables and calculated then climate indices. The trends of precipitation indices show evidence of an increase of total precipitation especially in northern French catchments in winter. The summer droughts are more intense and frequent. The extreme precipitation events do not show any significant increase. As for the temperature, all indices show a significant warming starting since the second half of the last century (Dubuisson et al., 2006).

In the Netherlands: Buishand (Royal Netherlands Meteorological Institute, KNMI) used a statistical relationship to describe the rainfall occurrence of the city of Bern (Switzerland). These relationships use atmospheric moisture and variables from NCEP re-analysis data. This methodology explores therefore the dependence of daily rainfall on several climate variables. The magnitude of potential changes in precipitation in a future climate was proved to be sensitive to the choice of the climate variables. This indicates that the regression form within the statistical downscaling approach should be applied within high correlations between precipitation and other climate variables (Buishand and Beckmann, 2002).

The table 4.3 below presents the downscaling approaches used for the climate projects presented and discussed in chapter 3 'section 3.6'

Project	Type of downscaling approach used
GPCP	Both dynamical and statistical downscaling methods
Abrupt Climate Change	-
AIACC	Dynamical downscaling
WRINCLE	Both dynamical and statistical downscaling methods
BIOCLIM (2000)	Statistical downscaling. The re-sampling method
MONARCH	Dynamical downscaling
REGIS	Both dynamical and statistical downscaling methods
ASCCUE	-
ESPACE	-
PRUDENCE	Dynamical downscaling

Table 4.3 Downscaling techniques used into international and regional climate projects.

4.6 Conclusion: Downscaling methods

The quality of information needed to perform hydrologic simulations require small temporal and spatial scales that are far to be reached by climate models, a fact raising the great importance of downscaling the climate information from GCMs/RCMs to try to overcome deficiencies in the local information which would compromise the hydrologic simulations.

A practical downscaling method has been developed in this chapter to construct climate change scenarios for the variables of precipitation and potential evapo(transpi)ration for the Flemish area in Belgium.

While dynamical downscaling method used by many impact studies takes into account the changes of probability density functions of most of the climate variables introduced into the climate models, the statistical downscaling methods generate information on high resolute scales while giving possibility to assess uncertainty.

The developed downscaling method is a combined dynamical-statistical downscaling approach based on perturbations. These last, which present the difference between current and future climate, will account for variable frequency and its dependency on time scale. This so-called "frequency perturbation" downscaling method takes into account the statistical behaviour of the variable (e.g., precipitation) for every event class (e.g., low, medium and extreme events) and for different time scales (daily, weekly, monthly seasonally) while gathering the highly resolute climate information provided by RCMs (The PRUDENCE project RCMs) with their different spatial resolutions and different emission scenarios.

Chapter 5

Climate Change Scenarios for Belgium

5.1 Introduction

Although the expected rise in average global temperature is relatively well known, the same does not apply to the regional distribution of climate change in particular with regard to water cycle and hydrology (Marbaix and van Ypersele, 2005). More complicated is the small size of Belgium (less than GCM grid size) which makes GCM results; with their large spatial resolutions; do not give a systematic overview of the future Belgian climate.

The huge climate data base provided by the PRUDENCE project has overcome this problem with 24 scenario simulations highly resolute and different emission scenarios all covering Flanders in small grid sizes and is therefore judged to be the most suitable climate data support for this study due to the large variety of climate physics, variety of spatial resolutions, the use of different emission scenarios and also to the given ability of assessing prediction uncertainty (see chapter 1 – section 1.4 and paragraph below).

Together with the chosen downscaling method: “the frequency perturbation method” (see chapter 4 – section 4.4.4) this chapter ensures that the needs of the Flemish community for future climate predictions are taken into account by presenting in details the PRUDENCE project and the procedure of creation of potential climate change scenarios for the variables of precipitation and potential evapo(transpi)ration.

Furthermore, a distinction should be made between climate change estimates and climate change scenarios. Climate change estimates are defined as estimates that have been determined on the basis of climate change research. This can be done on the basis of historical measurements or investigations with climate models. Climate change scenarios are interpretations of the scientific estimates. The scenarios might be the same for the whole Belgian area but estimates might differ from the coastal zone to the inland area.

The PRUDENCE project has been briefly described in chapter 1 (section 1.4), below is a detailed description of the climate data support of this study.

5.2 The PRUDENCE project

The understanding of the characteristics and mechanisms involved in the inter-annual variability of regional climate is as important to society as the availability of reliable and accurate weather forecasts; yet, our predictive capabilities are nowadays only tentatively reaching out to seasonal time scales. The correct representation of the physical processes involved in weather forecasting for Europe is less relevant during the season dominated by large scale circulation (fall, winter, spring) but becomes more important for the simulation of summer conditions, more dominated by local processes (Vidale et al., 2003). The representation of physical processes can also affect climate simulations, which can lead the modeled climate to "drift" and severely affect the quality of the information that can be produced by such modeling systems (Vidale et al., 2003). Better representations of the physical processes together with a tentative of enhancing spatial and time resolutions have been taken within the scope of the PRUDENCE project.

The PRUDENCE project is a large cooperative effort, involving many climate centers in Europe, with the purpose of quantifying the uncertainties involved in the simulation of climate and climate change. The PRUDENCE project homepage, with a more general view of the project's goals and achievements, can be found here: http://prudence.dmi.dk/. PRUDENCE aims to maintain and extend European pre-eminence in the provision of policy relevant information on climate and climate change and its interactions with society. State-of-the-art, high resolution, global and regional climate models developed for Europe are utilized to produce an objective probalistic estimate for uncertainty in future climate. The models are validated against quality controlled; high resolution grided datasets for Europe and applied at seasonal, monthly and daily time scales (DMI, 2004).

The main reason of thinking to plan such a PRUDENCE project was the important issue when considering adaptation and mitigation responses to climate change which is the uncertainty in the prediction of future climate. Uncertainties derived from model formulation are to be added together to those derived from natural climate variability and future emissions (Christensen and Christensen, 2007). As it was already proven with GCMs, a single realization of simulated climate is insufficient to provide the information needed for a comprehensive climate change impact assessment. PRUDENCE has made the first step in evaluating these uncertainties by running several RCMS (10 RCMs) and four ensemble GCMs for two emission scenarios (A2, B2) to derive future climate simulations.

An overall of 25 institutions comprise the research participants of this project, covering a wide range of research topics in order to maximize the utility of the project outputs. The partners of the project are European institutes from several countries. Below is table 5.1 with the PRUDENCE members that produced data relevant to the present project. Apart from the official name of each member and the country of origin, the table shows also the member code name in the database hosted in http://prudence.dmi.dk/data, as well as the GCM driving data and the RCM and the type of calendar used in the simulations.

The selection of the driving GCMs was made in collaboration with European climate modelling centers, when, at the time, atmospheric radiative forcing and matching sea-surface boundary conditions from coarse resolution GCMs were set to drive them. The SRES A2 and B2 emission scenarios were commonly conducted (Nakicenoic et al., 2000) which lead to distinct four set of GCM ensemble with typical resolution of 200 or 300 km. The GCMs presented as follows, form the basis of RCM scenario generation and uncertainty analysis (Christensen and Christensen, 2007).

PRUDENCE partner	Database name	Driving GCM/data	RCM
Météo France (France)	**CNRM**	Observed SST HadCM3 A2 HadCM3 B2 Arpège OPA B2	Arpège
Danish Meteorological Institute (Denmark)	**DMI**	HadAM3H A2 ECHAM4 OPYC (OGCM SSTs, A2, B2) ECHAM5 A2	HIRHAM/HIRHAM high resolution
Swiss Federal Institute of Technology (Switzerland)	**ETH**	HadAM3H A2	CHRM
GKSS Forschungszentrum Geesthacht GmbH (Deutschland)	**GKSS**	HadAM3H A2	CLM/CLM improved
Met. Office Hadley Centre (United Kingdom)	**HC**	HadAM3P HadAM3P B2	HadRM3P
The Abdus Salam Intl. Centre for Theoretical Physics (Italy)	**ICTP**	HadAM3H (A2, B2)	RegCM
Koninklijk Nederlands Meteorologisch Instituut, (Netherlands)	**KNMI**	HadAM3H A2	RACMO
Norwegian Meteorological Institute (Norway)	**METNO**	HadAM3H A2	HIRHAM
Max-Planck-Institut für Meteorologie (Deutschland)	**MPI**	HadAM3H A2	REMO
Swedish Meteorological and Hydrological Institute (Sweden)	**SMHI**	HadAM3H (A2, B2) ECHAM4 OPYC (A2, B2)	RCAO/RCAO high resolution
Universidad Complutense de Madrid (Spain)	**UCM**	HadAM3H (A2, B2)	PROMES

Table 5.1 PRUDENCE members data table.

- One ensemble using a GCM with driving conditions (A2 emission): the HadAM3H GCM with GCM with surface boundary conditions from 3 ensemble members of the coupled GCM HadCM3;
- One ensemble using four different GCMs with driving conditions (A2 emission scenario) from the same GCM; (the HadAM3H, ECHAM5, ARPEGE, and NASA FVGCM AGCMs);
- Two GCMs (HadAM3H and ARPEGE) with driving conditions from two GCM experiments performed with the same HadCM3 but with different atmospheric emissions (SRES B2 rather than A2);
- One AGCM (ARPEGE) with driving conditions from two different GCMs using the same emission (A2) (Christensen and Christensen, 2007).

Several European regional climate models were run using boundary conditions from the mentioned GCMs. The simulations' time scales were designed to provide the best possible present day global climate. They have been performed on the period 1960-1990 giving possibility to the model to spin up their surface variable during the first model year (Christensen and Christensen, 2007). More details about the above mentioned GCMs is given as follow.

- **HadAM3H**. This is an atmosphere global model developed at the Hadley Centre. The resolution of the model is considered high in its class and is about 150 km. HadAM3H is derived from the atmospheric component of HadCM3, the Hadley Centre's state of the art coupled model, with horizontal resolution of 3.75° latitude and 2.5° longitude (about 417 km x 278 km);
- **HadCM3**. HadCM3 is Hadley Centre's coupled atmosphere-ocean general circulation model. The atmospheric component of the model has variable horizontal resolution, about 417 km x 278 km at the Equator, reducing to 295 km x 278 km at 45° of latitude, and 19 vertical levels. One special feature of the atmospheric component is that it allows the simulation of emission, transport and chemistry of sulphur compounds and their effect on the climate variables. The oceanic component of the model runs at about 140 km x 140 km horizontal resolution and 20 levels. It can thus represent important details in oceanic current structures;
- **HadAM3P**. HadAM3P is a more recent version of the HadAM3H model. Therefore, it is an atmosphere only global circulation model;
- **ECHAM4**. This is an atmospheric general circulation model. It is derived from the weather forecast model of the European Centre for Medium Range Weather Forecasts (ECMWF). Numerous modifications have been applied to this model at the Max Planck Institute for Meteorology and the German Climate Computing Centre in order to make it suitable for climate simulations;
- **ECHAM5**. This is the fifth generation ECHAM model. Compared to the previous version, ECHAM4, it has a number of substantial improvements in numerics and physics of the model;
- **OPYC**. OPYC is an acronym for Ocean isoPYCnal model. The idea to use isopycnals as vertical coordinates in an OGCM comes from the observation that the interior of the oceans behaves as a rather conservative fluid. The model has been developed at the Max Planck Institute for Meteorology;
- **ARPEGE/OPA**. The ARPEGE model is an atmosphere general circulation model, derived from ARPEGE/IFS weather forecast model. The model has 30 vertical levels extending up to 70 km. OPA is an ocean GCM developed at the Laboratoire d'Océanographie Dynamique et de Climatologie (LODYC). It has 30 vertical levels, from which 10 are within the top 100 m.

While it is very interesting investigating the differences in these GCMs, this goes beyond the scope of PRUDENCE project were several RCMs (driven by these GCMs) were run for different emissions and resolutions in order to state the issue of uncertainty accountability between the different models as well as the regional results differences. Below is a brief description of PRUDENCE RCMs.

- **ARPEGE.** ARPEGE is the weather forecast model in use by the French Meteorological Service (Météo-France). ARPEGE-FIS is the ECMWF version, based on different physical parameterizations. There is also a third version of the model appropriately adapted for climate simulations. In this version the model has a variable resolution of 50 km over the Mediterranean and 450 km over the South Pacific. ARPEGE runs over 31 vertical levels;
- **CHRM.** The CHRM model is derived from the operational weather forecast model HRM of the German and Swiss Meteorological services (DWD and MeteoSwiss), which has been adapted for climate simulations by the Swiss Federal Institute of Technology (ETH). Its resolution is about 55 km and it has 20 vertical levels. It comprises a complete package of physical parameterizations, including a mass-flux scheme for vertical convection;
- **CLM.** CLM is the climate version of the weather forecast Lokalmodell (LM) of the German Weather service and they both share the same dynamics and physics. The CLM is a non-hydrostatic model that includes parameterized cloud microphysics (water and ice) and a moist convection scheme. Within PRUDENCE, the model is run in a grid of about 56 km and in 20 vertical levels;

- **HadRM.** This is the most recent (at the time of the PRUDENCE project) Hadley Centre regional climate model HadRM3H. It is a special version of the AGCM HadAM3H, running in higher resolution than the latter one and covering a limited area. HadAM3H in turn is an improved version of the HadAM3, which is the atmospheric component of the Hadley Centre latest, coupled AOGCM, HadCM3. The improvements include new parameterizations for certain cloud processes;
- **HIRHAM.** The HIRHAM used in the PRUDENCE project is an updated version of HIRHAM4. The dynamical part of the model is based on the hydrostatic limited area model HIRLAM, while the physical parameterizations originate from the general circulation model ECHAM4. These parameterizations include radiation and several processes involving land surface, clouds, sea surface, and sea-ice interactions. Model resolution is 50 km horizontally and 19 levels in the vertical direction;
- **PROMES.** This is again the climate version of the PROMES model. It is a hydrostatic and primitive equation model. Prognostic variables are potential temperature, surface pressure, horizontal wind components, specific humidity, cloud and rainwater. PROMES runs at 50 km resolution;
- **RACMO.** RACMO uses the semi-Lagrangian dynamical core of HIRLAM. The model has a resolution of about 50 km and it extends to 31 vertical levels.
- **RCAO.** RCAO is the SMHI Rossby Centre regional Atmosphere-Ocean model. It incorporates a regional atmospheric (RCA) and a regional ocean model (RCO), both developed in the Rossby Centre, and a river routine based on the HBV hydrological model and lakes. The RCA model has its roots to the limited area model HIRLAM and it is run in the resolution range 10-70 km and with 24-60 vertical levels. Variables are temperature, horizontal wind components, specific humidity, cloud water, turbulent kinetic energy, surface pressure, soil temperature and water content. The RCO model is based on the OCCAM version of the Bryan-Cox-Semtner primitive equation ocean model with a free surface;
- **REMO.** This regional climate model uses the dynamical core of the Europamodell/Deutschlandmodell of the German Weather Service and the physical parameterizations of ECHAM4. The geographical region covered includes Europe and part of the Atlantic Ocean. The model resolution is about 55 km and there are 19 vertical levels used, like in ECHAM4;
- **RegCM.** The dynamical core of the RegCM is equivalent to the hydrostatic version of the mesoscale model MM5 of NCAR/Pennsylvania State University. Surface processes are handled via the Biosphere-Atmosphere Transfer Scheme (BATS), while there are special schemes for precipitation and convection. Energy transfers involving radiation are computed with the radiation package of the NCAR Community Climate Model. The model resolution is 50 km.

The result data of PRUDENCE covers a large number of climatological and hydrological variables (precipitation, evapo(transpi)ration, mean sea level pressure, total radiation balance, cloud covering, 2-meter temperature, 10-m wind and humidity) and are stored at the Danish Meteorological Institute, the PRUDENCE project host institute. The results are available for download and encoded in the netCDF format. The data are available from daily to seasonal time resolutions and from 50 km to 12 km spatial resolutions.

5.3 Processing RCM data from the PRUDENCE project

PRUDENCE RCMs simulation results were processed by RMI (P. Baguis and E. Roulin). The last performed downloading the netCDF result files from PRUDENCE website. The files are large in size depending on spatial and temporal resolutions. They range from several megabytes to several gigabytes. The downloads have concerned the variables of interest to this study which are the precipitation and all variables serving to calculate evapo(transpi)ration through the Bultot equation (Bultot et al., 1983). Special code has been used to extract the data (IDL environmental software) from the closest model grid point to Uccle station therefore the results were provided in daily text files.

Rainfall results have been directly applied from the PRUDENCE RCM runs while potential evapo(transpi)ration was calculated using the Bultot method, standard used in Belgium. The meteorological variables needed to calculate the evapo(transpi)ration using the Bultot method (Bultot et al., 1983) are those of:

- Mean Sea Level Pressure (MSLP);
- Total radiation balance (SWdown);
- Cloud covering (clcov);
- 2-meter temperature (t2m);
- 10-meter wind (w10m);
- Humidity.

Further details about the Bultot method and the calculation of the potential evapo(transpi)ration variable can be found in the CCI-HYDR project report II (Boukhris et al, 2007).

5.4 PRUDENCE project technical shortcomings

Due to the large number of project partners across Europe and the use of several physical representations and different spatial and temporal resolutions in the RCMs, some shortcomings show up which might have impacts on the hydrological estimations. They are:

- The humidity variable: there is no uniform treatment of this variable across the PRUDENCE members. We actually find three different descriptions of the humidity: (1) as relative humidity, (2) as specific humidity and (3) as dew-point temperature;
- Not all times series are comparable;
- The download size especially with high resolute models;
- The different partners present two calendars: 360 days and Georgian year.

Nonetheless, PRUDENCE is very valuable data base for the present study as several advantages can be seen:

- Development of standard observed and climate models simulated data sets, for use by all partners and public;
- This would give possibility of analysis of trends in extremes, and their causes and impacts, over a wide variety of European regions;
- Having PRUDENCE results, you can be offered an inter-comparison of improved dynamical downscaling methods (used in PRUDENCE) and statistical downscaling methods using data from the second half of the 20th century (for most cases of EUROPE) and identification of the robust methods;
- As it is done in this study, PRUDENCE results give possibility of development of future climate change scenarios, particularly for extremes, for the late 21st century.

PRUDENCE has demonstrated an overall alternative approach in two areas. Firstly, it has provided high resolution data which are better suited to impact models for the high pleasure of regional impact analysis and secondly, by applying climate models for the present (control) period, during which observation are also available, modellers are able to assess the direct use of model outputs in climate change applications (Jacob et al., 2007).

5.5 Review of perturbation factors

The downscaling approach selected for this study is the combined dynamical – statistical downscaling method based on perturbations (see chapter 4 ‘downscaling methods’ – section 4.4.4 and figure 5.1).

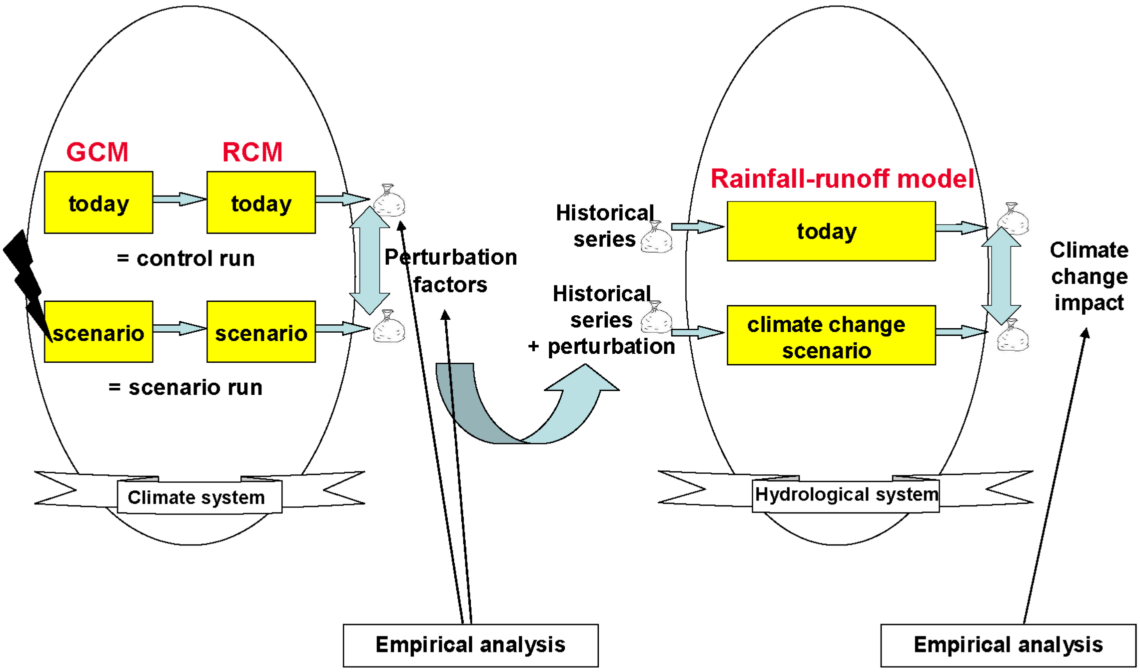


Figure 5.1: Schematic illustration of the selected perturbation approach.

The perturbations (differences between the current and future climate) can be derived in several ways. They can describe the difference in seasonal volumes of the hydro-climatological variables (e.g., rainfall, potential evapo(transpi)ration ETo). In this respect, the perturbations equal to the ratio between the total seasonal scenario volume and the total seasonal control volume of the hydro-climatological variable. The resulted perturbation is therefore applied to the original (observed record) series and then proceeded to climate change impact analysis.

They can present also the time step differences between control and scenarios' simulations. In this measure, the perturbations equal to the ratio of variable intensities of day 1 and day 1, day 2 and day 2, … of scenario versus control simulations.

A third way of perturbations, which is adopted for the present study, is to derive perturbations depending on the time scale and the intensity level or return period. For the rainfall variable, perturbations will furthermore be derived separately for the number or frequency of rainfall events (e.g., storm events) and the mean intensity per event. Both perturbations combined lead to perturbations in the mean intensity for a given aggregation level.

This approach is referred to as the frequency analysis method (see chapter 4 'downscaling methods' – section 4.4.4.2). It consists of comparing the complete frequency distribution between the RCMs control and scenarios' simulations. Therefore, the frequency analysis approach adopted extracts the perturbation factors by comparing statistical properties of the same variables between the simulated scenario and control time series.

5.5.1 Seasonal perturbation approach

In order to reach an adequate impact analysis of climate change, the support climate models should provide perturbation factors that take account of the seasonal dependency AND variable properties (e.g., rainstorm properties). In the European PRUDENCE project, different regional climate models have been applied. The differences in results between the different climate models provide moreover information to evaluate uncertainty in RCM simulation results.

In first case, by making the assumption that the perturbation factors are independent on the time scale, the PRUDENCE RCM factors have been calculated first by comparing the cumulative precipitation volumes per season period between the control and the scenario simulations. Table 5.2 presents the different PRUDENCE processed climate models, their spatial and temporal resolutions and the emission scenarios used.

Regional climate models (RCMs)	Spatial resolution (km)	Temporal resolution	Control period	Scenario period	Emission scenario
DMI-HC1	50	Daily	1961-1990	2071-2100	A2
DMI-HC2	50	Daily	1961-1990	2071-2100	A2
DMI-HC3	50	Daily	1961-1990	2071-2100	A2
DMI-F25	25	Daily	1961-1990	2071-2100	A2
DMI-ECS	50	Daily	1961-1990	2071-2100	A2
DMI-ECC	50	Daily	1961-1990	2071-2100	A2
DMI-ECC	50	Daily	1961-1990	2071-2100	B2
METNO-HAD	53	Daily	1961-1990	2071-2100	A2
METNO-HAD	53	Daily	1961-1990	2071-2100	B2
CRNM-DC9	59	Daily	1961-1990	2071-2100	A2
CRNM-DE5	59	Daily	1961-1990	2071-2100	A2
CRNM-DE6	59	Daily	1961-1990	2071-2100	A2
CRNM-DE7	59	Daily	1961-1990	2071-2100	A2
ETH-HC	55	Daily	1960-1990	2070-2100	A2
GKSS	55	Daily	1961-1990	2071-2100	A2
GKSS-sn	55	Daily	1961-1990	2071-2100	A2
ITCP	52	Daily	1961-1990	2071-2100	A2
ITCP	52	Daily	1961-1990	2071-2100	B2
KNMI	47	Daily	1961-1990	2071-2100	A2
SMHI-HC	49	Daily	1961-1990	2071-2100	A2
SMHI-HC	49	Daily	1961-1990	2071-2100	B2
SMHI-HC22	24	Daily	1961-1990	2071-2100	A2
SMHI-MPI	49	Daily	1960-1990	2071-2100	A2
SMHI-MPI	49	Daily	1960-1990	2071-2100	B2

Table 5.2 PRUDENCE regional climate model simulations.

The PRUDENCE seasonal perturbation factors have been calculated in two different ways following:

- The climatological seasons: these embraces winter (Dec, Jan, Feb), spring (Mar, Apr, May), summer (June, July, Aug) and autumn (Sep, Oct, Nov) (Figure 5.2). The hydrological seasons: contains winter season (Oct - March) and summer season (Apr – Sep) (Figure 5.3).

Tables 5.3 and 5.4 present the PRUDENCE precipitation factors respectively for the climatological seasons and the hydrological seasons. They are followed by table 5.5 presenting the potential evapo(tanspi)ration (ETo) factors.

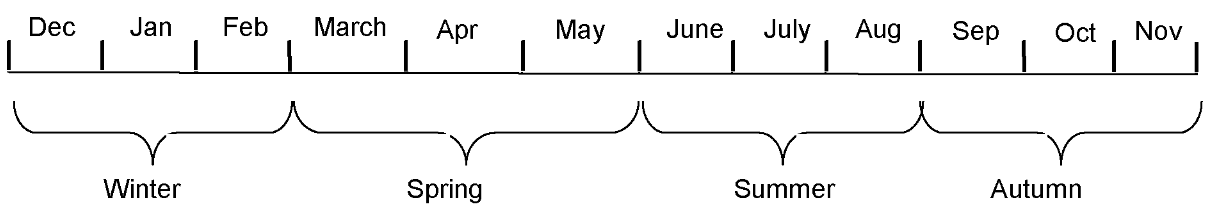


Figure 5.2 The climatological seasons.

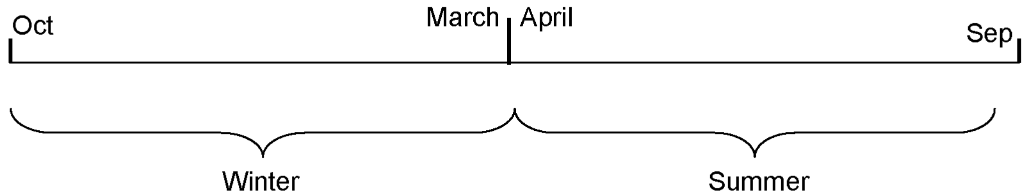


Figure 5.3 The hydrological seasons.

More information about the derivation of the PRUDENCE seasonal perturbation factors, its advantages and disadvantages followed by an impact study case can be found within the scope of the end user project for the Waterbouwkundig Laboratorium (WL) of the Flemish Government. The latter project is titled “Methodology for climate change impact analysis using the composite hydrograph method”. Boukhris et al (2006), test the climate change scenarios and adopt them for use in combination with the WL river modeling methodology. In that project, negligible differences are seen between the use of the climatological seasons and the hydrological seasons. It was thus decided to use the hydrological seasons in this study in order to derive perturbation factors and also for the impact analysis.

Regional Climate models (RCMs)	Precipitation volumes for control period (mm in 30 years)				Precipitation volumes for scenario period (mm in 30 years)				Emission scenario	Perturbation factors
	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn		
DMI-HC1	6915.97				6889.21				A2	**1.00**
		6324.7				4322.7			A2	**0.68**
			6702.71				5838.45		A2	**0.87**
				7434.83				8173.44	A2	**1.10**
DMI-HC2	6383.05				7377.88				A2	**1.15**
		6084.76				4796.12			A2	**0.78**
			6525.15				5877.3		A2	**0.90**
				7191.46				8473.1	A2	**1.17**
DMI-HC3	6578.37				7684.96				A2	**1.16**
		5646.99				4064.47			A2	**0.72**
			5867.88				5343.61		A2	**0.91**
				7343.31				8902.63	A2	**1.21**
DMI-F25	6281.65				6593.54				A2	**1.04**
		5688.33				4618.6			A2	**0.81**
			6375.08				5935.5		A2	**0.93**
				6661.18				7615.16	A2	**1.14**
DMI-ECS	7514.17				10675.2				A2	**1.42**
		7463.87				6582.5			A2	**0.88**
			8751.33				2849.79		A2	**0.32**
				8671.29				7321.47	A2	**0.84**
DMI-ECC	7514.17				6940.81				A2	**0.92**
		7463.87				5493.66			A2	**0.73**
			8751.33				7194.89		A2	**0.82**
				8671.29				9852.44	A2	**1.13**
DMI-ECC	7514.17				7891.54				B2	**1.05**
		7463.87				6358.11			B2	**0.85**
			8751.33				8034.67		B2	**0.92**
				8671.29				9754.25	B2	**1.12**
METNO-HAD	6839.69				7748.99				A2	**1.13**
		6421.29				4733.58			A2	**0.73**
			7574.02				6550.51		A2	**0.86**
				7656.74				8774.85	A2	**1.14**
METNO-HAD	6839.69				7080.23				A2	**1.06**
		6421.29				4964.72			B2	**1.03**
			7574.02				5873.93		B2	**0.77**
				7656.74				9248.46	B2	**0.77**
CNRM-DC9	9347.45				9578.08				B2	**1.20**
		7228.45				6594.5			A2	**0.91**
			5758.22				4964.47		A2	**0.86**
				5773.2				5849.68	A2	**1.01**

CNRM-DE5	9347.45				9555.34				A2	**1.02**
		7228.45				7602.66			A2	**1.05**
			5758.22				4902.1		A2	**0.85**
				5773.2				5754.74	A2	**0.99**
CNRM-DE6	9347.45				10539.79				A2	**1.12**
		7228.45				7014.59			A2	**0.97**
			5758.22				4332.42		A2	**0.75**
				5773.2				6253.3	A2	**1.08**
CNRM-DE7	9347.45				9506.08				A2	**1.01**
		7228.45				7993.21			A2	**1.15**
			5758.22				4756.69		A2	**0.82**
				5773.2				5982.47	A2	**1.03**
ETH-HC	5712.2				5968.1				A2	**1.04**
		5113				3969.0			A2	**0.77**
			5667				4767		A2	**0.84**
				5916.2				6527.3	A2	**1.10**
GKSS	8015.56				8816.14				A2	**1.09**
		6823.74				5739.57			A2	**0.84**
			8285.29				7858.9		A2	**0.95**
				9462.78				10409.81	A2	**1.10**
GKSS-sn	5902.79				6005.58				A2	**1.01**
		4926.17				3994.7			A2	**0.81**
			5901.59				5216.87		A2	**0.88**
				6473.15				7267.2	A2	**1.12**
ITCP	8400.2				8005.43				A2	**0.95**
		8371.38				7591.76			A2	**0.90**
			7849.05				7505.65		A2	**0.95**
				7846.49				9030.77	A2	**1.15**
ITCP	8400.2				7824.63				B2	**0.93**
		8371.38				7168.23			B2	**0.85**
			7849.05				7770.96		B2	**0.99**
				7846.49				8975.08	B2	**1.14**
KNMI	5524				5901				A2	**1.06**
		5110.6				3787.5			A2	**0.74**
			5681.2				5374.9		A2	**0.94**
				6251.8				6888.1	A2	**1.10**

Table 5.3 PRUDENCE RCM seasonal perturbation factors for precipitation (Climatological seasons).

Regional climate Models (RCMs)	Precipitation volumes for control period (mm in 30 years)		Precipitation volumes for scenario period (mm in 30 years)		Emission scenarios	Perturbation factors
	Winter	Summer	Winter	Summer		
DMI-HC1	13806.87		14171.19		A2	**1.03**
		13163.97		10468.03	A2	**0.80**
DMI-HC2	13091.76		14630.44		A2	**1.12**
		12281.71		11262.5	A2	**0.92**
DMI-HC3	13390.17		15542.53		A2	**1.16**
		11580.28		9861.44	A2	**0.85**
DMI-F25	12266.81		13337.49		A2	**1.09**
		12303.55		10848.5	A2	**0.88**
DMI-ECS	15290.42		18889.8		A2	**1.24**
		16523.31		7600.41	A2	**0.46**
DMI-ECC	15290.42		14821.22		A2	**0.97**
		16523.31		13765.49	A2	**0.83**
DMI-ECC	15290.42		16550.09		B2	**1.08**
		16523.31		14885.45	B2	**0.90**
METNO-HAD	13800.75		15338.87		A2	**1.11**
		14149.21		11692.17	A2	**0.83**
METNO-HAD	13800.75		14820.1		B2	**1.07**
		14149.21		11885.61	B2	**0.84**
CNRM-DC9	15529.36		15577.77		A2	**1.00**
		11542.57		10434.31	A2	**0.90**
CNRM-DE5	15529.36		16252.02		A2	**1.05**
		11542.57		10782.63	A2	**0.93**
CNRM-DE6	15529.36		17394.41		A2	**1.12**
		11542.57		101.35.42	A2	**0.88**
CNRM-DE7	15529.36		16578.04		A2	**1.07**
		11542.57		10723.59	A2	**0.93**
ETH-HC	15630		17687		A2	**1.07**
		12080		9785	A2	**0.81**
GKSS	16206.78		17958.77		A2	**1.11**
		15838.09		13944.58	A2	**0.88**
GKSS-sn	11644.01		12.484.34		A2	**1.07**
		11220.21		9404.68	A2	**0.84**
ITCP	16163.21		16320.15		A2	**1.01**
		15917.35		15121.77	A2	**0.95**
ITCP	16163.21		16071.47		B2	**0.99**
		15917.35		15163.16	B2	**0.95**

KNMI	11182.69		11596.38		A2	**1.04**
		11007.56		9703.35	A2	**0.88**
SMHI-HC	13077.89		13966.67		A2	**1.06**
		12855.15		10667.05	A2	**0.83**
SMHI-HC	13078		13380		B2	**1.02**
		12855		10999.4	B2	**0.85**
SMHI-HC22	13467.92		15418.77		A2	**1.14**
		13468.9		11518.56	A2	**0.85**
SMHI-MPI	14552.63		13822.84		A2	**1.20**
		15160.14		13684.15	A2	**0.95**
SMHI-MPI	14552.63		16065.95		B2	**1.10**
		15160.14		13826.98	B2	**0.91**

Table 5.4 PRUDENCE RCM seasonal perturbation factors for precipitation (Hydrological seasons).

Regional climate models (RCMs)	Emission scenario	Season	Perturbation factor
DMI-HC1	A2	Winter	1.16
	A2	Summer	1.21
DMI-HC2	A2	Winter	1.18
	A2	Summer	1.14
DMI-HC3	A2	Winter	1.25
	A2	Summer	1.14
DMI-F25	A2	Winter	1.11
	A2	Summer	1.18
DMI-ECS	A2	Winter	1.16
	A2	Summer	1.04
DMI-ECC	A2	Winter	1.40
	A2	Summer	1.35
DMI-ECC	B2	Winter	0.95
	B2	Summer	0.88
METNO-HAD	A2	Winter	1.23
	A2	Summer	1.22
METNO-HAD	B2	Winter	1.22
	B2	Summer	1.17
CNRM DC9	A2	Winter	1.16
	A2	Summer	1.06
CNRM DE5	A2	Winter	1.18
	A2	Summer	1.07
CNRM DE6	A2	Winter	1.22
	A2	Summer	1.10
CNRM DE7	A2	Winter	1.18
	A2	Summer	1.07
ETH-HC	A2	Winter	1.21
	A2	Summer	1.17
GKSS	A2	Winter	1.08
	A2	Summer	1.19
GKSS-sn	A2	Winter	1.13
	A2	Summer	1.20
ITCP	A2	Winter	-
	A2	Summer	-
ITCP	B2	Winter	-
	B2	Summer	-
KNMI	A2	Winter	1.16
	A2	Summer	1.16
SMHI-HC	A2	Winter	1.12
	A2	Summer	1.23
SMHI-HC	B2	Winter	1.06
	B2	Summer	1.17
SMHI-HC22	A2	Winter	1.13
	A2	Summer	1.14
SMHI-MPI	A2	Winter	1.34
	A2	Summer	1.41
SMHI-MPI	B2	Winter	1.27
	B2	Summer	1.25

Table 5.5 PRUDENCE RCM seasonal perturbation factors for ETo (Hydrological seasons).

Using all PRUDENCE RCM results, and based on the hydrological seasons, a calculation is made for the high, mean and lower perturbation factors for precipitation and ETo. This would give an idea on the range of variation for the future climate expectations. The results are given in table 5.6.

Variable	Season	Low scenario	Mean scenario	high scenario
Rainfall perturbations	Winter	0.97	1.07	1.24
	Summer	0.46	0.85	0.95
ETo perturbations	Winter	0.95	1.18	1.40
	Summer	0.88	1.16	1.41

Table 5.6 Lower, mean and high seasonal perturbation factors for precipitation and ETo derived from PRUDENCE RCMs (Hydrological seasons).

5.5.2 Frequency perturbation approach

Another possibility of deriving the perturbations is through the hydro-climatological variable frequency analysis. Referred to here as the frequency analysis method or the frequency perturbation approach, this method ensures that the perturbations in the observed events are consistent with similarly ranked events in the climate model series (see chapter 4 'downscaling method' – section 4.4.4.2). The frequency perturbation analysis investigates then the variation of the perturbation factors with respect to the frequency of the assigned event.

This method consists of calculating the average percentage change given in the RCM spatial grid resolution from current and future conditions, by comparing for each similar rank the ratio of hydro-climatological variable values between the control and scenario periods. In this respect, data are ranked from high to low values from current (1960-1990) conditions and compared to ranked data after RCM simulations for future (2070-2100) conditions. The derived perturbation factors are then used to scale the ranked historical record (Harrold and Jones, 2003; Richard et al., 2004).

This method ensures also that the perturbations are applied depending on the event's class. In fact, by carrying out a frequency perturbation analysis, events can be classified as low, medium, high and extreme. Such classification is very useful for modelling needs where some applications focus on a particular range of events.

By plotting the derived perturbation factors assigned to their frequencies, it is possible to check whether the variable extremes tend to have higher perturbations than the variable medium or low values. It is possible as well to decide if the perturbations are frequency dependent and therefore to apply an average factor only to a range of events having similar frequencies. In this study, a high variable threshold is selected in order to focus on the range of extremes.

The changes in the number of peaks between the control and the scenario periods will be taken into account and introduced into the original series as well. Methods for perturbation of the number of events will be further discussed.

5.5.2.1 Methodology for frequency perturbation approach

Applying the frequency perturbation approach assumes following five steps:

1. The selection of the RCM outputs to be processed (e.g., precipitation). The selection covers the control period results and the scenario period results. The control period results act as a baseline series which present the current climate condition;
2. The control and scenario period simulation results are ranked in descending order giving the rank one to the highest value in the series. It is often used that statistically equal variable values get different ranks;
3. Perturbation factors of the ranked series are calculated as the ratio between the scenario variable value and the control variable value for the same rank;
4. A probability of occurrence (Also exceedance probability) is assigned to each factor based on the rank of the variable values considered. The exceedance probability is a statistical measure of the empirically based frequency of being exceeded. This is referred to here as the frequency. For example, events with low magnitudes have high frequencies, extreme events have low frequencies;
5. Plotting the frequency-perturbation relation to investigate the variation of the perturbation factors for the extremes and the low values. A threshold might be obtained above which the perturbation factor is approximately constant.

Figure 5.4 presents the frequency- perturbation plot for precipitation extracted from the control and A2 scenario simulations for the DMI-HC2 model. The perturbation factors seem to increase slightly for frequencies higher than 0.1 year. They strongly decrease for the lower events. This decrease returns to the fact that climate models seem to poorly predict low rainfall events (wet days). A threshold of 0.1 year can be applied in this case and an average perturbation factor is calculated to represent the future extremes.

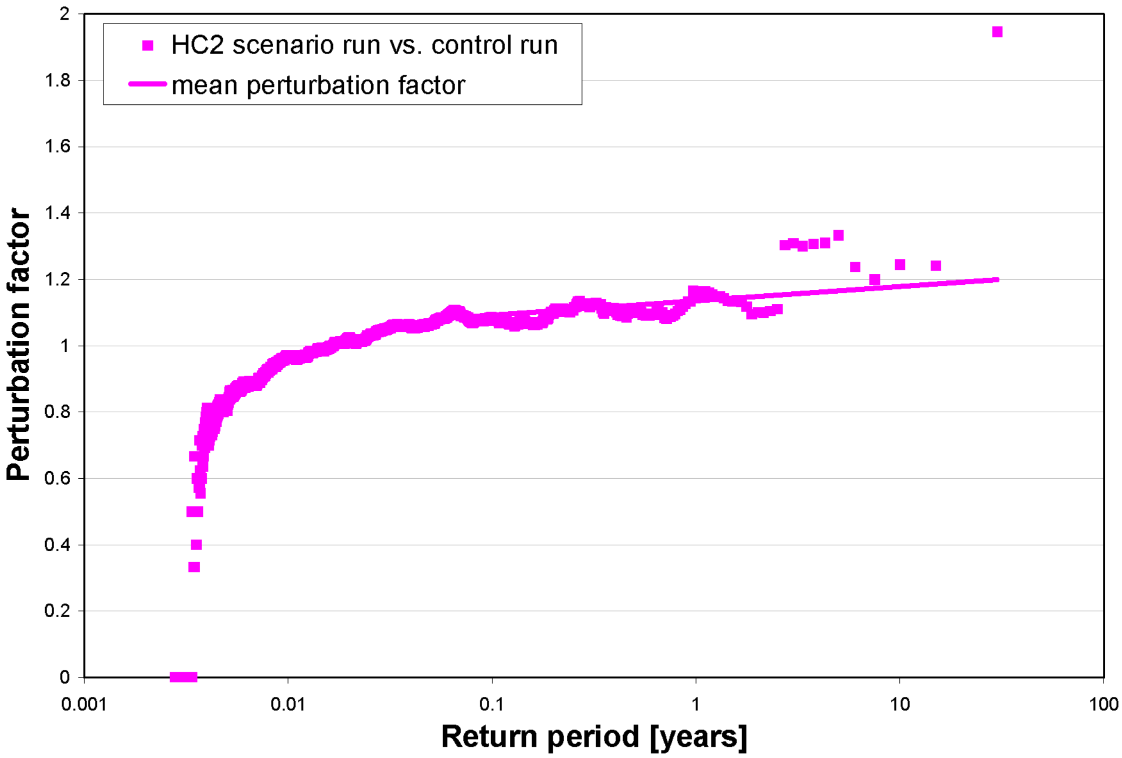


Figure 5.4 Frequency- perturbation plot for rainfall, DMI-HC2 scenario.

5.5.2.2 Advantages and disadvantages of the frequency perturbation approach

	Advantages	**Disadvantages**
Frequency perturbation approach	• Easy to apply and sensitive to all classes of events; • Local spatial and temporal variability are maintained; • Realistic climate sequences are generated; • Offers consistency check between distributions of the control and scenario series; • Helps towards climate model selection for impact analysis.	• The change (increase or decrease) in number of events is not taken into account.

Table 5.7 Advantages and disadvantages of the frequency perturbation approach.

5.5.2.3 Overview of the PRUDENCE frequency perturbation factors

The PRUDENCE frequency perturbation factors have been calculated for winter and summer periods corresponding to the Belgian hydrological seasons. They were calculated as well for different aggregation levels (daily data, weekly, monthly, seasonally and yearly). The factors mentioned in the tables below present the average perturbation factors for the extreme range of precipitation and evapo(transpi)ration. The extremes correspond to the events with a return period higher than 0.1 year. Tables 5.8 to 5.12 present the precipitation perturbation factors for different aggregation levels. The tables 5.13 to 5.17 present the PRUDENCE potential evapo(tanspi)ration (ETo) factors for different aggregations too. Both factors are calculated with the frequency perturbation approach.

a) *Factors for precipitation*

Model	Av. factor for return period >=0.1 years (Winters)	Av. factor for return period >=0.1 years (Summers)
DMI-HC1- HS1	1.10	0.98
DMI-HC1- HS2	1.04	0.94
DMI-HC1- HS3	1.03	0.90
DMI-HC2- HS1	1.07	1.04
DMI-HC2- HS2	1.14	1.00
DMI-HC2- HS3	1.14	0.96
DMI-HC3- HS1	1.03	1.11
DMI-HC3- HS2	1.10	1.07
DMI-HC3- HS3	1.09	1.03
DMI-F25	1.06	0.98
DMI-ECS	1.30	0.50
DMI-ECC-A2	1.10	1.04
DMI-ECC-B2	1.10	1.06
METNO-A2	1.13	0.89
METNO-B2	1.03	0.91
CNRM-DC9	1.05	0.91
CNRM-DE5	1.07	0.89
CNRM-DE6	1.15	0.83
CNRM-DE7	1.09	0.88
ETH-HC	1.04	0.95
GKSS-A2	1.09	1.05
GKSS-sn-A2	1.03	0.98
KNMI	1.06	1.03
ITCP-A2	0.95	1.10
ITCP-B2	0.95	1.07
SMHI-HC-A2	1.06	1.01
SMHI-HC-B2	1.02	0.99
SMHI-HC22	1.10	1.01
SMHI-MPI-A2	1.30	0.75
SMHI-MPI-B2	1.27	0.86

Table 5.8 Daily perturbation factors for precipitation.

Model	Av. factor for return period >=0.1 years (Winters)	Av. factor for return period >=0.1 years (Summers)
DMI-HC1- HS1	1.00	0.87
DMI-HC1- HS2	1.00	0.89
DMI-HC1- HS3	1.05	0.85
DMI-HC2- HS1	1.07	1.02
DMI-HC2- HS2	1.07	1.05
DMI-HC2- HS3	1.12	1.01
DMI-HC3- HS1	1.09	0.99
DMI-HC3- HS2	1.08	1.01
DMI-HC3- HS3	1.14	0.98
DMI-F25	1.06	0.94
DMI-ECS	1.14	0.62
DMI-ECC-A2	1.12	1.11
DMI-ECC-B2	1.10	1.03
METNO-A2	1.16	1.03
METNO-B2	1.12	0.94
CNRM-DC9	1.02	0.92
CNRM-DE5	1.06	0.81
CNRM-DE6	1.08	0.90
CNRM-DE7	1.09	0.99
ETH-HC	1.00	0.97
GKSS-A2	1.13	1.01
GKSS-sn-A2	1.09	1.00
KNMI	1.05	1.03
ITCP-A2	1.00	1.09
ITCP-B2	0.99	1.06
SMHI-HC-A2	1.05	1.00
SMHI-HC-B2	1.01	0.92
SMHI-HC22	1.09	1.00
SMHI-MPI-A2	1.28	0.78
SMHI-MPI-B2	1.25	0.84

Table 5.9 Weekly perturbation factors for precipitation.

Model	Av. factor for return period >=0.1 years (Winters)	Av. factor for return period >=0.1 years (Summers)
DMI-HC1- HS1	1.08	0.89
DMI-HC1- HS2	1.01	0.92
DMI-HC1- HS3	1.10	0.98
DMI-HC2- HS1	1.15	1.06
DMI-HC2- HS2	1.08	1.09
DMI-HC2- HS3	1.17	1.17
DMI-HC3- HS1	1.17	1.09
DMI-HC3- HS2	1.10	1.13
DMI-HC3- HS3	1.20	1.20
DMI-F25	1.11	0.93
DMI-ECS	1.14	0.79
DMI-ECC-A2	1.20	1.06
DMI-ECC-B2	1.19	1.02
METNO-A2	1.19	0.92
METNO-B2	1.19	0.84
CNRM-DC9	1.01	0.96
CNRM-DE5	1.03	1.04
CNRM-DE6	1.07	0.94
CNRM-DE7	1.00	1.06
ETH-HC	1.00	1.00
GKSS-A2	1.12	1.02
GKSS-sn-A2	1.06	1.00
KNMI	1.13	0.95
ITCP-A2	0.86	1.04
ITCP-B2	0.86	1.02
SMHI-HC-A2	1.12	0.92
SMHI-HC-B2	1.03	0.90
SMHI-HC22	1.16	0.95
SMHI-MPI-A2	1.23	0.79
SMHI-MPI-B2	1.20	0.79

Table 5.10 Monthly perturbation factors for precipitation.

Model	Av. factor for return period >=0.1 years (Winters)	Av. factor for return period >=0.1 years (Summers)
DMI-HC1- HS1	1.03	0.82
DMI-HC1- HS2	1.07	0.86
DMI-HC1- HS3	1.12	0.75
DMI-HC2- HS1	1.06	0.84
DMI-HC2- HS2	1.12	0.89
DMI-HC2- HS3	1.16	0.77
DMI-HC3- HS1	1.05	0.90
DMI-HC3- HS2	1.10	0.95
DMI-HC3- HS3	1.16	0.83
DMI-F25	1.09	0.89
DMI-ECS	1.22	0.46
DMI-ECC-A2	0.95	0.85
DMI-ECC-B2	1.05	0.91
METNO-A2	1.13	0.83
METNO-B2	1.09	0.80
CNRM-DC9	1.00	0.88
CNRM-DE5	1.05	0.93
CNRM-DE6	1.12	0.86
CNRM-DE7	1.06	0.92
ETH-HC	1.07	0.82
GKSS-A2	1.13	0.90
GKSS-sn-A2	1.08	0.85
KNMI	1.05	0.90
ITCP-A2	1.03	0.98
ITCP-B2	1.02	0.96
SMHI-HC-A2	1.08	0.84
SMHI-HC-B2	1.05	0.86
SMHI-HC22	1.17	0.88
SMHI-MPI-A2	1.13	0.63
SMHI-MPI-B2	1.21	0.75

Table 5.11 Seasonally perturbation factors for precipitation.

Model	Av. factor (30 years)
DMI-HC1- HS1	0.93
DMI-HC1- HS2	0.99
DMI-HC1- HS3	0.96
DMI-HC2- HS1	0.99
DMI-HC2- HS2	1.01
DMI-HC2- HS3	1.01
DMI-HC3- HS1	1.00
DMI-HC3- HS2	1.05
DMI-HC3- HS3	1.02
DMI-F25	1.00
DMI-ECS	0.84
DMI-ECC-A2	0.91
DMI-ECC-B2	1.00
METNO-A2	0.98
METNO-B2	0.95
CNRM-DC9	0.95
CNRM-DE5	1.00
CNRM-DE6	1.00
CNRM-DE7	1.00
ETH-HC	0.95
GKSS-A2	1.02
GKSS-sn-A2	0.97
KNMI	0.98
ITCP-A2	0.99
ITCP-B2	0.97
SMHI-HC-A2	0.96
SMHI-HC-B2	0.95
SMHI-HC22	1.02
SMHI-MPI-A2	0.94
SMHI-MPI-B2	1.03

Table 5.12 Yearly perturbation factors for precipitation.

b) *Factors for evapo(transpi)ration*

Model	Av. factor for return period >=0.1 years (Winters)	Av. factor for return period >=0.1 years (Summers)
DMI-HC1- HS1	1.03	1.13
DMI-HC1- HS2	1.03	1.09
DMI-HC1- HS3	1.95	1.07
DMI-HC2- HS1	1.15	1.12
DMI-HC2- HS2	1.14	1.08
DMI-HC2- HS3	2.18	1.05
DMI-HC3- HS1	0.62	1.15
DMI-HC3- HS2	0.62	1.11
DMI-HC3- HS3	1.28	1.09
DMI-F25	0.99	1.10
DMI-ECS	1.13	1.06
DMI-ECC-A2	0.4	0.93
DMI-ECC-B2	0.4	0.87
METNO-A2	1.09	1.13
METNO-B2	1.12	1.07
CNRM-DC9	1.15	1.12
CNRM-DE5	1.10	1.09
CNRM-DE6	1.19	1.07
CNRM-DE7	1.13	1.06
ETH-HC	1.13	1.11
GKSS-A2	1.01	1.09
GKSS-sn-A2	1.17	1.60
KNMI	1.07	1.12
SMHI-HC-A2	1.02	1.13
SMHI-HC-B2	1.03	1.07
SMHI-HC22	1.04	1.09
SMHI-MPI-A2	1.24	1.21
SMHI-MPI-B2	1.18	1.12

Table 5.13 Daily perturbation factors for ETo.

Model	Av. factor for return period >=0.1 years (Winters)	Av. factor for return period >=0.1 years (Summers)
DMI-HC1- HS1	1.20	1.29
DMI-HC1- HS2	1.05	2.9
DMI-HC1- HS3	1.14	2.82
DMI-HC2- HS1	1.10	0.68
DMI-HC2- HS2	0.97	1.19
DMI-HC2- HS3	1.05	1.16
DMI-HC3- HS1	1.21	0.64
DMI-HC3- HS2	1.05	1.13
DMI-HC3- HS3	1.14	1.10
DMI-F25	1.17	1.17
DMI-ECS	1.04	1.11
DMI-ECC-A2	2.31	0.8
DMI-ECC-B2	2.03	0.73
METNO-A2	1.20	1.22
METNO-B2	1.08	1.17
CNRM-DC9	1.09	1.13
CNRM-DE5	1.15	1.13
CNRM-DE6	1.13	1.13
CNRM-DE7	1.12	1.10
ETH-HC	1.15	1.11
GKSS-A2	1.22	1.18
GKSS-sn-A2	1.86	1.66
KNMI	1.25	1.14
SMHI-HC-A2	1.23	1.22
SMHI-HC-B2	1.15	1.15
SMHI-HC22	1.12	1.13
SMHI-MPI-A2	1.31	1.38
SMHI-MPI-B2	1.19	1.24

Table 5.14 Weekly perturbation factors for ETo.

Model	Av. factor for return period >=0.1 years (Winters)	Av. factor for return period >=0.1 years (Summers)
DMI-HC1- HS1	1.21	1.17
DMI-HC1- HS2	1.07	1.20
DMI-HC1- HS3	1.13	1.14
DMI-HC2- HS1	1.18	1.15
DMI-HC2- HS2	1.04	1.18
DMI-HC2- HS3	1.10	1.12
DMI-HC3- HS1	1.24	1.16
DMI-HC3- HS2	1.09	1.19
DMI-HC3- HS3	1.16	1.12
DMI-F25	1.21	1.14
DMI-ECS	1.21	1.12
DMI-ECC-A2	0.95	0.82
DMI-ECC-B2	0.80	0.74
METNO-A2	1.18	1.22
METNO-B2	1.05	1.14
CNRM-DC9	1.20	1.16
CNRM-DE5	1.17	1.17
CNRM-DE6	1.23	1.18
CNRM-DE7	1.18	1.15
ETH-HC	1.18	1.13
GKSS-A2	1.24	1.15
GKSS-sn-A2	2.08	1.62
KNMI	1.23	1.14
SMHI-HC-A2	1.18	1.22
SMHI-HC-B2	1.14	1.13
SMHI-HC22	1.14	1.12
SMHI-MPI-A2	1.33	1.43
SMHI-MPI-B2	1.20	1.30

Table 5.15 Monthly perturbation factors for ETo.

Model	Av. factor for return period >=0.1 years (Winters)	Av. factor for return period >=0.1 years (Summers)
DMI-HC1- HS1	1.14	1.29
DMI-HC1- HS2	1.09	1.25
DMI-HC1- HS3	1.14	1.29
DMI-HC2- HS1	1.11	1.29
DMI-HC2- HS2	1.05	1.26
DMI-HC2- HS3	1.10	1.30
DMI-HC3- HS1	1.16	1.24
DMI-HC3- HS2	1.10	1.20
DMI-HC3- HS3	1.15	1.25
DMI-F25	1.13	1.23
DMI-ECS	1.06	1.10
DMI-ECC-A2	2.10	0.60
DMI-ECC-B2	1.86	0.53
METNO-A2	1.13	1.34
METNO-B2	1.12	1.28
CNRM-DC9	1.05	1.11
CNRM-DE5	1.18	1.10
CNRM-DE6	1.21	1.13
CNRM-DE7	1.19	1.10
ETH-HC	1.11	1.26
GKSS-A2	1.11	1.23
GKSS-sn-A2	1.38	1.66
KNMI	1.17	1.16
SMHI-HC-A2	1.13	1.28
SMHI-HC-B2	1.08	1.20
SMHI-HC22	1.09	1.20
SMHI-MPI-A2	1.34	1.46
SMHI-MPI-B2	1.21	1.32

Table 5.16 Seasonally perturbation factors for ETo.

Model	Av. factor (30 years)
DMI-HC1- HS1	1.21
DMI-HC1- HS2	1.15
DMI-HC1- HS3	1.20
DMI-HC2- HS1	1.21
DMI-HC2- HS2	1.15
DMI-HC2- HS3	1.19
DMI-HC3- HS1	1.19
DMI-HC3- HS2	1.14
DMI-HC3- HS3	1.18
DMI-F25	1.17
DMI-ECS	1.09
DMI-ECC-A2	0.9
DMI-ECC-B2	0.81
METNO-A2	1.22
METNO-B2	1.19
CNRM-DC9	1.10
CNRM-DE5	1.12
CNRM-DE6	1.15
CNRM-DE7	1.11
ETH-HC	1.17
GKSS-A2	1.17
GKSS-sn-A2	1.57
KNMI	1.16
SMHI-HC-A2	1.20
SMHI-HC-B2	1.14
SMHI-HC22	1.14
SMHI-MPI-A2	1.40
SMHI-MPI-B2	1.25

Table 5.17 Yearly perturbation factors for ETo.

5.6 Selection of potential climate change scenarios for Belgium

5.6.1 Selection methodology

Two criteria are used for selection of future Belgian climate change scenarios. Climate models that satisfy the two criteria will be accepted to build climate change scenarios for Belgium (exception made for the Hadley Center models DMI-HC, where the second criterion will be decisive in the selection), the others will be systematically rejected. In the following analysis, we implemented two selection cases and potential rejection of some of the DMI-HC models. The selection or potential rejection will have, as follows, great impact on the range of uncertainties. This selection methodology is qualified as an empirical selection procedure. These criteria are defined as below:

1. Criterion 1: consists on visually checking the perturbation factors for the different RCMs for precipitation and potential evapo(transpi)ration for a given aggregation level. The factors that vary within the same range will be accepted. The ones showing higher or lower variations (outliers) will be rejected. For instance, for the daily aggregation level, it is expected during the winter season to have factors varying positively around the values of (1 – 1.15) indicating an increase in rainfall (Figure 5.5). The DMI-ESC model shows higher factor comparing to other RCMs, the same for SMHI-MPI models (both simulations A2 and B2). On the other hand, the ITCP model presents a decreasing factor, which makes it apart from all the RCMs and therefore will be potentially rejected from the daily winter simulations. (Figure 5.5, the rejected A2 simulations are marked in red and the rejected B2 simulations are marked in blue).

   For the summer period, the figure 5.6 shows very low factor with the DMI-ECS model and very high factors with the two scenario simulations SMHI-MPI-A2. These models are therefore potentially removed form the daily simulations of the summer period.

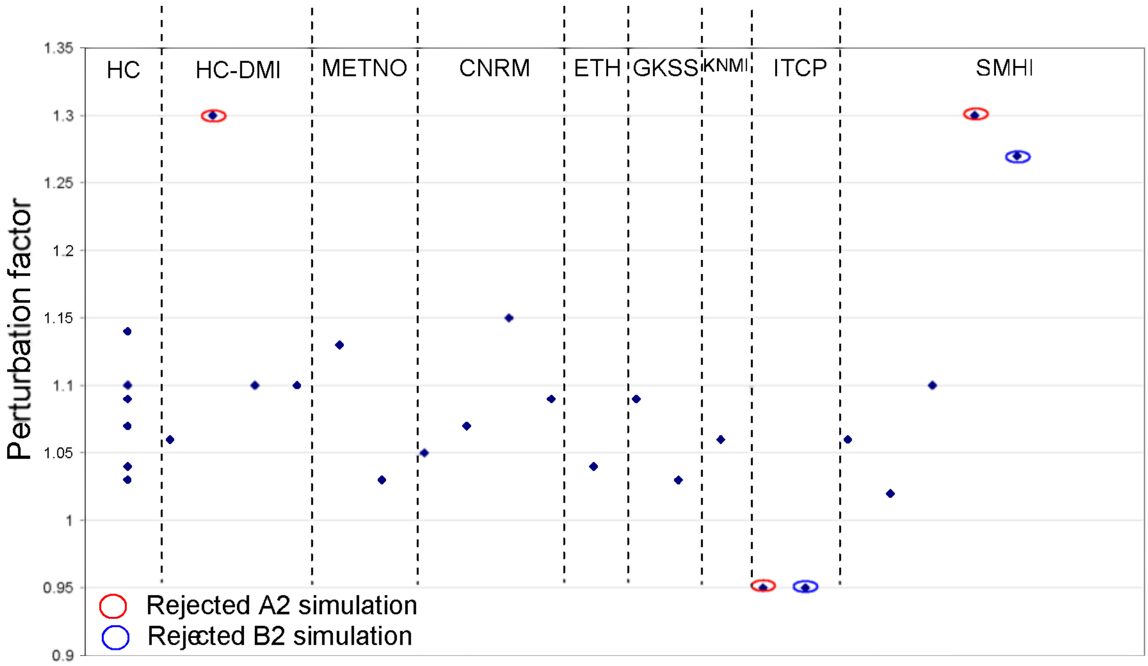


Figure 5.5 Daily precipitation perturbation factors for winter.

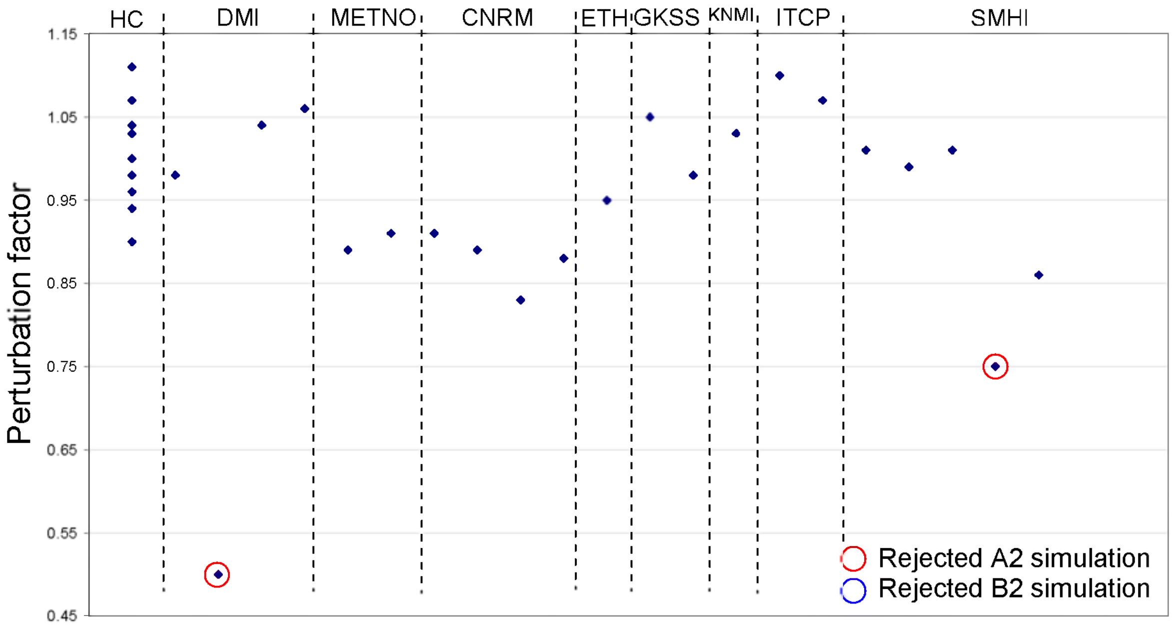


Figure 5.6 Daily precipitation perturbation factors for summer.

2. Criterion 2: For the models that will be potentially rejected giving criterion 1, a consistency check with the historical data is made in order to confirm or infirm the assumption of rejection.

This criterion is due to the fact that the PRUDENCE RCMs cover the entire European area and are calibrated and validated for a number of climatologic and rainfall stations spread over Europe, but maybe not specifically for Belgium. So their simulation results might not represent Belgium well. In order to solve the problem of systemic deviations or biases between the climate models results and the present climate, the control GCM/RCM results are mapped to the historical record (Uccle station record) using the frequency analysis approach. The climate model baseline that satisfies criterion 1 and meets closely with the historical records is considered accurate for climate change scenarios for Belgium, and will be used (accepted by statistical hypothesis testing). The others will be rejected. The statistical hypothesis testing will take into account the uncertainties in quantiles derived from the frequency analysis approach due to data limitation or randomness. This will require confidence intervals to be defined for the empirical frequency distributions or the calibrated extreme value distributions.

The problem is however that a large deviation with historical data does not involve necessarily that also the predicted impact of climate change is inaccurate. For this reason, comparison with historical data is only carried out for the simulations with the climate models for which very high or very low perturbation factors are found (factors which do not satisfy criterion 1). For instance the ITCP model that has been potentionally rejected within criterion 1, presents large deviation with the Uccle data which makes it subject of total rejection (Figure 5.7).

By potentially rejecting some GCM/RCM simulations, we are removing part of the uncertainties that might be introduced into the hydrological simulation by less accurate climate model results (Figure 5.7). It might, however, also introduce a risk of underestimating the real uncertainty levels.

Specific exception is made however for the Hadley Center models DMI-HC. These models (three control and scenario simulations DMI-HC1/DMI-HS1, DMI-HC2/DMI-HS2 and DMI-HC3/DMI-HS3) present the specificity that control and scenario runs can be combined. Therefore we can combine the control of the first run (DMI-HC1) with the scenario simulation of the second or third run (DMI-HS2 or DMI-HS3) and the same for the other control runs. Nine perturbation factors are thus derived for each aggregation level for the DMI-HC models. It might happen that some of these combined perturbation factors show very high or very low values and are subject to rejection (case of monthly summer rainfall, see Appendix A) but at the same time, other combinations containing the same models show good range of perturbation factors. In this respect we hesitate about accepting or rejecting the high and low factors. We decided therefore to evaluate the two cases (acceptance of the deviated combined factors in a first case and rejecting them in a second case) in order to assess the range of uncertainties in the climate scenarios for a given aggregation level.

One other important point to keep in mind is the influence of the areal reduction factors (ARFs). As mentioned in chapter 4 ‘downscaling methods’, section 4.4.2.1, the ARFs are factors for transformation of point precipitation to areal precipitation. This is due to the fact that PRUDENCE RCMs provide average grid precipitation which is compared to point precipitation (rain gauge).

ARFs are defined as the ratio between the average areal precipitation and the point precipitation. Also here distinction can be made between mean seasonal factors and factors for extreme quantiles.

Gellens (2003) demonstrates that, for Belgium, the empirical ARFs are site dependent and are varying between 0.8 and 0.9. In this research, a constant ARF is decided to be taken and is equal to 0.85. An assumption is also made for the independency of the ARFs on the aggregation level and the different frequency classes.

The ARFs do not introduce any changes in the selection of the future Belgian climate scenarios as these lasts are mostly dependent on the variation of the perturbation factors but they should be applied in the impact analysis.

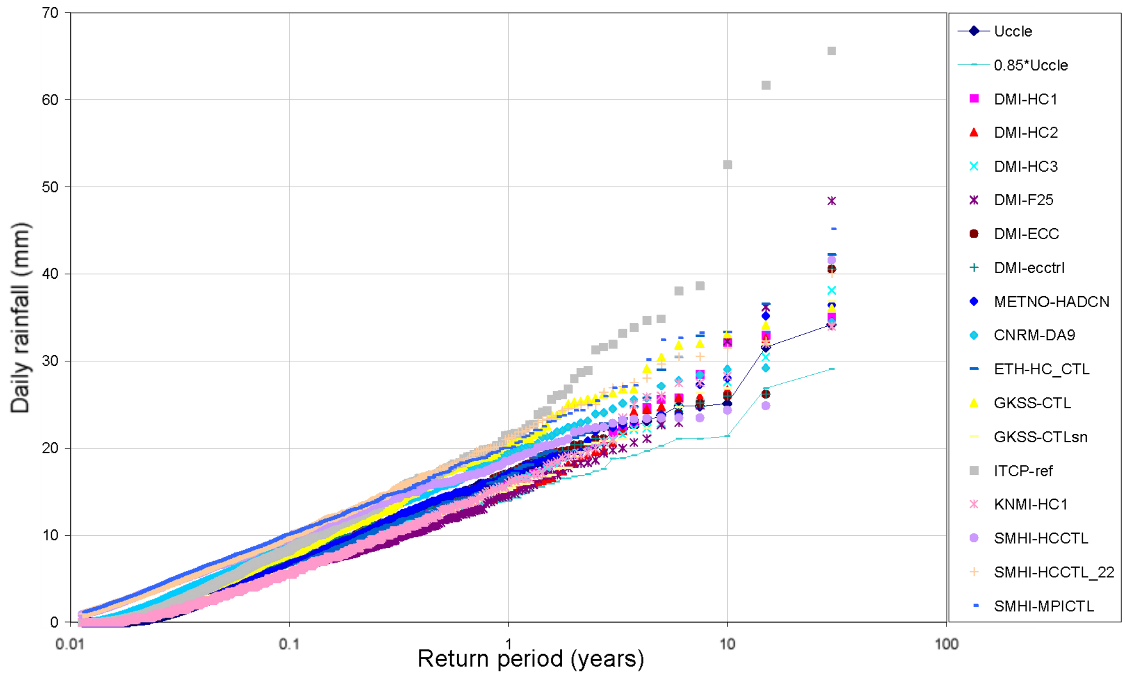


Figure 5.7 Daily winter rainfall. PRUDENCE RCMs vs. historical data.

5.6.2 Climate change scenarios selection

The factors differ strongly depending on the climate model, spatial resolution and scenario used. They depend as well on the data aggregation level. The uncertainties on potential climate change scenarios are therefore particularly large.

For the daily aggregation case, the models DMI-ECS, ITCP-A2, ITCP-B2, SMHI-A2 and SMHI-B2 have been rejected from the winter simulation as they provide very high and very low factors. As for the summer the same Danish model (DMI-ECS) is removed along with SMHI-A2 and SMHI-B2.

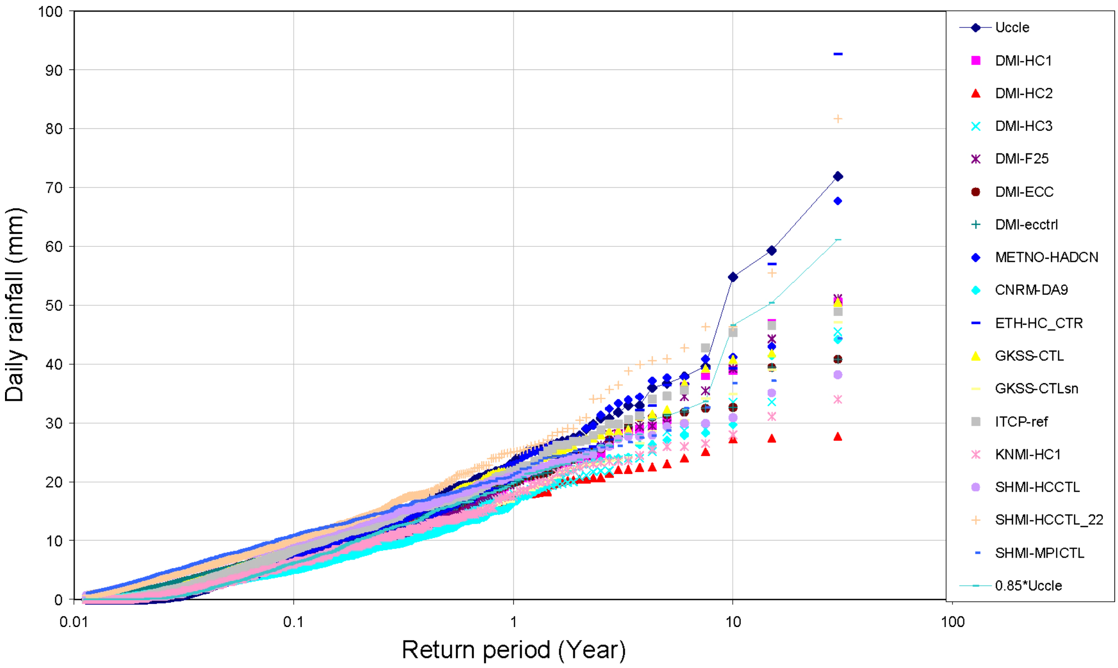


Figure 5.8 Daily summer rainfall. PRUDENCE RCMs vs. historical data.

When checking with criterion 2 (Figure 5.7, figure 5.8), it appears that the potentially rejected climate models present considerable deviations with the historical Uccle rainfall depending on winter and summer periods.

In the weekly aggregation level, and following the same procedure, the models METNO-HAD-A2, ITCP-B2, SMHI-MPI-A2 and SMHI-MPI-B2 have been rejected from the winter simulation. In summer simulations the models DMI-ECS, DMI-ECC-A2, CNRM-DE5 and SMHI-MPI-A2 have been rejected. The consistency check with the winter and summer weekly distributions confirms the rejection (Appendix A).

As for the monthly aggregation level, the winter simulations show several models to be rejected. They are DMI-ECC-A2, DMI-ECC-B2, METNO-HAD-A2, METNO-HAD-B2, ITCP-A2, ITCP-B2 and SMHI-MPI-A2.

The consistency check with the monthly winter distribution confirms clearly the choice of the rejected models (Appendix A).

As for the summer, the models, DMI-ECS, METNO-HAD-B2, SMHI-MPI-A2 and SMHI-MPI-B2 are rejected. In a first case, we accepted here the DMI-HC models although some of them show high factors. This returns to what we stated in the previous paragraph. In a second case these factors will be rejected (Appendix A).

In the seasonal aggregation level, the models DMI-ECS, DMI-ECC-A2, SMHI-HC22 and SMHI-MPI-A2 were removed from the winter simulations. As for the summer, the models DMI-ECS, ITCP-A2 and ITCP-B2 are to be rejected. The same remark is made here for the DMI-HC models (Appendix A).

The same procedure was applied for the evapo(transpi)ration variable for the daily data (Figure 5.9 and figure 5.10) and for every aggregation level (Appendix B). The results are shown in table 5.18. This table summarizes the rejected models for precipitation and evapo(transpi)ration for different aggregation levels by taking into account the first case of accepting the DMI-HC combined models.

Table 5.19 summarizes the rejected models following the second case of potentially rejecting the DMI-HC models from the monthly and seasonally summer simulations.

Appendix A & B present RCM factors' variations for different aggregation levels for rainfall and evapo(transpi)ration.

What is remarked is that for most of the aggregation levels, the Danish model DMI-ECS, DMI-ECC-A2 and the two simulations of the Italian model ITCP (A2, B2) and the Swedish model SMHI-MPI with its two simulations (A2, B2), provide factors with generally very high or very low perturbations for both winter and summer. This is probably due to the underlying GCMs.

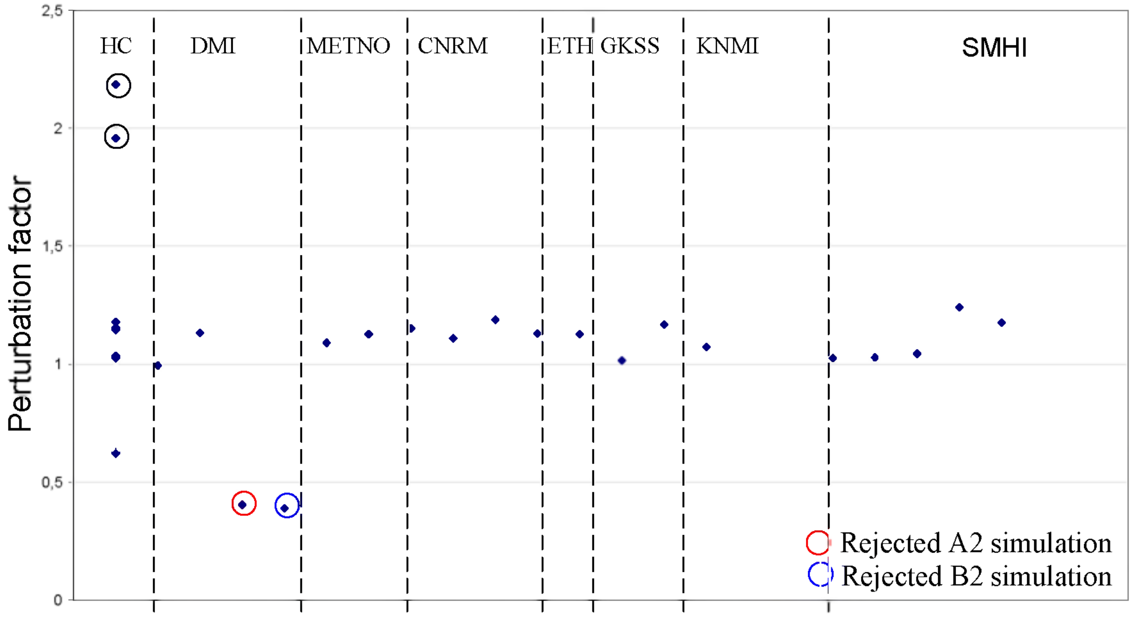


Figure 5.9 Daily evapo(transpi)ration perturbation factors for winter.

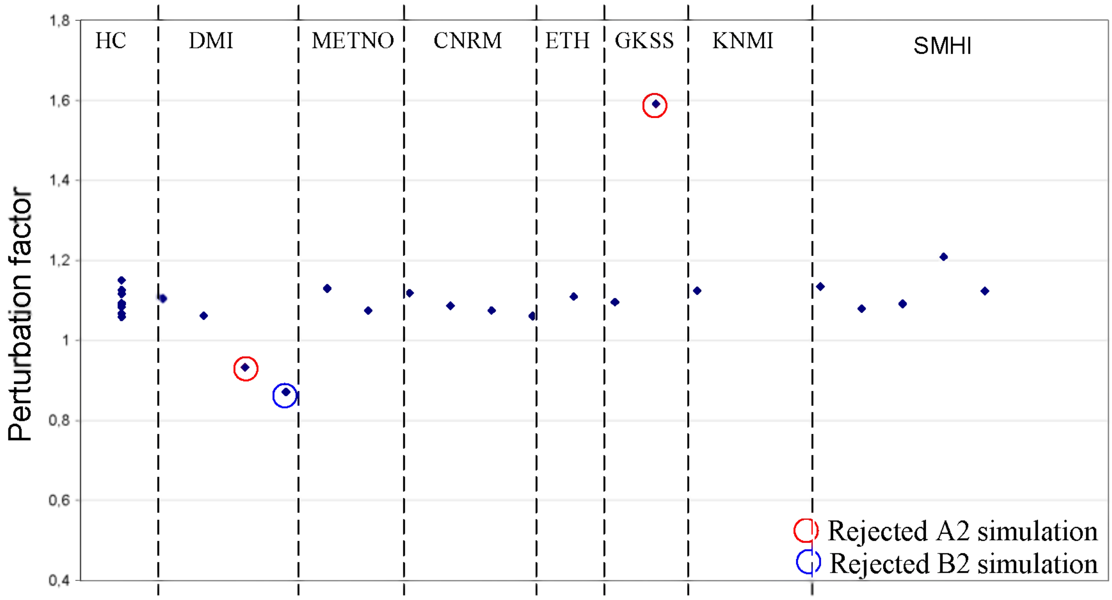


Figure 5.10 Daily evapo(transpi)ration perturbation factors for summer.

Rejected models	Daily data		Weekly data		Monthly data		Seasonally data	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Precipitation	DMI-ECS ITCP-A2 ITCP-B2 SMHI-MPI-A2 SMHI-MPI-B2	DMI-ECS SMHI-MPI-A2 SMHI-MPI-B2	METNO-HAD-A2 ITCP-B2 SMHI-MPI-A2 SMHI-MPI-B2	DMI-ECS DMI-ECC-A2 CNRM-DE5 SMHI-MPI-A2	DMI-ECC-A2 DMI-ECC-B2 METNO-HAD-A2 METNO-HAD-B2 ITCP-A2 ITCP-B2 SMHI-MPI-A2	DMI-ECS METNO-HAD-B2 SMHI-MPI-A2 SMHI-MPI-B2	DMI-ECS DMI-ECC-A2 SMHI-HC22 SMHI-MPI-A2	DMI-ECS ITCP-A2 ITCP-B2
ETo	DMI-ECC-A2 DMI-ECC-B2	DMI-ECC-A2 DMI-ECC-B2 GKSS-sn-A2	DMI-ECC-A2 DMI-ECC-B2 GKSS-sn-A2	DMI-ECC-A2 DMI-ECC-B2 GKSS-sn-A2	DMI-ECC-A2 DMI-ECC-B2 GKSS-sn-A2	DMI-ECC-A2 DMI-ECC-B2 GKSS-sn-A2 SMHI-MPI-A2 SMHI-MPI-B2	DMI-ECC-A2 DMI-ECC-B2 GKSS-sn-A2 SMHI-MPI-A2	DMI-ECC-A2 DMI-ECC-B2 GKSS-sn-A2 SMHI-MPI-A2

Table 5.18 Rejected models among PRUDENCE RCMs (first case: DMI-HC models being selected)

Rejected models	Daily data		Weekly data		Monthly data		Seasonally data	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Precipitation	DMI-ECS ITCP-A2 ITCP-B2 SMHI-MPI-A2 SMHI-MPI-B2	DMI-ECS SMHI-MPI-A2 SMHI-MPI-B2	METNO-HAD-A2 ITCP-B2 SMHI-MPI-A2 SMHI-MPI-B2	DMI-ECS DMI-ECC-A2 CNRM-DE5 SMHI-MPI-A2	DMI-HC3/DMI-HS3 DMI-ECC-A2 DMI-ECC-B2 METNO-HAD-A2 METNO-HAD-B2 ITCP-A2 ITCP-B2 SMHI-MPI-A2	DMI-HC3/DMI-HS3 DMI-HC2/DMI-HS3 DMI-HC3/DMI-HS2 DMI-ECS METNO-HAD-B2 SMHI-MPI-A2 SMHI-MPI-B2	DMI-ECS DMI-ECC-A2 SMHI-HC22 SMHI-MPI-A2	DMI-HC1/DMI-HS3 DMI-HC2/DMI-HS3 DMI-HC3/DMI-HS2 DMI-ECC-A2 CNRM-DC9 CNRM-DE6 ITCP-A2 ITCP-B2 SMHI-MPI-B2
ETo	DMI-HC2/ DMI-HS3 DMI-HC1/DMI-HS3 DMI-HC3/DMI-HS1 DMI-HC3/DMI-HS2 DMI-ECC-A2 DMI-ECC-B2	DMI-ECC-A2 DMI-ECC-B2 GKSS-sn-A2	DMI-ECC-A2 DMI-ECC-B2 GKSS-sn-A2	DMI-HC1/DMI-HS2 DMI-HC1/DMI-HS3 DMI-HC2/DMI-HS1 DMI-HC3/DMI-HS1 DMI-ECC-A2 DMI-ECC-B2 GKSS-sn-A2	DMI-ECC-A2 DMI-ECC-B2 GKSS-sn-A2	DMI-ECC-A2 DMI-ECC-B2 GKSS-sn-A2 SMHI-MPI-A2 SMHI-MPI-B2	DMI-ECC-A2 DMI-ECC-B2 GKSS-sn-A2 SMHI-MPI-A2	DMI-ECC-A2 DMI-ECC-B2 GKSS-sn-A2 SMHI-MPI-A2

Table 5.19 Rejected models among PRUDENCE RCMs (second case: DMI-HC models being rejected).

As a result, we are able to remove part of the uncertainties from the future Belgian climate change scenario provided by PRUDENCE RCMs by removing the inconsistent climate model perturbation factors. Among the selected RCMs, the problem of choosing the most representative model for Belgium is complicated by the fact that the RCMs results depend totally on their physical concepts, resolutions and chosen emission scenarios. For instance, assume that we have a model control result for a given resolution and emission scenario that meets closely with the Uccle record and gives an acceptable range of perturbation factors, and therefore is considered to be accurate for future Belgian climate scenarios. There are, however, also model control results (with different resolutions and different emission scenarios) that meet also closely with Uccle record and also provide a good range of perturbation factors. In this respect, we are unable to have a base of selection of which model is most suitable to describe the future Belgian climate. Hence, it was judged that the entire group of selected PRUDENCE RCMs is "good" for representing Belgian climate change scenarios, none is the best and none is better than another. In this way, we can build low, mean and high scenarios for the variables of precipitation and potential evapo(transpi)ration independently of the climate models' sources, physics and resolutions and this is done for each aggregation level and accounting for the joined uncertainty.

The tables 5.20 and 5.21 present the three scenarios (low, mean and high) for both previous cases (1: including DMI-HC combined models, 2: rejecting DMI-HC combined models). They are followed by figures 5.11, 5.12, 5.13 and 5.14 showing respectively these low, mean and high scenarios for winter and summer daily perturbation factors. The different aggregation levels scenarios are presented in appendix C.

Aggregation level			Low scenario	Mean scenario	High scenario
Daily	Rainfall	Winter	1.02	1.08	1.15
		Summer	0.83	0.99	1.11
	ETo	Winter	0.62	1.14	2.18
		Summer	1.05	1.10	1.21
Weekly	Rainfall	Winter	1.00	1.07	1.14
		Summer	0.85	0.98	1.09
	ETo	Winter	0.97	1.14	1.31
		Summer	0.64	1.27	2.90
Monthly	Rainfall	Winter	1.00	1.09	1.20
		Summer	0.84	1.01	1.20
	ETo	Winter	0.81	1.16	1.33
		Summer	1.12	1.16	1.22
Seasonally	Rainfall	Winter	1.00	1.08	1.20
		Summer	0.75	0.87	0.95
	ETo	Winter	1.05	1.13	1.21
		Summer	1.10	1.23	1.34

Table 5.20 Low, mean and high scenarios for precipitation and potential evapo(transpi)ration (first case).

Aggregation level			Low scenario	Mean scenario	High scenario
Daily	Rainfall	Winter	1.02	1.08	1.15
		Summer	0.83	0.99	1.11
	ETo	Winter	1.00	1.10	1.24
		Summer	1.05	1.10	1.21
Weekly	Rainfall	Winter	1.00	1.07	1.14
		Summer	0.85	0.98	1.09
	ETo	Winter	0.97	1.14	1.31
		Summer	1.10	1.17	1.38
Monthly	Rainfall	Winter	1.00	1.09	1.17
		Summer	0.84	0.98	1.09
	ETo	Winter	0.81	1.16	1.33
		Summer	1.12	1.16	1.22
Seasonally	Rainfall	Winter	1.00	1.08	1.20
		Summer	0.77	0.86	0.95
	ETo	Winter	1.05	1.13	1.21
		Summer	1.10	1.23	1.34

Table 5.21 Low, mean and high scenarios for precipitation and potential evapo(transpi)ration (second case).

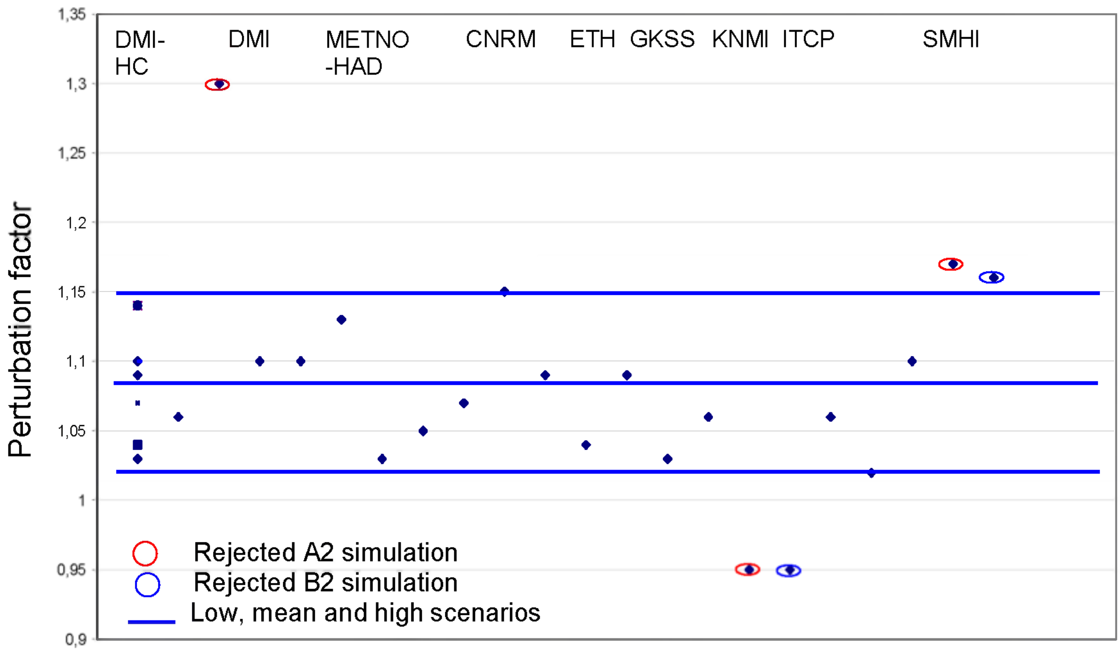


Figure 5.11 Low, mean and high scenarios for daily winter precipitation.

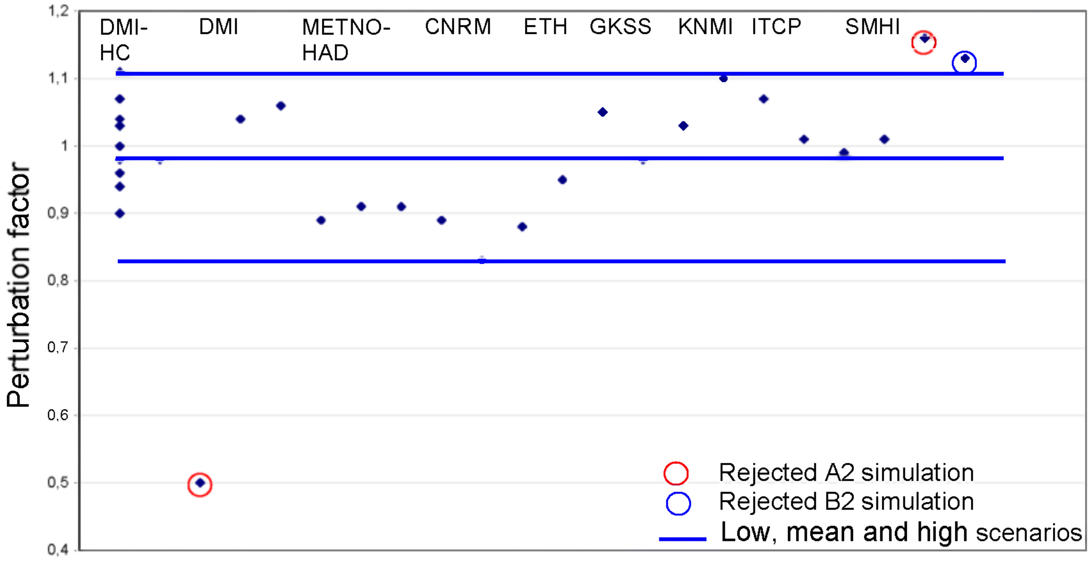


Figure 5.12 Low, mean and high scenarios for daily summer precipitation.

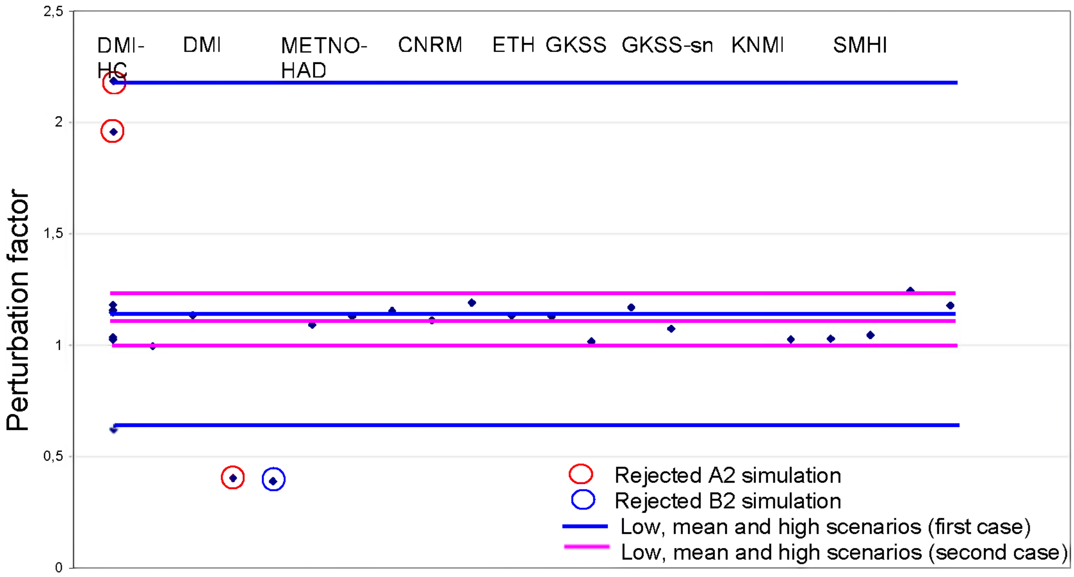


Figure 5.13 Low, mean and high scenarios for daily winter potential evapo(transpi)ration.

It is obvious from tables 5.20 and 5.21 and from figure 5.13 that the second RCMs selection case (rejection of some of the combined DMI-HC models without looking at the possible combinations between the RCMs or the supported GCM) provides consistent range of variation of the perturbation factors on the overall RCMs and thus largely reduce the uncertainty introduced through DMI-HC models within the first selection case. Therefore, the second selection case has been chosen to build climate change scenarios for Belgium.

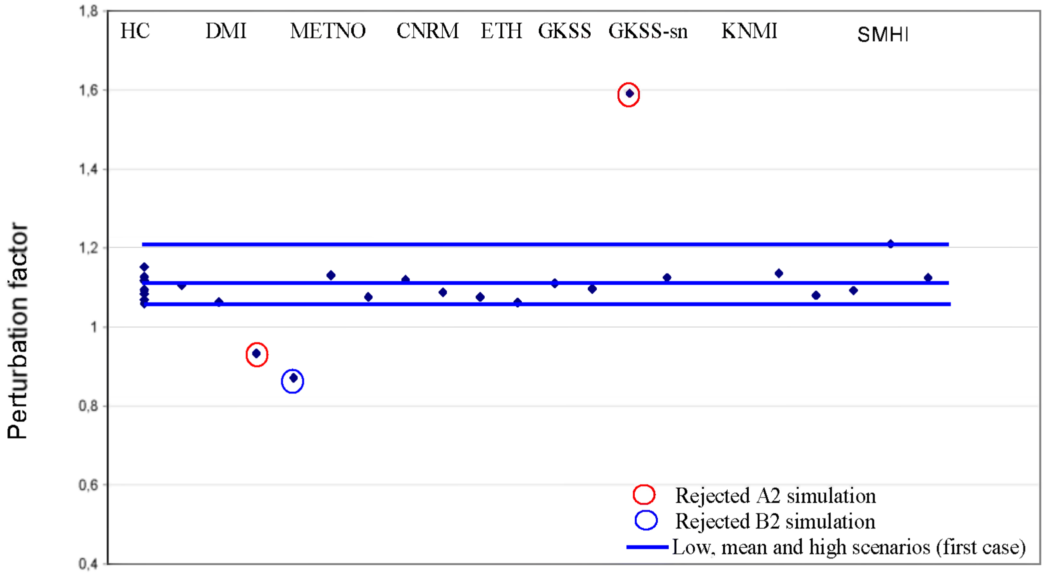


Figure 5.14 Low, mean and high scenarios for daily summer potential evapo(transpi)ration.

5.7 Comparison with the seasonal volume perturbation approach

When the seasonal volume perturbation approach is applied to calculate perturbation factors, the scenarios of table 5.22 were derived.

Variable	Season	Low	Mean	High
Precipitation perturbation	Winter	1.00	1.08	1.16
	Summer	0.80	0.87	0.94
ETo perturbation	Winter	1.06	1.17	1.27
	Summer	1.04	1.15	1.25

Table 5.22 Low, mean and high scenarios for precipitation and potential evapo(transpi)ration derived from the seasonal volume perturbation approach.

By comparing the two approaches (frequency and seasonal volume perturbation approaches), it appears that both methods provide very close results with slightly higher values (4% higher) for the high seasonal winter precipitation scenario and the seasonal summer evapo(transpi)ration (9%) with the frequency perturbation approach. This returns to the fact that only extremes were considered in the last approach. However the whole distribution is taken into account within the seasonal volume perturbation approach (Figure 5.15, Figure 5.16 and figure 5.17).

It is remarked that for the winter season, whether for rainfall or evapo(transpi)ration, the perturbation factors vary constantly with the aggregation level. The same is seen for the summer evapo(transpi)ration. Therefore average factors for each scenario are to be taken independently from the aggregation levels.

As for summer rainfall, the perturbation factors show decreasing trend for high aggregation levels. This issue is further investigated in this study where a perturbation in the number of summer events is needed (see section 5.8). Table 5.23 presents the average factors for winter rainfall and winter/summer evapo(transpi)ration for each scenario. The summer rainfall scenarios are given for the “asymptotic value” towards smaller (daily) time scales.

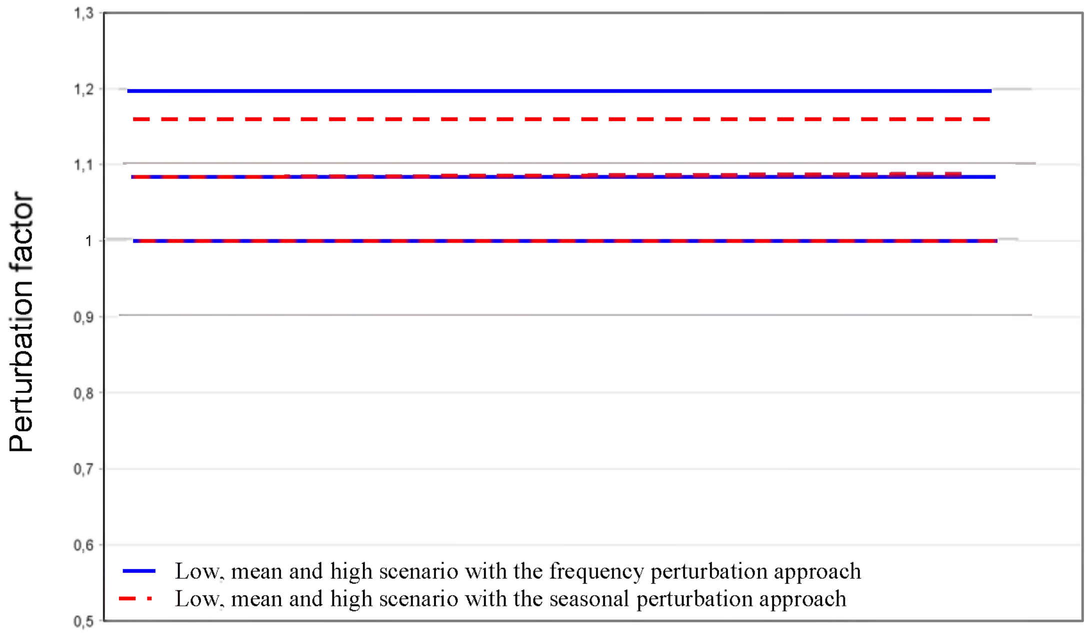


Figure 5.15 Comparison of low, mean and high scenarios for seasonal winter precipitation between the frequency perturbation approach (using the second case with seasonal aggregation level) and the seasonal volume perturbation approach.

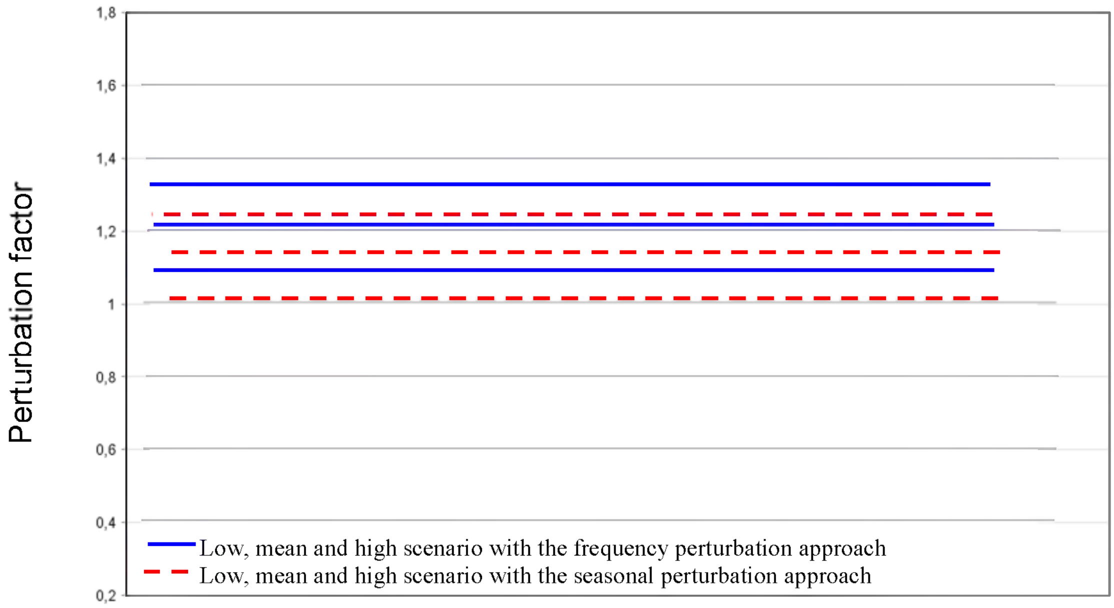


Figure 5.16 Comparison of low, mean and high scenarios for seasonal summer ETo between the frequency perturbation approach and the seasonal volume perturbation approach.

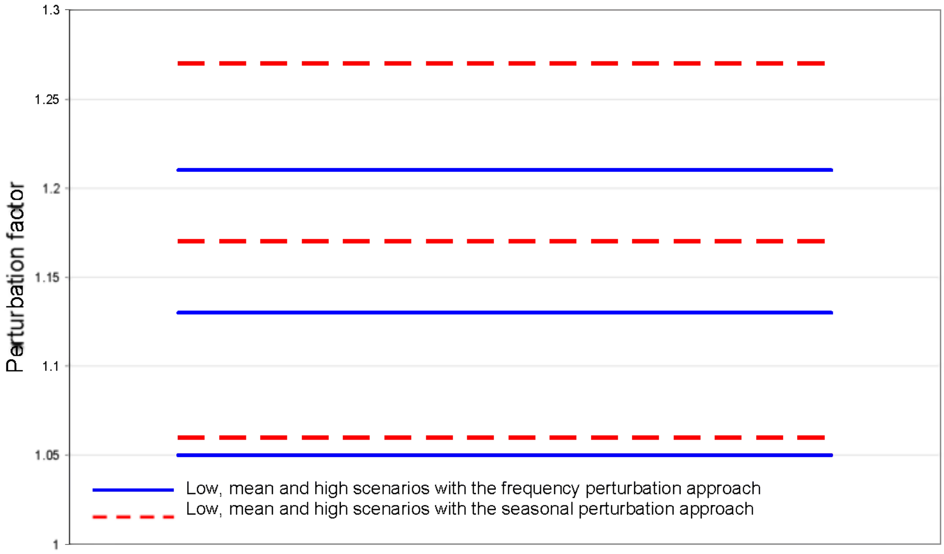


Figure 5.17 Comparison of low, mean and high scenarios for seasonal winter ETo between the frequency perturbation approach and the seasonal volume perturbation approach.

As an overall result, climate change scenarios are built for the future hydro-climatological conditions of Belgium and concern the variables of precipitation and ETo. The below factors present the most likely Belgian future climate scenarios provided within the range of PRUDENCE RCMs.

Scenario	Low	Mean	High
Winter rainfall	1.00	1.08	1.16
Summer rainfall	0.83	0.99	1.11
Winter ETo	1.00	1.13	1.27
Summer ETo	1.10	1.16	1.29

Table 5.23 Climate change scenarios for Belgium for precipitation and ETo.

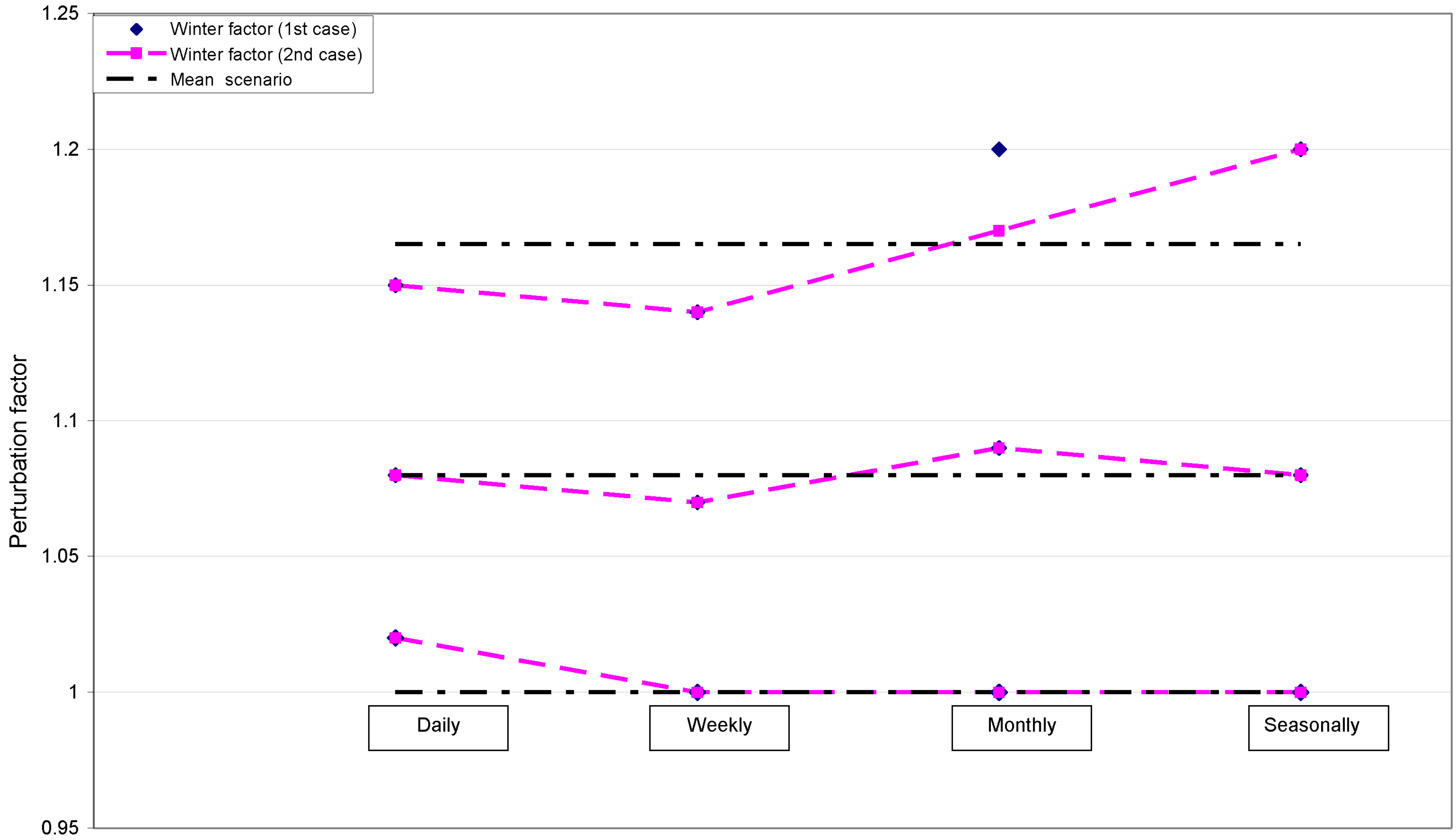


Figure 5.18 Low, mean and high scenarios for winter precipitation for different aggregations (first and second selection case included).

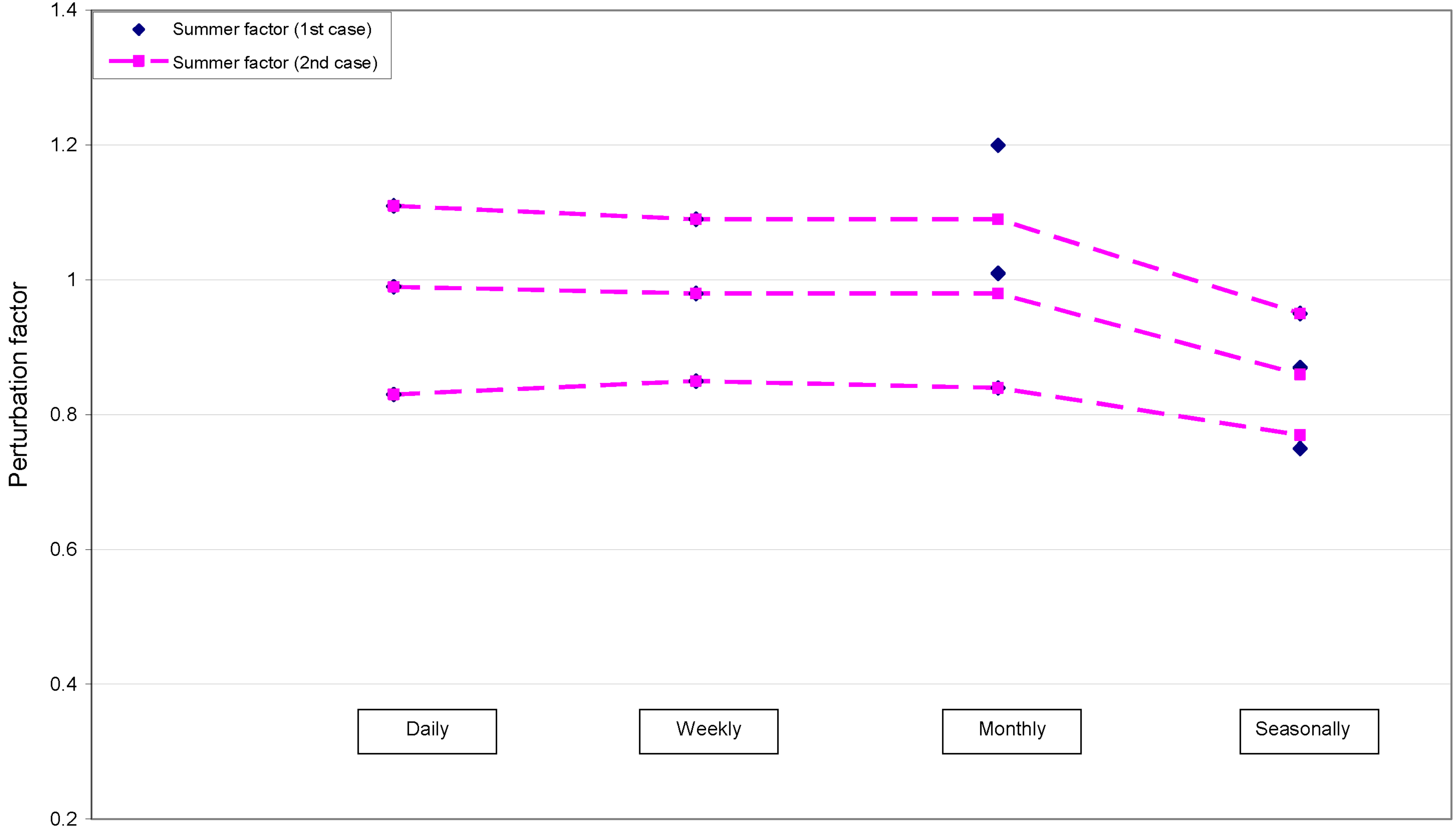


Figure 5.19 Low, mean and high scenarios for summer precipitation for different aggregations (first and second selection case included).

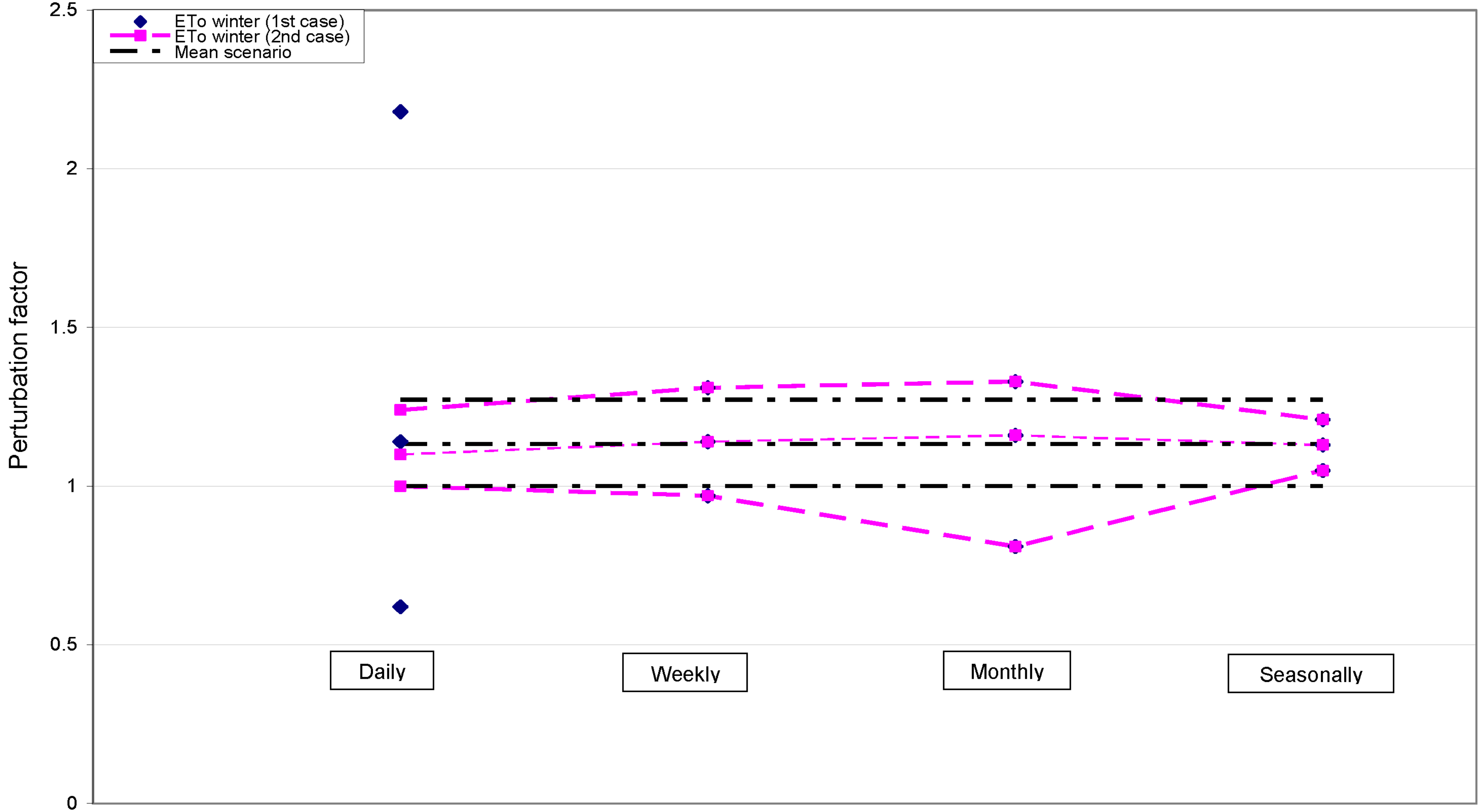


Figure 5.20 Low, mean and high scenarios for winter ETo for different aggregations (first and second selection case included).

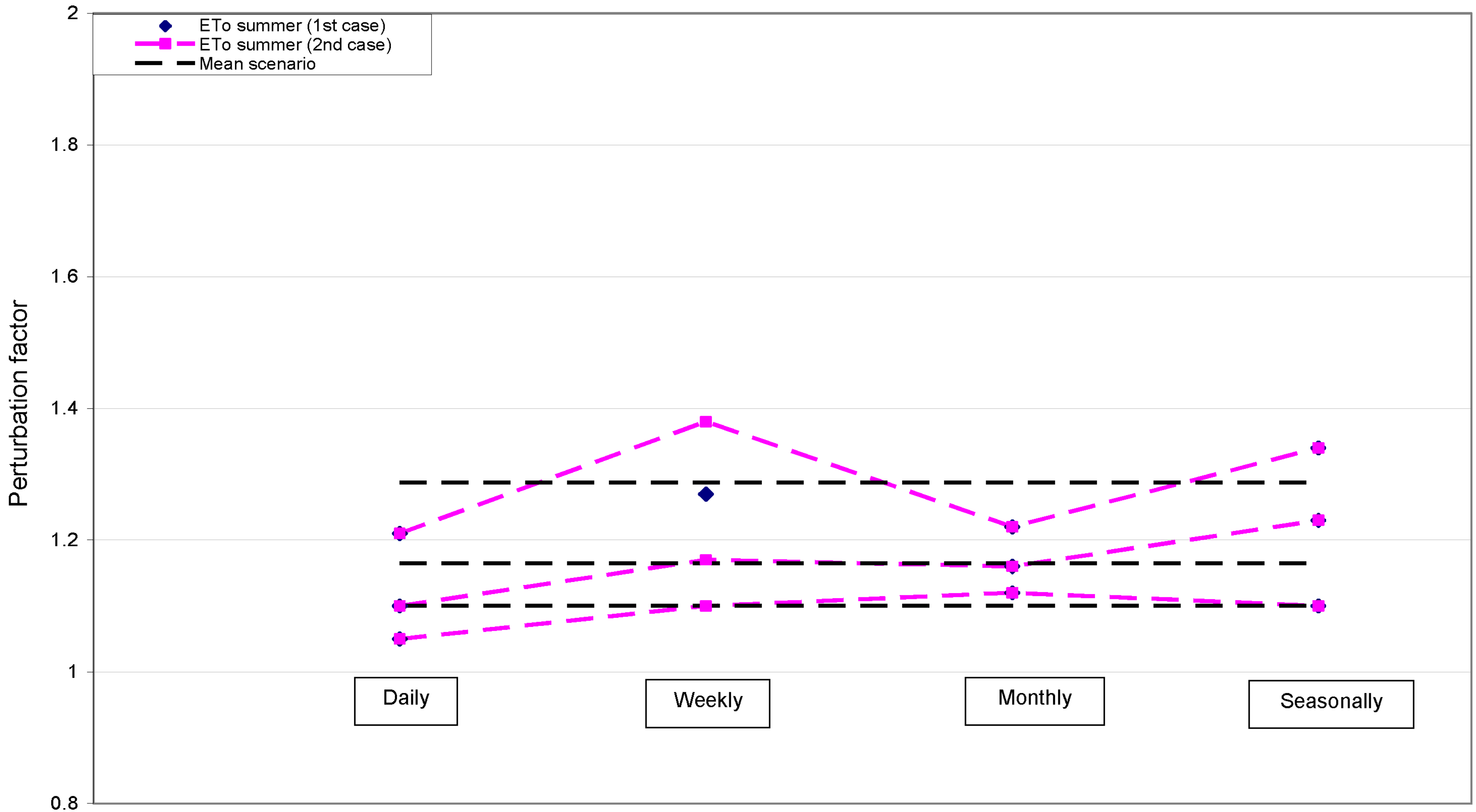


Figure 5.21 Low, mean and high scenarios for summer ETo for different aggregations (first and second selection case included).

5.8 Perturbation in number of events

As one analyses figures 5.18 and 5.19 regarding the Belgian high, mean and low scenarios for rainfall in winter and summer, two important points show up which would have great impacts on the hydrological estimations at different time scales:

- Figure 5.18 shows that winter rainfall factors are varying constantly around 1 to 1.15 for all the time scales, indicating that the factors are time scale independent. In another sense, the plot indicates that climate change has a similar impact on different rainfall time aggregation levels in winter e.g., the rainfall peaks will be affected similarly as the low storms.
- Figure 5.19 shows that summer rainfall factors present a decreasing trend for high aggregation levels (almost a decrease of 20% from the daily to the seasonal time scale). This indicates that the summer rainfall factors are time scale dependent.

In order to explain the decreasing trend in the summer rainfall factors, one should keep in mind that the factors are obtained by calculating the ratio of mean rainfall intensities from scenario and control periods. Seasonal intensities are obtained by aggregation from daily events. Therefore, if the perturbation factor for summer rainfall intensities decreases, this means that the scenario period intensity decreases in value, which, from its side, means that the number of “rainy days” serving to aggregate to seasonal time scale is decreasing within the scenario simulations. This means that for daily summer rainfall, the RCMs are predicting less summer storms.

It, therefore, could be important to perturb the number or frequency of summer storms next to the perturbations in the rainfall intensities (for a given storm). In fact, both types of perturbations affect rainfall quantiles. In this way, the total perturbation approach that we are applying in this study intrinsically accounts for both the changes in rainfall intensities and rainfall frequencies in a combined way, which makes it a strong approach. Further investigations in this subject are being done under the CCI-HYDR project where a procedure is under development to perturb rainfall series both for the frequencies (changing the number of rain storms or wet days in the series) and the rainfall intensity magnitude per rain storm or wet day. It then will be checked whether both factors can explain the total perturbation factors on rainfall quantiles derived in this study. The importance of this approach lays in the tentative to know how does climate change affect the number of summer storms and if this change is rainfall intensity dependent.

5.9 Changes in number of summer storms above given threshold

As this study concerns the hydrological extremes, it was decided, next to the quantification of the perturbations on the rainfall quantiles, to identify also the change in the number of storm scenarios focusing on the range of extremes using a Peak Over Threshold (POT) approach.

5.9.1 Peaks Over Threshold approach

The old method adopted for estimating the return period value for specific values used in water balance studies is commonly based on the adjustment of the yearly extreme values to an extreme value distribution (Gumbel, 1958; Castillo, 1988).

However, the main shortcoming for such an approach is the limited length of the available record. For example, if annual maximum extremes are used, the fitting of the probability distribution often relies on just 25-30 years long time series which verifies the large uncertainties in the estimating results (Claps, 2003). To reduce these uncertainties, one might use short aggregation time data (daily, hourly data) within a Peaks Over Threshold (POT) framework, in which the idea is to use more than one extreme value per year or to use all significant, but independent, peaks in the time series.

By considering peak events instead of annual maximum extremes, the number of available data for statistical processing would be increased considerably. The POT method is therefore based on utilizing all peak events of the available time series exceeding a specified threshold. This approach suggests two main steps: the selection of the threshold or the selection of the peak values, and the estimation of the distribution properties using statistics above the threshold. The first step is very critical and can affect the efficiency of the method.

In practical applications, the POT method is done through:

- The identification of the peak events assigned to their magnitude. Several criteria exist in the literature to identify the peaks (instantaneous or aggregated values). In this study, the method of Willems (2000) is adopted where the POT selection is simulated using three "independency" criteria;
- A threshold is then applied to the obtained sequence of peak events. The problem of choosing the most appropriate threshold is still under analysis in many researches. The method developed by Willems (2000) and used in the standard methodology for river flood modelling by the WL river authority is applied.

One of the bases of the POT method is the Generalized Pareto Distribution (GPD). In fact, the work made by Pickands (1975) showed that the probability distribution of the extremes converges to the GPD as the threshold becomes higher. The assumption of a Poisson process for the exceedance times combined with the GPD will lead to the Generalized Extreme Value (GEV) distribution in case annual maximum extremes would be used (Willems, 1998).

The cumulative distribution function of the GPD is:

$$G(y) = p[Y \leq y] = 1 - (1 - \gamma \frac{y}{\beta})^{-\frac{1}{\gamma}} \tag{5.1}$$

where β is a scale parameter, γ is called the extreme value index and determines the shape of the distribution. The cases of $\gamma > 0$, $\gamma = 0$ and $\gamma < 0$ correspond to Fréchet, Gumbel (Type I) or exponential and reverse Weibull respectively.

The asymptotic result followed by the GPD distribution above a high threshold (fact that was shown by Pickands, 1975) can be used within the equation to present the excess within the cumulative distribution function. To illustrate, let x be an observed variable and x_t a threshold. Given that $x > x_t$, for very large x_t, the excess $y = x - x_t$ can be presented by the cumulative distribution function GPD (Willems, 1998).

Willems (2000) states explicitly and clearly the totality of the statistical concept of the POT selection and the different notions of probability distributions for the hydrological extreme value analysis. The POT selection of this study will be based on Willems' WETSPRO software (Willems, 2004b).

The method of Willems for POT selection is based on "independency criteria" that are assigned to extract the independent extremes (rainfall peaks) along the time series.

The criteria are:

- The time span between the two peaks should be longer than a given period;
- The peaks should be higher than a limited rainfall intensity:

$$R_{max} > R_{lim}$$

- The minimum rainfall between two independent peak events should reach a small value (e.g., zero for f=1 indicating that the two rainfall events need to be separated by a dry period):

$$\frac{R_{min}}{R_{max}} \leq f$$

The POT method has the advantage that the selected extremes cover now a more extensive range of events varying from small, more frequent to large, exceptional events.

During each event, different variables can be defined: rainfall peak, mean and minimum rainfall, event duration, event volume, etc. It is clear that rainfall peaks (instantaneous or averaged over a specific aggregation period) determine flood events, and consequently the climate change perturbations to these events have impact on flood frequencies. Similar considerations can be made for rainfall intensities over large aggregation levels and their interrelation with droughts.

5.9.2 *Identifying changes in number of summer storms*

After running a POT selection on all RCMs daily summer rainfall, the daily peaks distributions (peak values against return period) were plotted for control and scenario simulations of each RCM.

Once the plots are made, a comparison is made with focus on the number of storms in control and scenario simulations. The percentage difference in the number of peaks between control and scenario simulations corresponding to the same intensity level is then calculated. This is done for the whole range of intensity levels.

If S_x is the number of scenario events above the intensity level *x* and C_x is the number of control events above the same rank *x,* the percentage of difference in the number of peaks is given by P_x:

$$P_x = \left(\frac{S_x - C_x}{C_x}\right)100\% \qquad (5.2)$$

The different percentages for each RCM are therefore plotted (example of DMI-HC2 model, figure 5.22) and averaged for specific ranges of return periods.

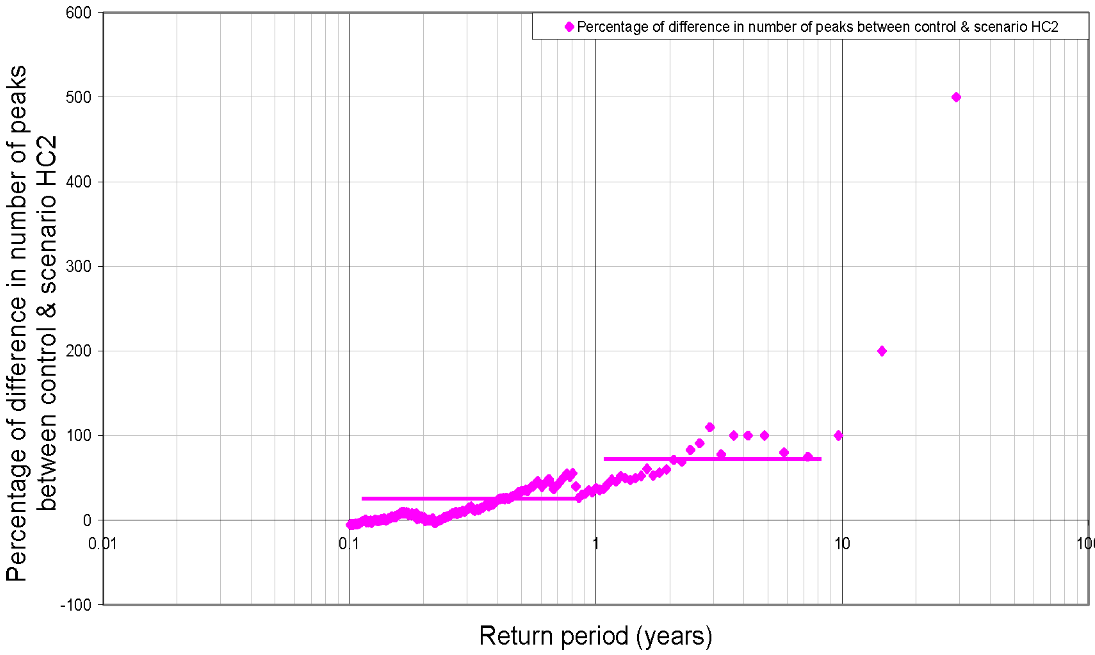


Figure 5.22 Percentage of difference in number of peaks between control and scenario runs for DMI-HC2.

The analysis for the DMI-HC2 model results, in the figure 5.22 above, indicates that summer rainfall peaks ranging from 0.1 to 1 year return period are expected to have an increase in the number of events or of the mean intensity per event. The increase is higher for higher return periods. The average increase is about 20%, but might go up to values of 100% or more for the longer return periods.

As another example, the METNO-HAD model with its both scenarios (A2 and B2) shows different results (Figure 5.23) where the short return period peaks present small decrease for both A2 and B2 scenarios of about -5% to -10%. For return periods higher than 1 year, a large difference is seen in predicting the number of events where METNO-HAD-A2 simulates an increase of about +30% while METNO-HAD-B2 expects a decrease of about -40%.

The previous two examples indicate that it is difficult to judge whether the high return period intensities would increase. Indeed, uncertainty remains large regarding the percentage of variation in the intensities of summer storms which varies from model to model and is totally depending on the return period. However, the general tendency (from most of the RCM runs) (see Appendix E) shows that the long return period events converge to an increase (sometimes considerable increase), but the small events will have a decrease. In a volume balance calculation, the resulted volume is going to show little decrease as the volume reduced by the large number of small events is bigger than the volume increased by the high events.

We proceed similar to the frequency perturbation approach by plotting the total range of variation of the percentage P_x for the different RCM runs depending on the different return periods. Mean percentages for P_x are calculated for ranges of return periods as specified in table 5.24. These mean percentages are plotted in figure 5.24 for the different RCM runs. Runs presenting very high and/or very low percentages are similarly rejected. Based on the accepted percentages, low, mean and high scenarios are built for the number of summer events in figure 5.24.

It is important to mention that building the different scenarios depends strongly on positioning the percentages to specified return periods in each range. Because the return periods vary from very short to several years of return period, the built scenarios will show as well a range of variation presenting the uncertainty bounds for each frequency class. Figure 5.24 and table 5.24 show the scenario results for daily summer events. The uncertainty bounds are presented by dotted lines in figure 5.24, again in the form of high, mean and low values.

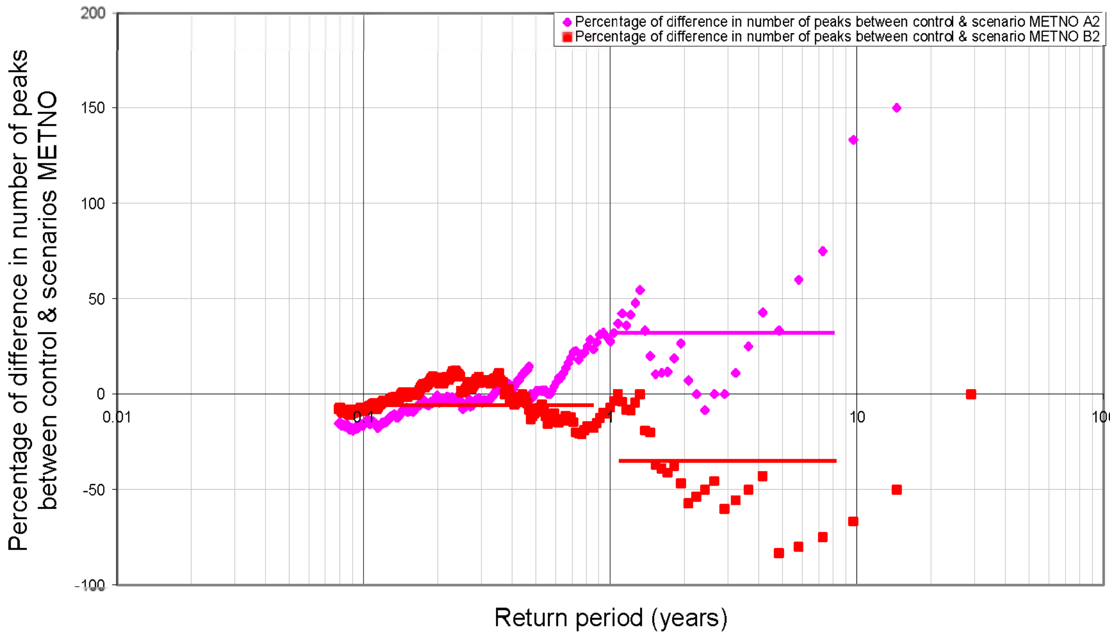


Figure 5.23 Percentage of difference in number of peaks between control and scenario runs for METNO-HAD model.

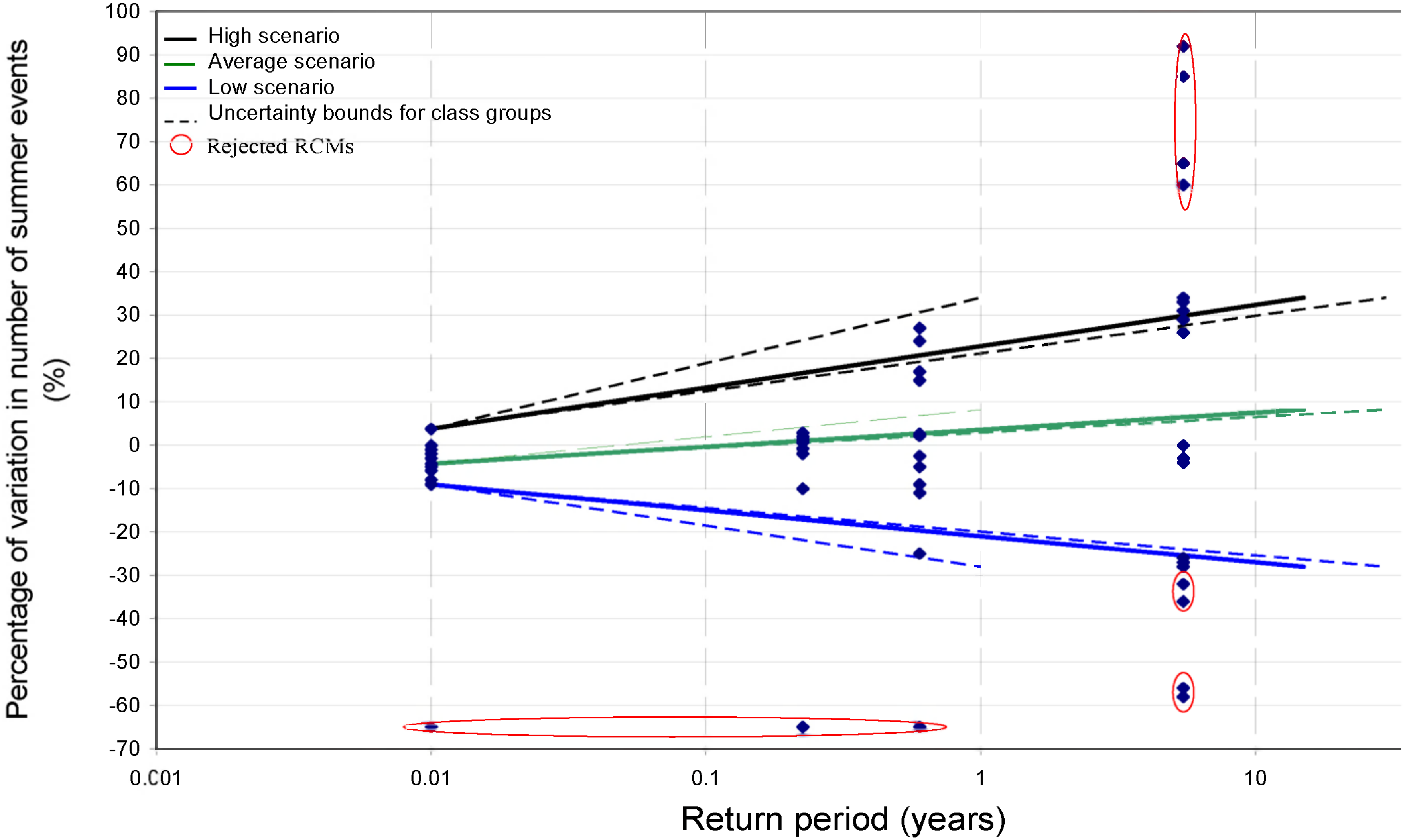


Figure 5.24 Low, mean and high scenarios for changes in number of summer precipitation events vs. event's return period.

Return period (years)	Low scenario	Mean scenario	High scenario
<0.2	-9%	-4.21%	+3.85%
0.2 - 0.25	-10%	0	+2.85%
0.25 - 1	-25%	+2.19%	+27%
1 - 30	-28%	+8.25%	+34%

Table 5.24 Low, mean and high scenarios for number of summer events.

5.10 Conclusion: Climate change scenarios for Belgium

An empirical selection methodology has been adopted in this chapter to build potential climate scenarios for future Belgian (Flanders) climate based on PRUDENCE regional climate models' results and concerned the variables of rainfall and potential evapo(transpi)ration. A further advanced statistical selection methodology is under development within the CCI-HYDR project. In that approach both frequencies (number of storms) and the amplitudes of the rainfall intensities are perturbed in a separate way to explain the combined effect on the perturbations in extreme rainfall quantiles as derived in this study.

These scenarios consist of sequences of low, mean and high factors to perturb intensities and frequencies as well. The mean scenarios might provide the best estimates; the low and high scenarios present the range of uncertainties in rainfall quantiles (reflecting the combined effect of changes in both intensities and frequencies). The joined uncertainty is potentially large. Predicted future winter rainfall is supposed to increase by 8% for the mean scenario and by 16% for the high scenario while it would decrease in summer by 1% for the mean scenario and by 17% for the low scenario.

As for potential evapo(transpi)ration, the results show a predicted increase for the mean and high scenarios by respectively 13% and 27% in winter and by 16% and 29% in summer. The low scenario remains similar to the current conditions.

The scenarios suggested above were produced based on consistency check with Uccle data and on rejection of some RCM runs and are given for different aggregation levels ranging from daily to seasonally time scales, which give opportunity to hydrological modellers and water managers to select scenarios for specific applications.

The results show that scenarios differ from winter condition to summer condition and are, for summer rainfall, time scale dependent. The change in number of rainfall events in summer largely differs for different frequency classes.

Chapter 6

Climate change impact analysis: The Dender case

6.1 Introduction

Understanding how climate change may affect regional and local-scale processes is vital to developing the capacity to adapt to these changes (IPCC, FOAR 2007).

Small water resource systems are particularly sensitive to climate change impacts (IPCC, TAR 2001). The hydrological regime of such environments is strongly influenced by rainfall variations and water management processes. A modification of the prevalent climate variables (e.g., rainfall) could have a significant impact on flood risk and water use highly dependent on the hydrological regime, such as navigation. In the Scheldt River Basin District, most rivers have important socio-economical role at different scales.

In Belgium, the water management has been transferred to the regions since 1985. Hence both the Walloon region, Brussels and Flanders are responsible for the water management. Within Flanders the navigable rivers are managed by the WL, the non-navigable watercourses 1st category are managed by the Environmental Administration (AMINAL) and non-navigable watercourses 2nd and 3rd categories are managed by Provinces and municipalities. During flood events and depending on the magnitude of the event, the crisis management is coordinated by the Governor of a Province or the Minister of Internal Affairs.

Nearly all Flemish cities historically originated along rivers and low-lying flat floodplains have become now densely populated areas. This explains why these vulnerable areas still have to cope with the effects of flooding and damage. While economists might expect the winter rainfall increase to induce efficient navigability and economical stability, the local population is more concerned about questions referring to the system's security.

Few studies have addressed climate change impact on hydrological extremes in Flanders although its high importance. Boukhris et al (2006) assessed climate change impact on the hydrological extremes in three sub-basins of the Dender basin using a seasonal volume perturbation approach. Over this PhD study, the previous research has been further developed and refined based on advances in downscaling techniques and in creation of climate scenarios.

The present chapter aims at presenting the methodology of climate change impacts on catchment scale hydrology at an hourly time scale - including extreme situations - rather than average hydrological response. The obtained results present the expected hydrological system modifications' range to the climate change scenarios that have been developed for Belgium (see chapter 5). Ultimately, these results should enable the answer to the following question: Given the modelling uncertainties (climate models and hydrological models), does climate change cause significant modifications to the hydrological system?

All necessary tools to conduct this methodology have been developed and gathered in this study. The PRUDENCE project allowed the climate support data (see chapter 3), the frequency perturbation method has been developed and chosen as downscaling method (see chapter 4), and climate change scenarios for Belgium have been created (see chapter 5) to be applied within the hydrological model (discussed in this chapter).

The presented analysis does not address other potential modifications of the studied system such as degree of urbanization or population growth that can be assumed to have a considerable impact on the system management. The potential impact of climate change is analyzed considering the water resources system, as it exists today and applied upon the Dender basin taken as a detailed case study.

6.2 Climate change impact analysis: hydrological modelling and statistical post-processing

After being derived, the perturbation factors forming the climate scenarios generated in the previous chapter (see chapter 5 'Climate change scenarios for Belgium' – section 5.7, table 5.23) serve to perturb the inputs' variables of the calibrated hydrological model NAM (e.g., precipitation, ETo) implemented by the Hydraulics Laboratory of K.U.Leuven and the Waterbouwkundig Laboratorium (WL) for hydrological management.

The perturbations in table 5.23 of chapter 5, were extracted for daily data (RCMs data) and applied upon hourly precipitation and potential evapo(transpi)ration data of the hydrological NAM model. As it was shown in section 5.7 of chapter 5, the perturbation factors do not vary largely with the time aggregation levels (from daily to seasonal time aggregations), it was assumed that the factors would remain the same in average towards smaller time scales (hourly) and so the same derived factors served to perturb the NAM model hourly input files.

These perturbation factors were applied separately for winters and summers as for the three scenarios upon the current conditions NAM input files. In this respect, beside the original input file (representing the current conditions), three other files were generated representing the low, mean and high predicted climate scenarios. The generated files were proceed to hydrological simulations to assess climate change impacts on hydrological extremes.

The hydrological model results are therefore extracted, processed and compared to the original results (representing the current climate conditions) in terms of hydrological extremes. This processing contains the following steps:

- An estimation of the variations of the high flow peaks and composite hydrographs throughout a peak over threshold method followed by an extremes value analysis;
- Elaboration of the flood maps and flood risk maps;
- An estimation of the variation on the low flow peaks;
- A statistical summary on the percentage of variation of other variables (e.g., overland flow, actual evapo(transpi)ration).

We proceed below with a short description of the hydrological model applied and the extreme value analysis.

6.2.1 Hydrological model

6.2.1.1 NAM model

NAM (recently called RR) is a hydrological module linked to the Mike11 software of the DHI Water & Environment, Denmark (DHI, 2004). NAM model simulates the rainfall-runoff generation at the catchment scale.

Totally based on the differences of water content, NAM describes the land phase of the hydrological cycle through four different and interrelated storage systems. Figure 6.1 presents the structure of NAM, followed by a description of its concept.

The four storage systems of NAM are:

- Snow storage;
- Surface storage;
- Lower zone storage (root zone);
- Groundwater storage.

The surface storage and lower zone storage are mainly characterized by their actual soil water content presented respectively in figure 6.1 by U and L and by their maximum capacity to hold the water, respectively U_{max} and L_{max}.

It is due to a continuous calculation of the ratios $\frac{U}{U_{\max}}$ and $\frac{L}{L_{\max}}$ that NAM calculates the amount of water percolating between each storage system, simulates the catchment runoff and gives information about other variables of the land phase of the hydrological cycle, such as temporal variation of actual evapo-transpiration, ground water level, infiltration, percolation, overland runoff, interflow groundwater and recharge. The basic model inputs are meteorological data which are precipitation, potential evapo(transpi)ration and also temperature in case the modeler wants to rout the snow storage to the whole simulation. On this basis, NAM produces, as main results, catchment runoff and ground water level values as well as information about other elements such as temporal variation of the actual evapo(transpi)ration and the temporal variation of the soil moisture content and the groundwater recharge. The runoff is split conceptually into overland flow, interflow and baseflow components.

6.2.1.2 Subflows

The modelling concept of NAM consists that the part of rainfall that did not infiltrate will runoff as an overland flow (top-right of figure 6.1). The other part will be split into two fractions. The “DL” fraction will feed the root zone or the lower zone storage, as the fraction “G” will percolate deep towards the groundwater storage.

The interflow is assumed to be proportional to the soil moisture in the surface storage U and it is linearly dependent of the water content of the root zone. Both the surface zone and the root zone are subject to water loss due to actual evapo(transpi)ration which varies the water moisture content and the fraction “*G*” recharging the groundwater storage. The following equations illustrate the basic calculations made within NAM for overland flow and interflow:

$$QOF = CQOF \frac{(\frac{L}{L_{max}}) - TOF}{1 - TOF} P_n, \quad for \frac{L}{L_{max}} > TOF \tag{6.1}$$

$$QOF = 0, \quad for \frac{L}{L_{max}} \leq TOF \tag{6.2}$$

$$QIF = (CKIF)^{-1} \frac{(\frac{L}{L_{max}}) - TIF}{1 - TIF} U, \quad for \frac{L}{L_{max}} > TIF \tag{6.3}$$

$$QIF = 0, \quad for \frac{L}{L_{max}} \leq TIF \tag{6.4}$$

Where *QOF* and *QIF* denote respectively the part of net precipitation (P_n) which contributes to overland flow or interflow, *CQOF* is the overland flow runoff coefficient ($0 \leq CQOF \leq 1$) and *TOF* is the threshold value for overland flow ($0 \leq TOF \leq 1$), *CKIF* is the time constant for interflow and *TIF* is the root zone threshold value for interflow ($0 \leq TIF \leq 1$).

The overland flow is simulated within NAM model through two linear reservoirs plugged in series, having the property of the same time constant (*CK1*/*CK2*) (Figure 6.1) or reservoir constant. The reservoir constant equals the time during which the reservoir flow is reduced to a fraction exp (-1) = 0.37 of its original storage. The interflow volumes are additionally routed through a third reservoir with reservoir constant *CKIF*.

From the other side, the groundwater storage behaves also as a linear reservoir storage where its input "*G*" and output "baseflow" are related with an exponential relation with a different time constant (*CKBF*, figure 6.1) than the other storage systems.

The baseflow is generally qualified as "slow flow". Its amount is dependent on the soil moisture content in the root zone. From another side, groundwater storage feeds the lower zone by capillarity flux, its amount depends on the soil moisture content $\frac{L}{L_{max}}$.

6.2.1.3 *Actual Evapo(transpi)ration*

E_a denotes the actual rate of the evapo(transpi)ration E_p lost in the surface and lower zone storage. The atmospheric demands of evapo(transpi)ration will be taken first from the surface zone. If the demand is more severe, then the missed part will be taken from the lower zone storage as the roots are active. It is therefore obvious that the actual evapo(transpi)ration rate is proportional to the soil moisture content in this zone. This is why, NAM calculates the E_a according to the following equation:

$$E_a = E_p \frac{L}{L_{max}} \tag{6.5}$$

To conclude, NAM simulates the total catchment runoff through different sub-flows: overland flow, interflow and baseflow. This sub-division aims to describe the behaviour of a two plugged linear reservoirs (surface zone), plus a second reservoir (root zone) and a third linear reservoir presenting the groundwater zone. This description is mainly based on variation of the water moisture content in each zone.

The NAM model can be qualified as a lumped, conceptual model with moderate input requirements. It is a well-proven modelling and engineering tool and has been implemented and applied in several cases at the WL and the Hydraulics Laboratory of K.U.Leuven.

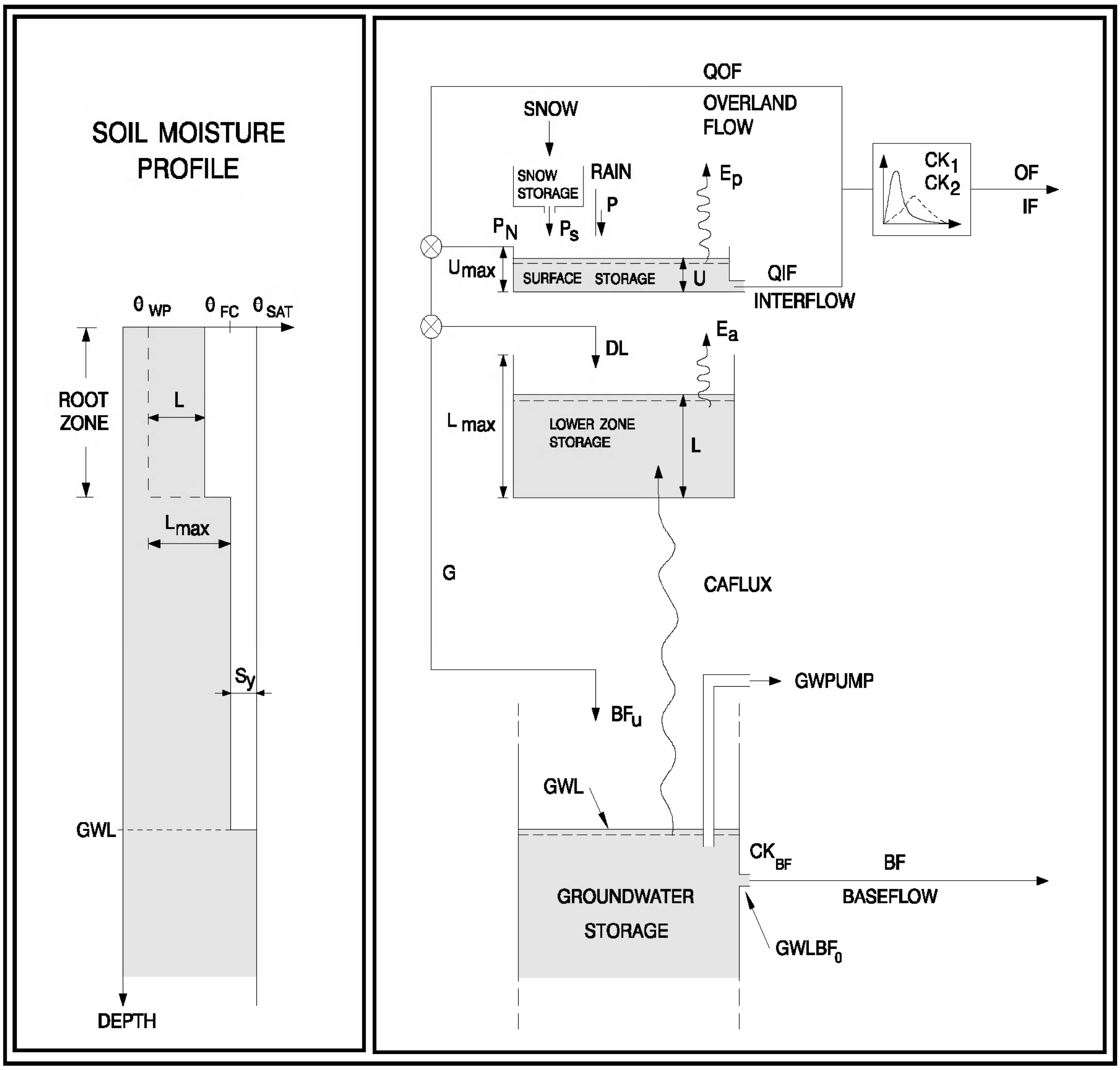


Figure 6.1 NAM model structure (DHI, 2004).

6.2.2 *Extreme value analysis*

The hydrological model results are statistically processed in order to investigate the climate change impact on the extremes and their related probabilities. For this analysis, an extreme value analysis is implemented applying Extreme Value Theory (EVT) concepts.

EVT covers the analysis of stochastic processes for the purpose of estimating the probabilities of rare events. It is frequently used in environmental studies (Smith, 2001; Katz et al., 2002) and financial studies (McNeil, 1998) to produce distributions to fit data consisting of maxima or minima in random samples, as well as to model the distribution of excess over thresholds, and to estimate parameters of arbitrary distributions. Such analysis is often made difficult by uncertainties in the statistics due to scarcity of data. For instance, in meteorology, extreme value analyses have been performed for the prediction of damaging rain, maximum frost, and extreme winds. For hydrological studies, EVT is mostly applied to analyze certain return periods of extreme floods.

In modelling the extreme events of a random variable, the EVT provides results on the asymptotic behaviour of the extreme realizations (maxima and minima) while making a classification of contentious distributions according to the behaviour of the tail region or their extreme realizations. The theory distinguishes three stable distributions for the maximum values of a random variable, called Generalized Extreme Value Distributions (GEV), and three associated Generalized Pareto Distributions (GPD), which are the limiting distributions for the tail region of the pertinent distribution of the analysed process (Beirlant et al., 1996; Beirlant et al., 2004).

6.2.2.1 Methods for assessment of extreme events

Several approaches exist to investigate the frequency of extreme events, and to describe the stochastic behaviour of the extremes and their return periods. They can be classified in parametric or non-parametric methods, methods focusing on the complete dataset or only on the extremes (the distribution's tail), methods based or not based on stochastic simulations and methods based or not based on extreme value theory.

- The parametric methods are based on fitting particular distribution to a set of observed or simulated data. The main disadvantage of this approach is that return period distributions derived are not representative for tail estimation. In this way, the extremes' distributions are far from being asymptotic (Karl and Knight, 1998; Jones and Reid, 2001; Rusticucci and Vargas, 2002);

- Non-parametric methods do not take into consideration events beyond sample range and also do not indicate the tail form. Following this method it is very difficult to estimate extreme quantiles;

- Stochastic methods (Mainly Monte Carlo) generate situations that develop data based on random traction from some stochastic projections. These approaches most often assume normality and thus do not accommodate observed fat tails in distribution data. Monte Carlo techniques could be successfully carried out for data already simulated from extreme value distributions (Palutikof, 1999);

- The EVT approach is designed for tail estimation, it is able to estimate extreme quantiles for a short record of data. McNeil (1998) considers EVT to be the most honest approach to measure the uncertainty inherent to extreme data. The theory is described in the next section.

6.2.2.2 EVT theory

EVT concerns the behaviour of the extremes of a process. The fundamentals of this probability theory have been known since about the beginning of the twentieth century where Fisher and Tippet (1928) were among the first to develop the EVT with the derivation of the asymptotic distribution of the sample maxima. They applied it to wave heights, a threshold was chosen in the record and only values above are used in the extreme value analysis. The modelling of these extreme waves has been performed with a GPD theory as shown by Pickands (1975).

Let $X_1, X_2, \ldots, X_n$ be a series of independent random observations of a random variable X with the distribution function $F(x)$. To model the upper tail of $F(x)$, consider k exceedance of X over a threshold u and let $Y_1, Y_2, \ldots, Y_k$ denote the excesses (or peaks), e.g., $Y_i = X_i - u$. Pickands (1975) showed that, in some asymptotic sense, the conditional distribution of excesses follow the Generalized Pareto Distribution. Thus the distribution function of $Y_i = [(X_i - u) | X_i > u]$, $i = 1,2,\ldots, k$, is given as:

$$GPD(Y) = 1 - \left(1 + \frac{\sigma(Y-u)}{\gamma}\right)^{\frac{-1}{\sigma}}$$

where u, σ and γ denote the location, scale and shape parameters, respectively.

6.2.2.3 *EVT forms*

The Extreme Value Analysis describes the extreme value behavior with four characteristics: the shape and scale parameter of the GPD, the threshold and the number of values in the dataset. With this parameterization the uncertainties and load factors can be derived.

Extreme Value Theory exists in conventional and modern forms. The conventional form (old form) was produced as a result of scientific investigations based on the work of Fisher and Tippett (1928) and of Gumbel (1958). These last stated that under certain conditions the distribution of the standardized maxima/minima converges to one of these three distributions (Gumbel, Frechet and Weibull) as the size of the series increases (Gnedenko, 1943).

- The Gumbel distribution is with a normal upper tail (exponential decreasing form);
- The Frechet distribution is with a heavy upper tail and infinite higher moments;
- The Weibull distribution is with a light or bounded upper tail (Figure 6.2)

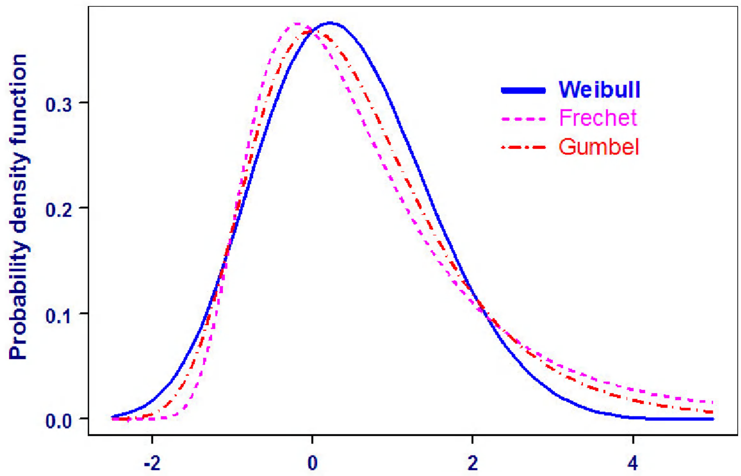


Figure 6.2 Different forms of GEV distribution (McNeil and Frey, 2000).

A standard combination of these three basic forms would provide the Generalized Extreme Value (GEV) distribution. This technique is often referred to as ''the annual maximum method'', because in practice it is often applied considering annual maxima.

The modern form of the EVT is known as a ''threshold'' form and it states that data exceeding a certain threshold (high) are approximately distributed as the Generalized Pareto Distribution (GPD) which is the analogue of the GEV distribution for annual maxima. The GPD based on values above threshold has proven to be more flexible than the GEV annual maxima (Smith, 2001) and can deal with asymmetries in the tails (McNeil and Frey, 2000). The GPD in turn presents different classes depending on the value of σ which shapes the tail of the distribution (Willems, 1998). For the case $\sigma = 0$, the tail decreases in an exponential way; as for the case $\sigma > 0$, the tail decreases following the Pareto distribution. The distributions are bounded in the upper tail for the case of $\sigma < 0$ (Beta) (Figure 6.3). In hydrological applications, the classes $\sigma = 0$ and $\sigma > 0$ are frequently met.

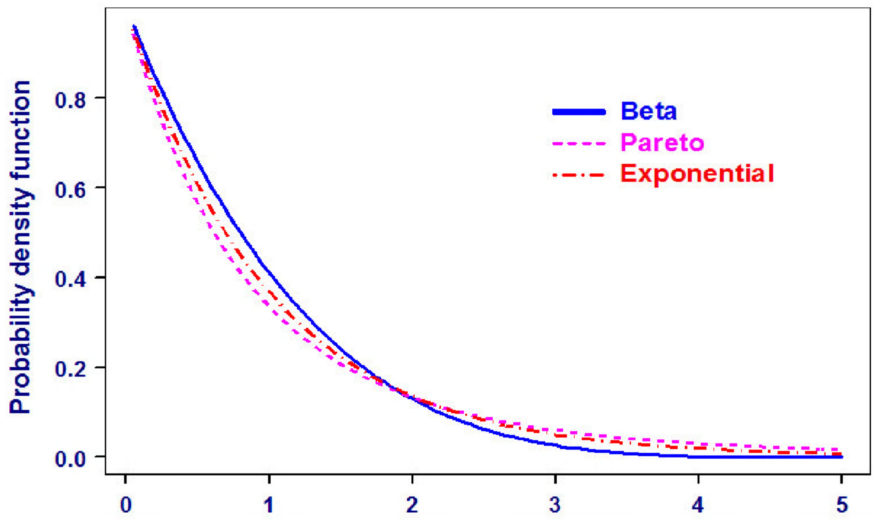


Figure 6.3 Different classes of GPD distribution (McNeil and Frey, 2000).

Applications of the EVT forms are generally restricted by the data length, and serial correlation of a meteorological/hydrological parameter (e.g., the size of the tail and time dependency). The POT-method is suggested to be used for dependent processes (McNeil and Saladin, 1998; Smith, 2001). The IPCC (TAR, 2001) recommended the use of the POT method rather than annual maxima in climate change impact assessment.

6.2.2.4 Fitting methods

The literature embraces several methods to evaluate parameters of the applied distribution in order to assess how well the parametric model fits the data. The most often used techniques are:

- The Maximum Likelihood techniques (ML);
- The Bayesian techniques;
- The L-moments techniques;
- The graphical techniques.

Voting for one or another technique depends on the chosen distribution model; on the length of the data and on the threshold level. For instance, application of the Poisson-GPD model often lies in using the ML or Bayesian techniques for meteorological and hydrological studies (El-Jabi, 1998; Smith, 2001). Smith (2001) used ML and Bayesian techniques for data generated by GCMs/RCMs.

The L-moments based are preferably applied when dealing with small data length (Kharin and Zwiers, 2000). As for the graphical techniques, they include examination of the quantile-quantile (Q-Q) plot which is widely used to explore data and to carry on fitness tests. In a Q-Q plot, empirical quantiles are shown against theoretical ones to determine if the two data sets come from populations with a common distribution (Beirlant et al., 1996; Beirlant et al., 2004). With the word "quantile", we mean the value corresponding to a fraction (or percent) of points below or above that given value. For example, the 0.4 (or 40%) quantile is the point at which 40% percent of the data fall below and 60% fall above the quantile (Willems, 2000).

Parameter estimation with the Q-Q plot technique can be done through regression (R) in the Q-Q plot (Beirlant et al., 1996; Beirlant et al., 2004). The technique was called QQR method in Willems et al (2007).

In the QQR method for extreme value analysis, the empirical quantiles (for example the selected POT discharges) are plotted against the theoretical ones according to an assumed probability distribution, assuming the same empirical probability of exceedance for both. If the data are consistent with the assumed theoretical distribution, the points on the Q-Q plot lie approximately on a straight line. The distribution function tested with the Q-Q plot technique is generally named with the same distribution type. The normal, lognormal, exponential, Pareto, Weibull, etc. distributions can be used in the plot.

In this study, after sorting the extremes extracted by the POT selection, let y_i be the observed extremes, i=1,…,m with ($y_1 \geq ..... \geq y_m$), their corresponding empirical exceedance probability is calculated by:

$$p_i = \frac{i}{(m+c)} \tag{6.6}$$

where c is a plotting position score number taken here equal to 1 (according to the Weibull plotting position).

In absence of the distribution parameter values, the extremes analysis can go then through the adopted Q-Q plot approach. In the last, the quantile function, a linear function to the exceedance probability that is totally independent of the distribution parameters, is plotted in abstraction to the distribution function. The quantile function for the case of exponential and Pareto Q-Q plots are given in the following (Willems, 1998):

$$-\ln(\frac{i}{m+1})$$

The power of the Q-Q plot in examining the distributional shape seems to be easily applied with detecting the deviation from the linearity. In addition, other kinds of difference between the shapes like skewness of shape in the tails can be identifiable too.

Due to its easy concept and large application in the Hydraulics Laboratory of K.U.Leuven, the QQR method is being used in this study. Willems (1998) discussed the analysis of the shape of the tail of a distribution as follows:

For normal tail:

- In the exponential quantile plot: the upper tail points tend towards a straight line;
- In the Pareto quantile plot: the upper tail points continuously bend down;

For heavy tail:

- In the exponential quantile plot: the upper tail points continuously bend up;
- In the Pareto quantile plot: the upper tail points tend towards a straight line;

For light tail:

- in the exponential quantile plot: the upper tail points continuously bend down;
- in the Pareto quantile plot: the upper tail points also continuously bend down.

6.2.3 Methodology for low flow minimas

After extracting the hydrological model results, the POT will be taken on $\frac{1}{Q}$ instead of Q, where Q refers to the simulated runoff time series. In this respect, the selected peaks by the POT method are actually low flow minimas. In this study, we proceed using seasonal perturbation factors for the low flow minima's while further analyses are taking place within the CCI-HYDR project.

6.3 Hydrological impact analysis: The Dender case results and discussion

This paragraph is an overview of the obtained results after applying the methodology described above on the Dender basin. Thus we will go through the different steps separately to investigate climate change impact on hydrological extremes on a sub-basin scale where we will present respectively:

- The percentage of variation of the high flow hourly peaks and changes into the composite hydrographs;
- The percentage of changes of the low flow;
- A statistical summary on the variation of the variables of overland flow (O.F.) and ETa;
- A general overview on the variation of the flooded areas due to climate change scenarios and damage risk calculation.

The following graphs present the methodology results of climate change impact on hydrological extremes for the VHA zone “410” of the Dender basin chosen as detailed case study. Other results for the remaining sub-basins of the Dender and all the Flemish basins can be found in Appendix F.

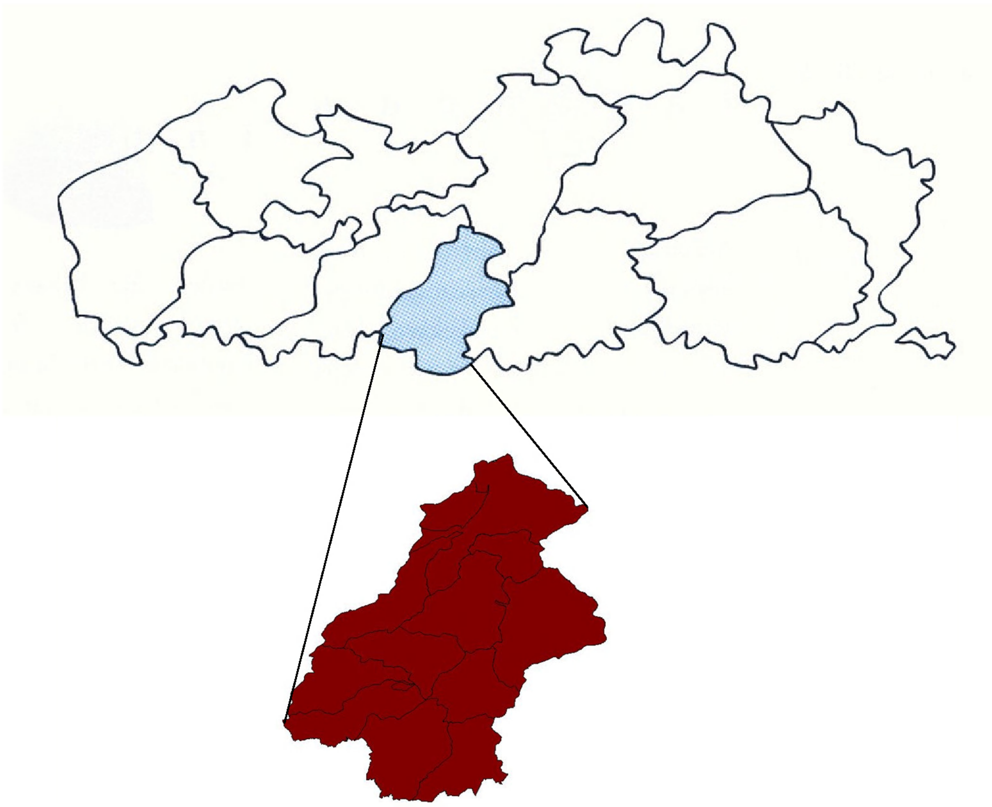


Figure 6.4 Location of the Dender basin

The Dender basin is a well-known basin for the Flemish scientific community due to the extensive hydrologic and hydrodynamic modelling work done on it. A detailed hydrodynamic river model was constructed for the river Dender using the MIKE11 software from Danish Hydraulic Institute. All hydraulic structures are implemented and validated based on water level measurements up- and downstream of the structures (Willems et al., 2002).

Detailed cross-section survey was made available by the WL, with cross-section measurements every 50 m. Floodplains were modeled using quasi 2D flood modelling approach. The model is used in combination with lumped conceptual models for the 12 hydrographic sub-basins in the river basin, for the simulation of both historical events and synthetic flood events (Willems et al., 2002). The model is currently in use at WL for flood management in the river basin in order to construct flood maps and flood risk maps.

From the other side, using the quasi 2D hydraulic floodplain model, in combination with lumped conceptual models for the different sub-basins in the river basin and the hydrodynamic model for the river, historical flood events were simulated for validation needs. By the means of composite hydrographs, also flood events for various return periods were simulated. Based on a digital elevation model (DEM) and a GIS system, the spatial extent of these flood events can be visualized (Willems et al., 2001).

The Dender basin was also the subject of other investigations within a European Space Agency (ESA) project (Flood risk and damage Assessment using Modelling and Earth observation techniques "FAME"), where additional tools were made available by use of satellite derived flood maps. The project showed improvements in flood modelling by use of earth observation products (both radar-based ERS SAR and ENVISAT ASAR images for flood mapping, and Landsat ETM+ and IKONOS imagery for land use mapping).

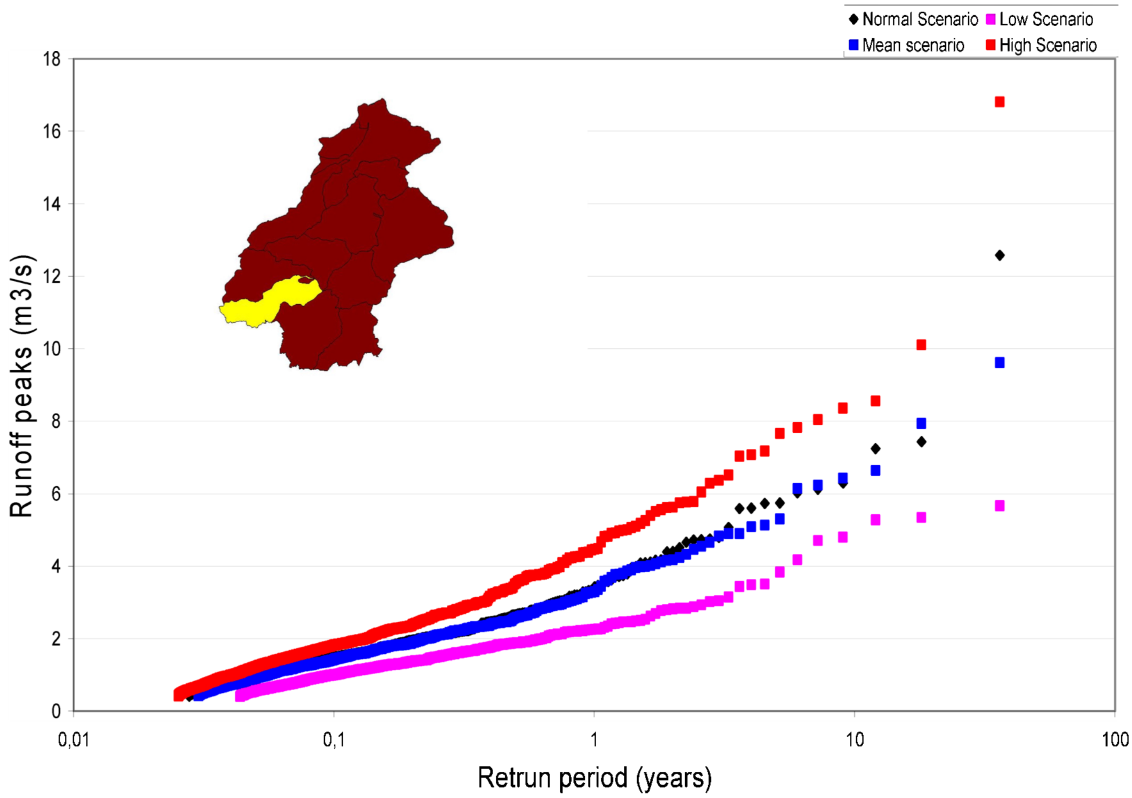


Figure 6.5 Return period hourly high flow peaks (60 mins) for the low, mean and high scenarios for the VHA zone 410 of the Dender basin.

The figures 6.5 and 6.6 show respectively, for the sub-basin 410 of the Dender, the NAM hourly (60 min) runoff peaks behaviour after climate change scenarios forcing. Figure 6.5 presents the Q-Q plot where for all the scenario cases, the runoff peaks' distribution has been fitted to the exponential distribution above a selected threshold. Selection of the exponential distribution (normal tail) has been done graphically by means of the exponential Q-Q plot. The runoff peaks asymptotically converge towards a straight line in the exponential Q-Q plot for the higher thresholds (Figure 6.5) showing an exponential distribution. The exponential distribution correspondingly has been calibrated by linear regression in the exponential Q-Q plot above a selected threshold. This threshold value was taken as the runoff peak value at which the MSE of the regression is minimal.

The original distribution (Actual condition) shows a shift up or down depending on the applied scenario. This shift (difference between the peaks) is small for low return periods but grows bigger for high return periods. These increases/decreases in the hourly peaks are clearly presented in Figure 6.6 for every climate scenario where the percentage of variation of the runoff peaks (difference between the new resulted runoff peaks after applying climate scenarios and the actual runoff peaks reported to the actual ones) is plotted depending on the return periods. For the mean scenario, climate change would not introduce big variation where, in average, the runoff peaks would have -2% of change. In opposite for the low and high scenarios, the 410 sub-basin answers severely with respectively -30% and +25% changes in the runoff peaks, accounting for the range of uncertainty and increasing therefore the risks of droughts and floods (Figure 6.6).

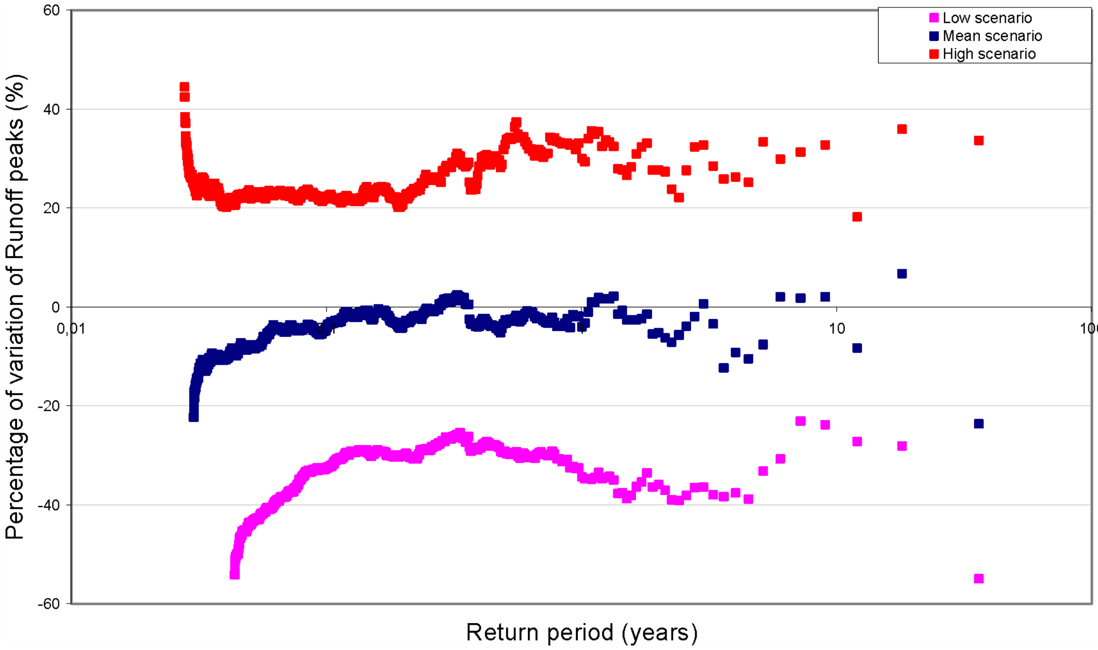


Figure 6.6 Percentage of variation of the hourly high flow peaks (60 mins) for the low, mean and high scenarios for the VHA zone 410 of the Dender basin.

Average percentage of variation of high flow (%)	Low scenario	Mean scenario	High scenario
Sub-basin 410	-30	-2	25

Table 6.1 Percentage of variation of hourly peaks due to climate change scenarios.

The percentages of variation in hourly runoff peaks for the different sub-catchments of the Dender basin are presented in figure 6.12. Overland flow volumes show similar behaviour to the runoff peaks (Figure 6.13), where big and moderate decreases in volumes are expected respectively for the low and mean scenarios. As for the evapo(transpi)ration (Figure 6.14), slight differences are seen between the three scenarios where the overall percentage of variation increases up to 15%, a result that is expected as the majority of climate models predict regional warming by an increase in temperature.

6.3.1 Dender basin composite hydrographs factors

The composite hydrograph is a rainfall-runoff discharge hydrograph which corresponds to a specific return period. The composite hydrographs are constructed in a way that the average discharge equals a specific return period for all durations that are considered centrally in the hydrograph (Vaes et al., 2000; Vaes and Willems, 2002).
An important feature with the composite hydrographs lays in the fact that they can be used as input for hydrodynamic river models (Willems and Vaes, 2003). In fact, based on results of the NAM hydrological model simulations for the different Flanders basins, composite hydrographs were derived using an extreme value analysis applied on the long term hydrological results, and

based on the calculation of “discharge/duration/frequency (QDF) relationships” for different ranges of time aggregation levels (Timbe, 2007).

The hydrodynamic river models (MIKE11) consider the composite hydrographs as input files (upstream boundary) presenting each the hydrological contribution of every branch of the considered basin. The time between each contribution into the main river is taken into account into the hydrodynamic simulations. The composite hydrographs are usually joined with composite limnigraphs for the downstream condition in order to draw up an accurate simulation along the main river course and to specify a safety level in each point (Willems and Rombauts, 2004).

The composite hydrographs for flood probability and flood risk studies showed to be efficient and is being currently used for real time flood investigation and by the WL in several flood forecasting studies. Climate change is expected to induce changes into the composite hydrographs’ behaviour due to the changing behaviour in the catchment rainfall-runoff. It remains then to investigate the possible impact of the different climate change scenarios on the composite hydrographs and indeed into the probabilities of flood risk. Estimating the variations of the composite hydrographs is very important with respect to the assessment of the intensity of a certain event corresponding to a certain return period. This is very important for dimensioning needs and for damage calculation assessment. The above described methodology has been applied for the entire Flanders’ basins. The detailed example of the VHA zone 410 of the Dender basin is given below.

It has been remarked that the percentages of variations of the high flows present three important properties that will have great impact on the composite hydrographs:

- Above certain threshold corresponding to the extremes (~ 0.1 year return period), the factors vary independently of the return periods (Figures 6.7, 6.8, 6.9, 6.10);
- The factors vary nearly independently of time aggregation levels (Figures 6.7, 6.8, 6.9, 6.10);
- The average value of the factors above the ~0.1 year return period are nearly the same and constant for all the time aggregation levels (Table 6.2).

Therefore, it has been decided to use the average factor calculated for each time scale (aggregation levels) for every sub-basin of the Dender. The factors of variation of the composite hydrographs for the Dender basin for each scenario are presented in Table 6.3. The variations of the composite hydrographs obviously correspond with the variations seen in the high flows for each scenario. Indeed, for instance, the original composite hydrographs for the VHA zone 410 of the Dender basin increase by about 25% for the high scenario, decrease by 2% and by 30 % respectively for the mean and low scenarios. The original composite hydrographs (and QDF relationships) will then have a shift up or down independently on the return periods but only function of the climate scenarios (Figure 6.11).

It is to be mentioned that the table and figures below describe the tested methodology and results on the VHA zone 410 of the Dender basin, while the same procedure has been applied for all other sub-basin of the Flemish area (results in Appendix F).

Time aggregation level (min)	Low scenario	Mean scenario	High scenario
60	-30.07	-1.98	25.43
180	-29.67	-1.87	24.67
720	-27.80	-1.55	21.92
1440	-26.54	-1.04	21.25
2880	-26.70	-1.21	20.91
43200	-30.96	-1.00	22.92
Average	**-28.16**	**-1.53**	**22.83**

Table 6.2 Percentage of variation of the high flow factors for different aggregation levels for the low, mean and high scenarios for the VHA zone 410 of the Dender basin.

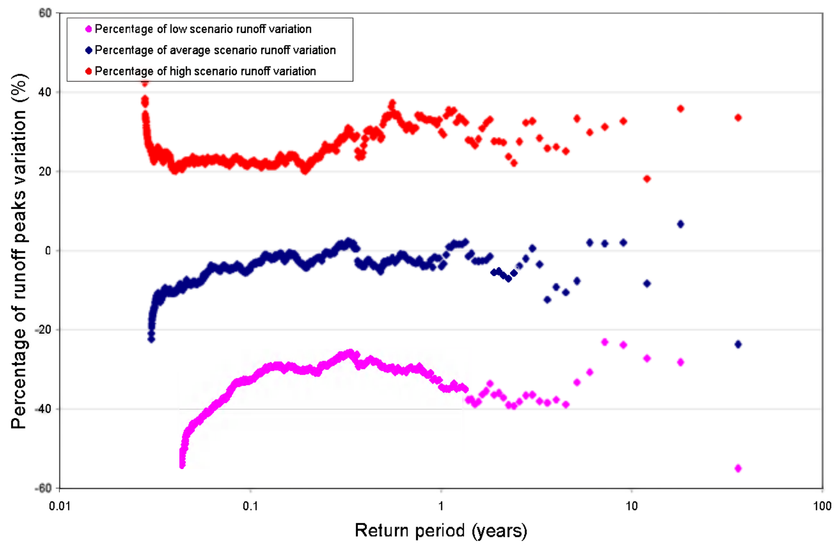


Figure 6.7 Percentage of variation of the hourly high flow peaks (60 mins) for the low, mean and high scenarios for the VHA zone 410 of the Dender basin.

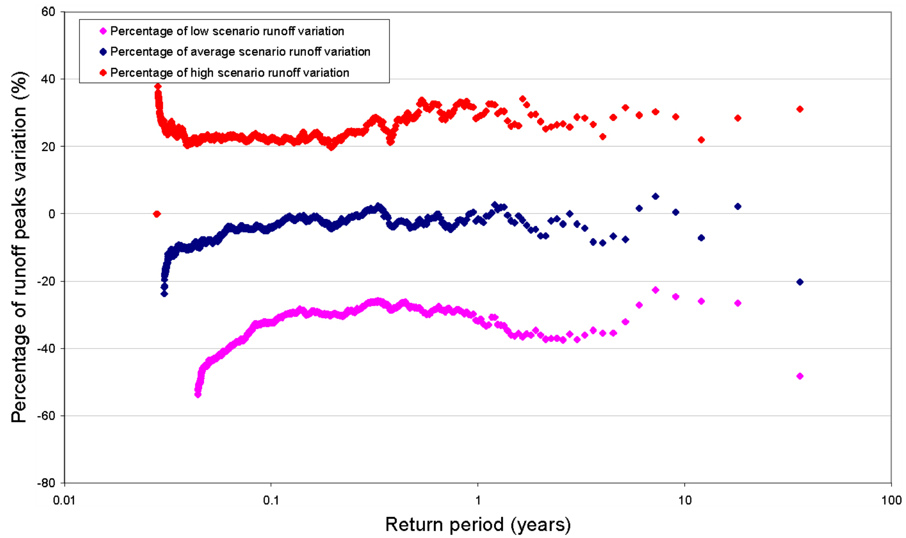


Figure 6.8 Percentage of variation of the (180 mins) high flow peaks for the low, mean and high scenarios for the VHA zone 410 of the Dender basin.

Figure 6.9 Percentage of variation of the (720 mins) high flow peaks for the low, mean and high scenarios for the VHA zone 410 of the Dender basin.

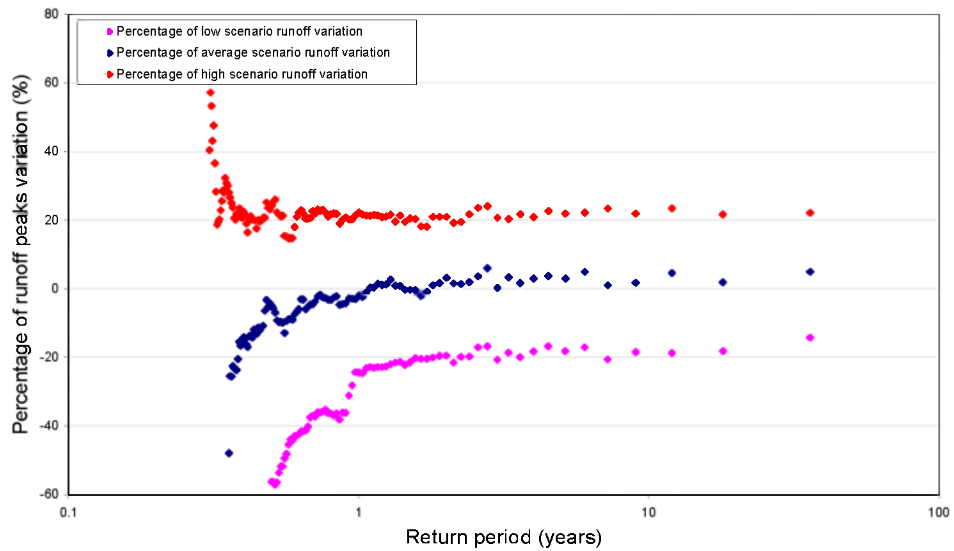


Figure 6.10 Percentage of variation of the (43200 mins) high flow peaks for the low, mean and high scenarios for the VHA zone 410 of the Dender basin.

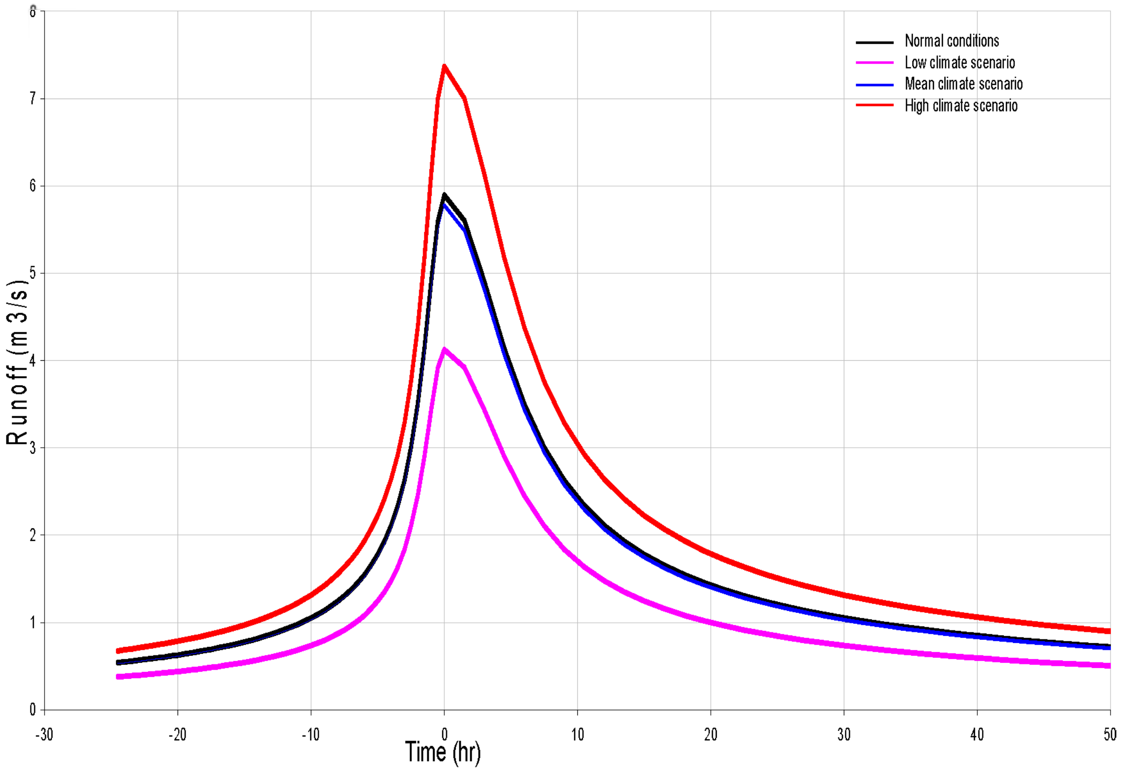


Figure 6.11 Perturbed composite hydrographs the VHA zone 410 of the Dender basin due to climate change scenarios.

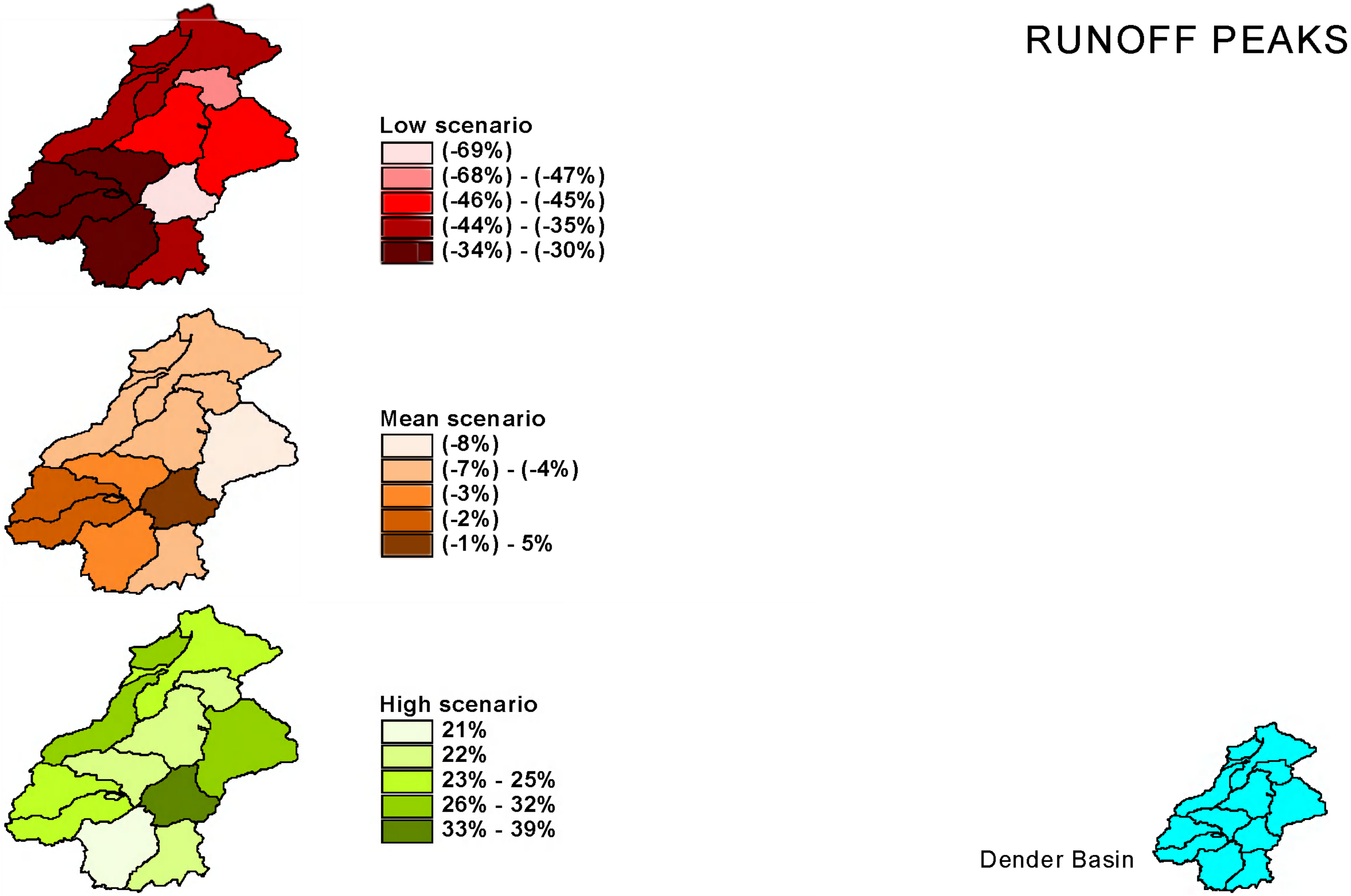


Figure 6.12 Percentage of variation of hourly runoff peaks for the low, mean and high scenarios for the Dender basin, regional differences.

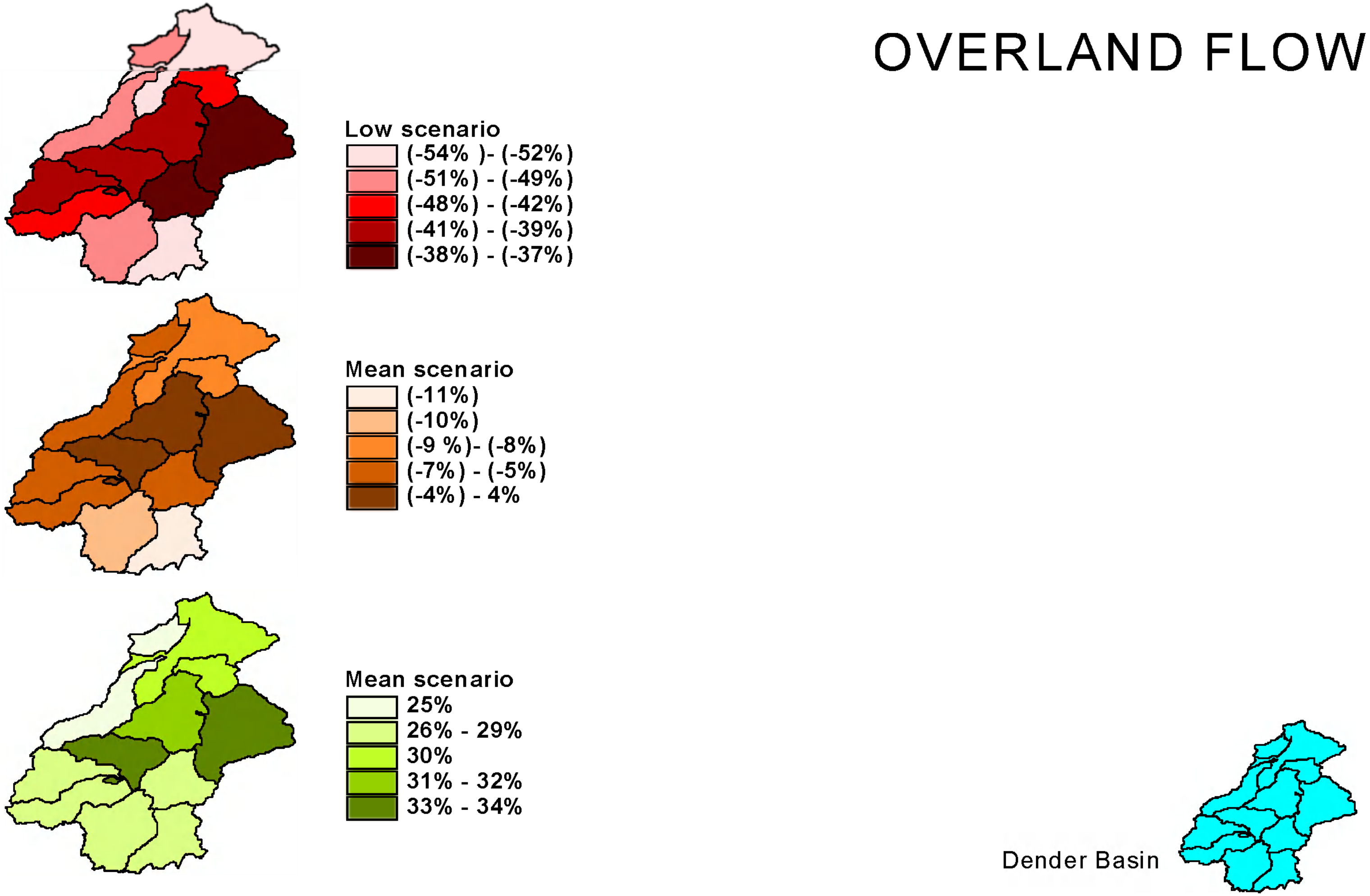


Figure 6.13 Percentage of variation of hourly overland flow volumes for the low, mean and high scenarios for the Dender basin, regional differences.

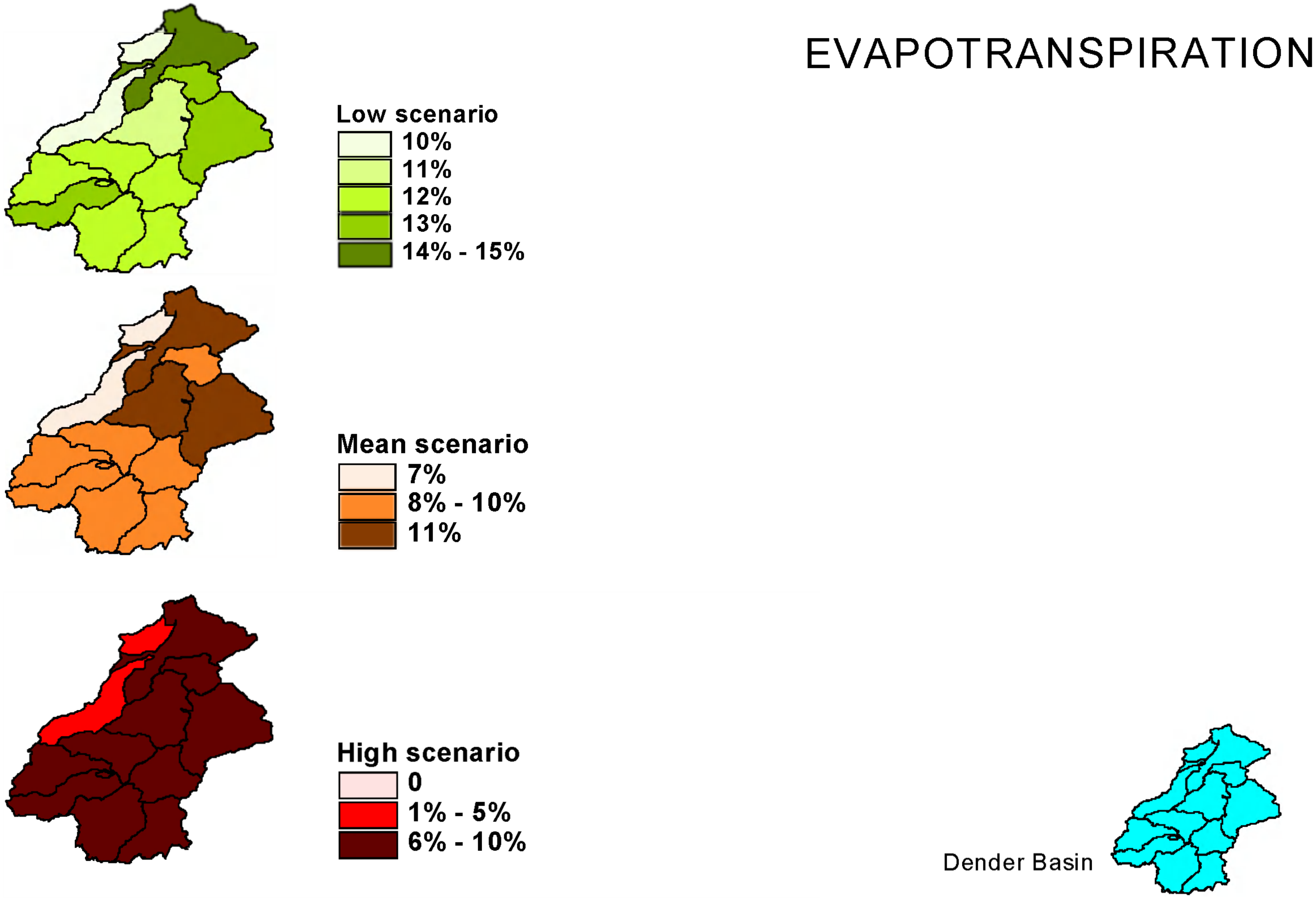


Figure 6.14 Percentage of variation of hourly ETa volumes for the low, mean and high scenarios for the Dender basin, regional differences.

Sub-basin	Low scenario	Mean scenario	High scenario
400	-34.08	-3.88	21.84
401	-31.21	-2.92	21.37
410	-28.16	-1.53	22.83
411	-27.15	-1.23	22.20
420	-31.21	-2.92	21.37
421	-71.64	5.84	35.74
422	-36.38	-4.32	32.07
423	-45.61	-4.32	22.02
430	-51.65	-25.72	23.54
431-2	-42.41	-4.30	26.93

Table 6.3 Percentage factors of variation of the composite hydrographs for the low mean and high scenarios for the sub-basins of the Dender basin.

As for low flows, the Q-Q plots (Figures 6.15, 6.16) indicate considerable decrease in runoff minima to low extents for the climate scenarios. In fact, the quantiles show an average decrease of -60% for the low scenario and -7% for the high scenario. This result is often seen for all the sub-basins of the Dender, indicating that low flow problem might become more severe in the future and more important than the increase in flood risk.

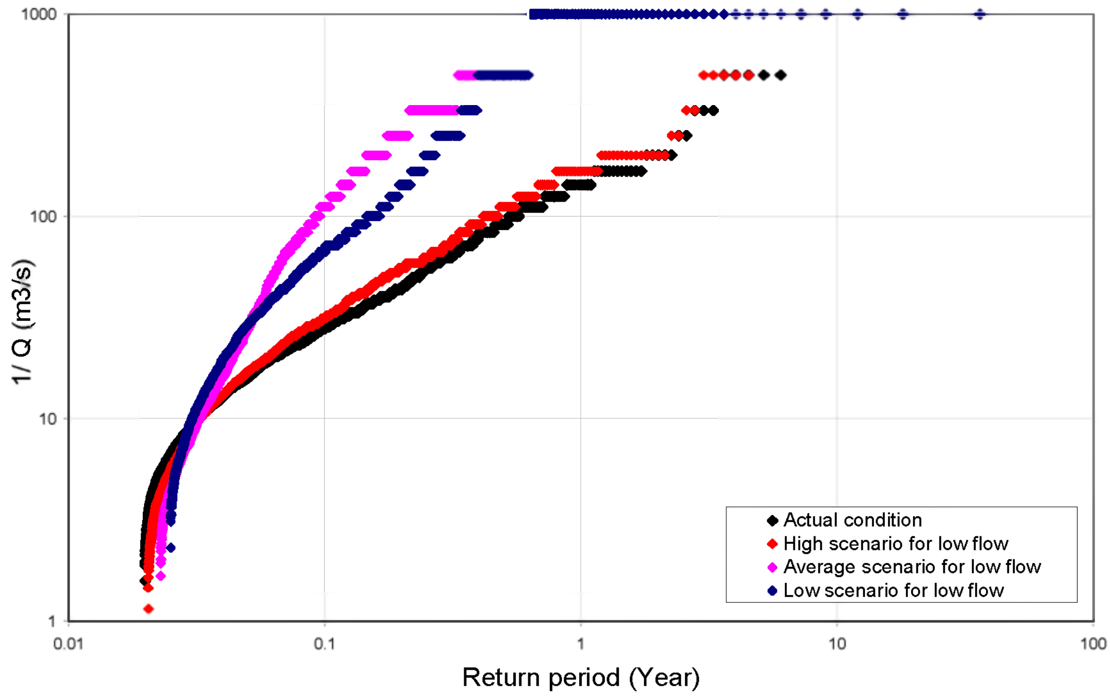


Figure 6.15 Return period hourly minima flow for the three climate change scenarios for the VHA zone 410 of the Dender basin.

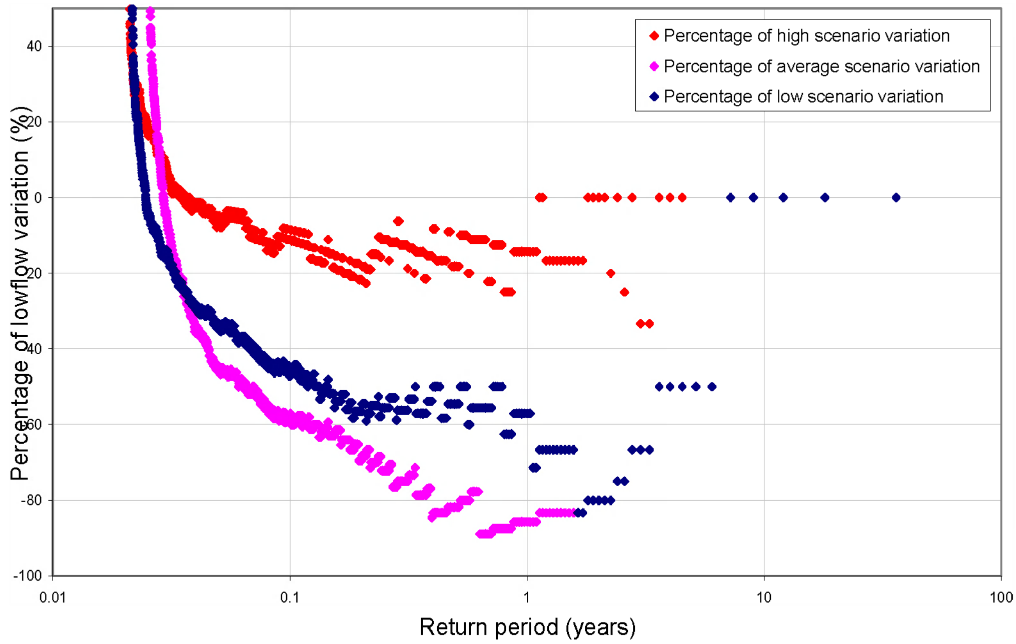


Figure 6.16 Percentage of variation of the hourly minima flow (60 mins) for the low, mean and high scenarios for the VHA zone 410 of the Dender basin.

Average percentage of variation of Low flow (%)	Low scenario	Mean scenario	High scenario
Sub-basin 410	-60	-45	-7

Table 6.4 Percentage of variation of hourly minima flow due to climate change scenarios for the VHA zone 410 of the Dender basin.

The Figure 6.17 presents the percentage of variation of the hourly low flow minimas for the different sub-catchments of the Dender basin. The different sub-catchments react differently although the response remains negative in all the cases of climate scenarios.

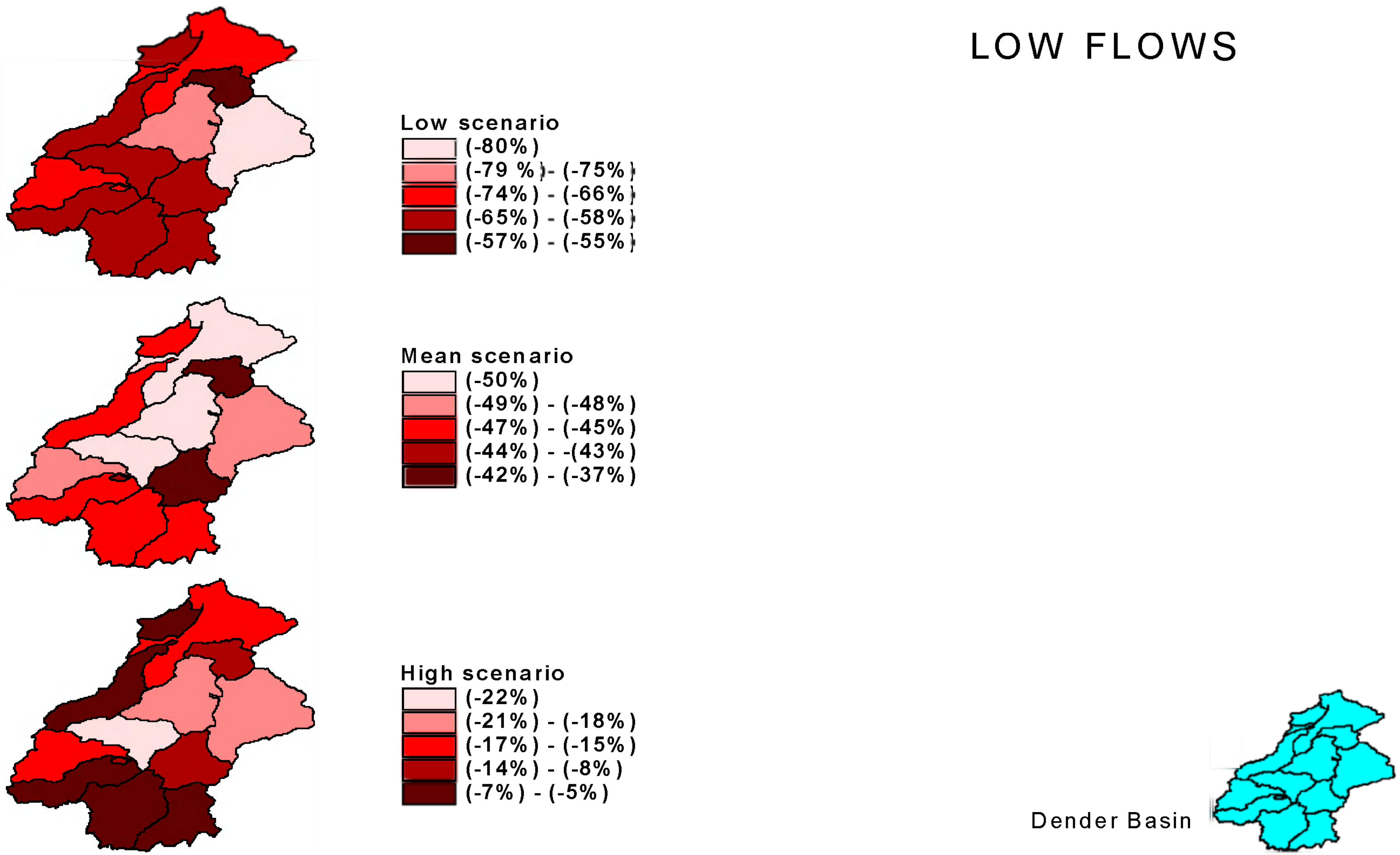


Figure 6.17 Percentage of variation of hourly low flow minimas for the low, mean and high scenarios for the Dender basin, regional differences.

6.3.2 Dender basin flood maps

Flood mapping is the process of identifying on a map, areas at risk of flooding. It provides a good foundation for efficient flood-risk management (Mikko et al., 2006). Flood maps can be used when drawing up flood-risk management plans, for preventing flood damages, in land use planning, for providing information on floods, in rescue operations and in determining the lowest allowed construction elevation to avoid flood risk.

In mapping the flooded areas, attention must be paid to the reliability and accuracy of the source information as the flood map can describe an observed flooded area (a historic flood map) or a simulated flooded area with an indication of the flood probability irrespective of whether a flood has occurred or not (an inundation map or a flood hazard map). The historic flood maps are based on observations and thus they are reliable, especially if the observed flooded area is derived from accurate aerial photographs or satellite images or from the field markings. However, there is often no source information available or historic flood maps are only available for a limited historic period. In this case the flooded area has to be modeled. In flood modelling, flood scenarios can be simulated for several different return periods.
One challenge of flood modelling is estimating water levels of rare, major flood events. Many factors of uncertainty are included in the estimation due to the short term reliable hydrologic observations. The discharges and water levels can be estimated using statistical methods or by modelling the hydrologic cycle (runoff models). Usually water levels are calculated in the river locations using one-dimensional hydraulic models. Two-dimensional models can be used in the complex reaches (Galantowicz, 2002). The most important inputs of the models are the geometry of the river bed and discharge information (Timbe, 2007).
In flood modelling, one important additional input is the digital elevation model (DEM) of the earth's surface. The DEM is a digital representation of ground surface topography or terrain; it is also widely known as a digital terrain model (DTM). A DEM can be represented as a raster (a grid of squares) or as a triangular irregular network. DEMs are commonly built using remote sensing techniques; however, they can also be built from land surveying. DEMs are used often in geographic information systems, and are the most common basis for digitally-produced relief maps. The DEM accuracy affects essentially the one of the flood hazard mapping and the cost. An accurate DEM can be produced, for example, from aerial photographs or laser scanning. Both methods are fairly expensive. The “interferometric synthetic aperture radar” technique is sufficient to generate digital elevation maps with a resolution of around ten meters (Galantowicz, 2005).
The quality of a DEM is a measure of how accurate elevation is at each pixel (absolute accuracy) and how accurately is the morphology presented (relative accuracy) (Reed and Adams, 2006). Several factors play an important role:

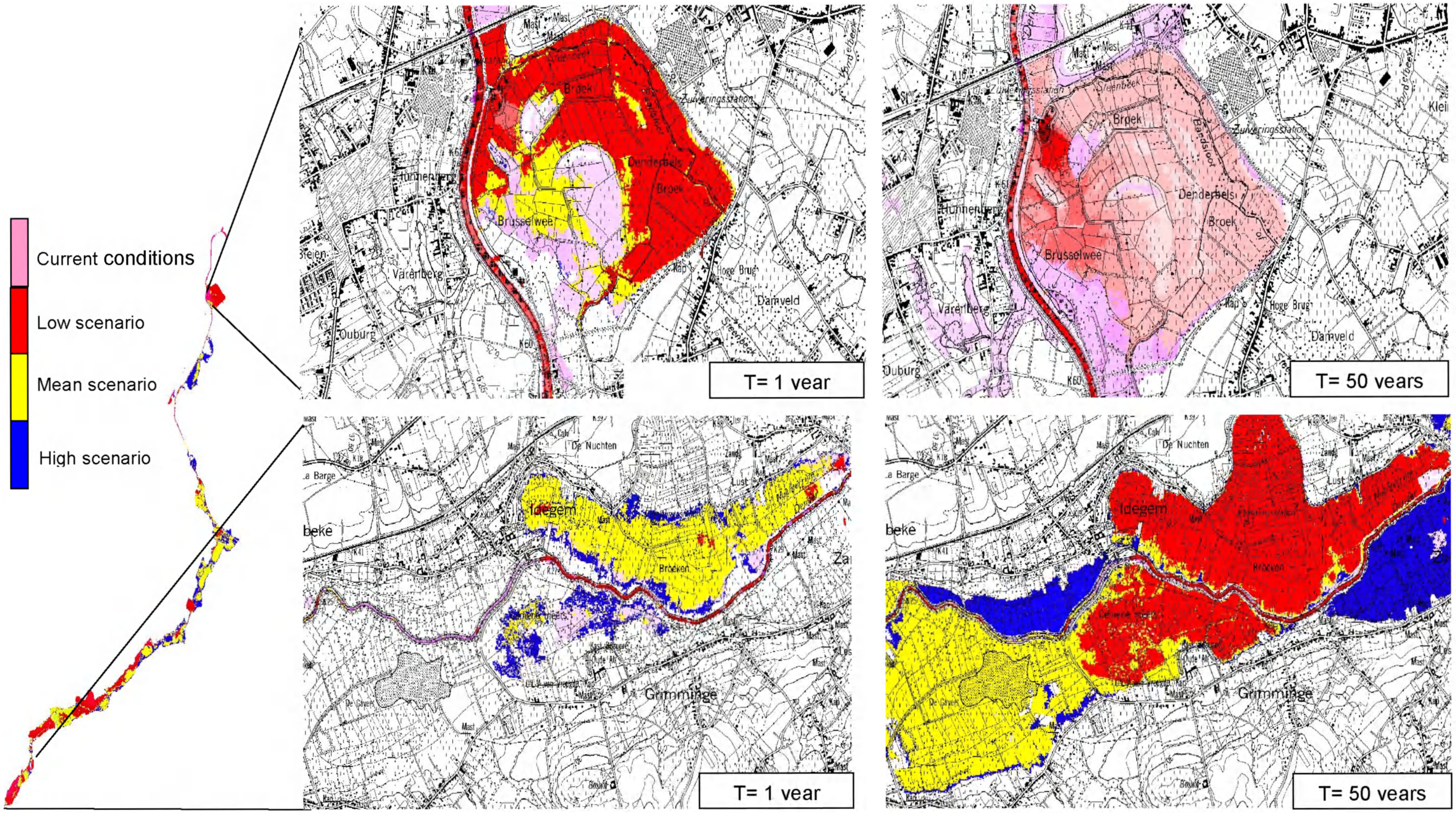
- Terrain roughness;
- Sampling density (elevation data collection method);
- Grid resolution or pixel size;
- Interpolation algorithm;
- Vertical resolution;
- Terrain analysis algorithm.

Inundated areas and water depths can be digitally modeled with the above-mentioned information using GIS software by reducing the digital elevation model of the earth's surface from the digital elevation model of the water surface.
In this study, the methodology of WL and the Hydraulics Laboratory of K.U.Leuven is applied. This methodology uses a quasi 2D hydraulic floodplain model, in combination with lumped conceptual models for the catchment rainfall-runoff (NAM from DHI) along with a hydrodynamic model for the river (MIKE11 from DHI).

Historical flood events are simulated to validate the model(s), whereafter composite hydrographs can be simulated, which represent flood events for given return periods. The simulated spatial extents of the floods can be visualized by means of the DEM in a GIS system.

The flood mapping procedure starts with the hydrological model simulations of composite hydrographs which feed the hydraulic model. The hydraulic model results are in turn communicated to a GIS system which is used to draw geometrical data from the DEM. ArcView/MIKE-GIS data have been used to implement this procedure and to draw flood maps for different return periods (Willems et al., 2001; Willems et al., 2002).

The previous methodology was implemented by WL as standard approach for flood probability mapping and on the basis of flood risk calculations. The WL fed this study with the necessary inputs of calibrated hydraulic models and different DEMs (10m resolution) for the different catchments of the Flanders area. The flood mapping simulation time depended on the complexity of the hydraulic model structure, it expanded from 3 to 4 hours for a single simulation. Flood maps for different climate scenarios and different return periods were derived. Below are the resulted flood maps for the Dender basin for different return periods (1, 50 and 100 years) (Figure 6.18) where the flood extension largely depends on the chosen climate scenarios. For the high return periods, the flood extent might cause considerable damage especially while expecting a high rainfall climate scenario.



Current conditions
Low scenario
Mean scenario
High scenario
T= 1 year
T= 50 years
T= 1 year
T= 50 years

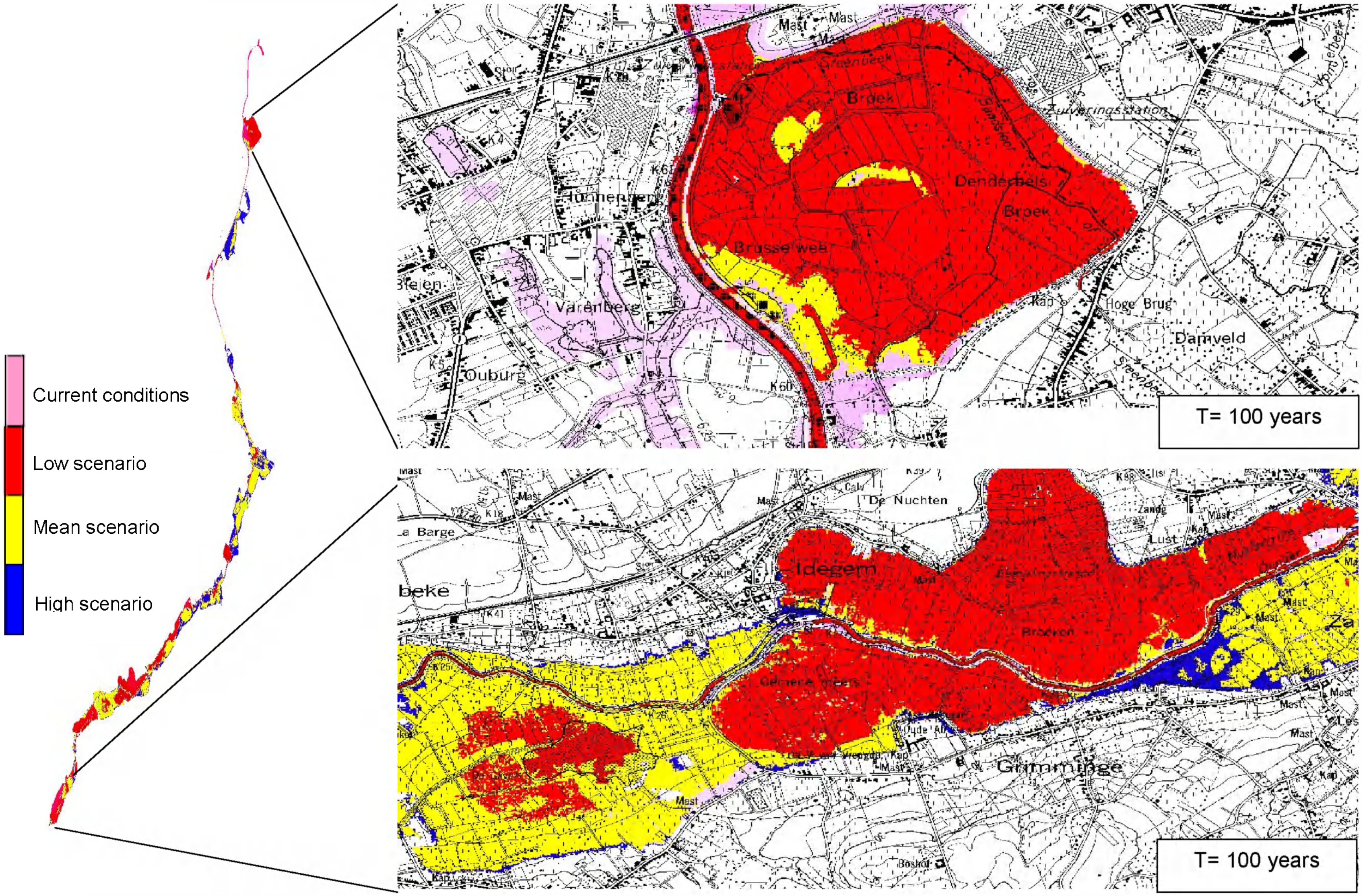


Figure 6.18 Flood maps for sub-regions around Overboelare and Idegem in the Dender basin for the three climate scenarios and return periods of 1, 50 and 100 years.

6.3.3 Dender basin risk calculations

The possible threats that might be caused by climate change on hazards are of major assessment concern. In this respect, assessing damage that might be caused by severe floods or long period droughts in a certain area during a certain period of time, would provide an ultimate view on possible climate change effects and thus would make the state prepared to face back the possible damage.

The scientific literature is rich with several definitions and representations of the term “risk”. We have chosen to use a technical definition of the concept “risk”. Risk is defined as the compete set of scenarios (*Si*), the likelihood (*Li*) and the consequences (*Ci*) of each scenario, that is the set of all *i* triplets (*Si, Li, Ci*) (Kaplan, 1997). Hellevik (1999) states that risk is a “measureable/operational definition of a theoretical variable, e.g., it is an operational variable”. Gray and Wiedemann (1999) give a similar definition.

In general terms, risk is defined as the product of frequency (or probability) of a particular event and the consequence of that event, in terms of life losses, financial cost and/or environmental impact. Risk calculation may be carried out quantitatively by the general expression of the risk (*R*) where *R* equals to the damage (*S*) caused by an event multiplied by the probability (*P*) of occurrence of that event (equation 6.7) (Van Dyck, 2007; Hellevik, 1999; Barneich et al., 1996).

$$R = S * P \tag{6.7}$$

Obviously, in terms of this research, the extreme floods/droughts events have an annual frequency (λ) of occurrence. This changes the equation (6.7) to be:

$$R = S * \lambda \tag{6.8}$$

The damage may itself be the product of several factors (conditional probabilities) resulting on the final outcome of the event.

Barneich et al (1996) insisted on the fact that a correct risk assessment exercise should go through five important steps which we summarize below:

(1) Definition of problem serving to risk assessment;

(2) Hazard analysis: which includes the identification of the hazards and characterization of its nature, e.g., mechanics of the flood flow in terms of water depth, direction and velocity;

(3) Consequence analysis: which includes an estimation of the potential number of people impacted by the floods, an assessment of the likely property damage due to the floods and an evaluation of other flooding impacts such as costs to businesses, environmental damage…etc;

(4) Risk calculation though a correct expression;

(5) Risk evaluation: which includes an investigation of the risk mitigation options and an assessment of the costs and benefits of these options.

By applying the above recommended steps to the present study, it appears that the points (1), (2) and (3) are set. In fact, the desired risk assessment exercise aims to evaluate the possible climate change risk for the Dender basin in terms of hydrological extremes (mainly floods). As for the flood physical characteristics (depth, direction and velocity) in every branch of the rivers considered, they were calculated and modeled through the hydrodynamic model Mike11 for the Dender and through models for topographical information (DEM: Digital Elevation Models). The estimation of the number of people and property affected by the possible flood has been provided through land use information. The point (5) falls beyond the scope of the present study as it concerns mainly the decision makers to implement adaptation measures.

Hence, our risk assessment for the river floods returns to the quantification of the risk (point (4)) through an appropriate equation. The paragraph below discusses this issue.

6.3.3.1 Risk calculation models

Jonkman and Van Gelder (2002) used an overall risk assessment approach to quantify risk to life due to flooding in the Netherlands. Same procedure has been used over the last decade in Australia, New Zealand and the USA for construction safety assessment (Optimx, 2002). The general expression for quantitatively estimating the risk is:

$$R = P_{(H)} * P_{(S:H)} * P_{(T:S)} * V * E \tag{6.9}$$

Where,

R : Annual risk (which may be thought of as the annual probability of fatality or property damage in financial terms);

$P_{(H)}$: Annual probability of flood event;

$P_{(S:H)}$: Probability of spatial impact given the hazardous event e.g., the likelihood of homes, businesses etc. being in the path of the flooding;

$P_{(T:S)}$: Temporal probability of the consequence occurring e.g., probability of the element at risk being present within the area affected by the flooding when the flood occurs;

V : Vulnerability of the element at risk given the presence of the element at risk within the area affected by the hazardous event, or more precisely, the portion of its value that would be damaged;

E : The value of the element at risk itself (individual, group or property…etc).

In some cases, the above risk equation takes into account several detailed features as the seasonal variation of the number and distribution of people in the flood zones, where the high season (high risk season) encompassing December to end of January, in opposite to the May-August period where low people distribution is found during the holiday period along with low flood risk. The above flood risk model accounts also for the type of the day where the calculation considers whether the flood hazard occurs on a weekend or public holidays, a normal work or school day. Further details account the time of the day whether the flood strikes in daylight or in darkness which in turn affects the degree of evacuation and varies therefore the percentage of losses and mortalities. In this respect, the number of people potentially exposed to flood hazard at every location is calculated which represents the percentage of population at risk.

When multiple damages can occur, the equation (6.8) must be further generalized to consider all possible damages from zero to infinity each with their own occurrence rate (Van Dyck, 2007):

$$R = \int_{S=0}^{\infty} s * \lambda[s < S < s + ds]$$

Where λ (s) is the annual occurrence rate with which damage *S* is larger or equal to *s*. This can be written also as:

$$R = \int_{S=0}^{\infty} s * [\lambda(s) - \lambda(s+ds)]$$

$$= \int_{S=0}^{\infty} - s * [\lambda(s+ds) - \lambda(s)] \tag{6.10}$$

$$= \int_{S=0}^{\infty} - s * \frac{d}{ds}[\lambda(s)]ds$$

For a ranked set of increasing damages S_i, $i=1,\ldots,n$, associated with return periods T_i, the exceedance occurrence rate $\lambda(s_i)$ is approximated by $\frac{1}{T_i}$ for sufficiently large T_i.

To quantify equation (6.10), a continuous curve $\lambda(s)$ should be fitted to the possible $\lambda(s_i)$, $i=1,\ldots,n$ and depending on the assumed shape, different numerical approximations can be proposed. Quite often, it will be assumed that $ln(\lambda)$ varies linearly with either S or $ln(s)$ depending on the pattern that is formed from the data $\lambda(s_i)$. The rate of damages between S_i and S_{i+1} is in any case $(\frac{1}{T_i} - \frac{1}{T_{i+1}})$. Using the mid-point value $\frac{S_i + S_{i+1}}{2}$ as a single approximation to the average damage between S_i and S_{i+1}, a possible approximation corresponds to:

$$R \cong \sum_{i=1}^{n-1} (\frac{1}{T_i} - \frac{1}{T_{i+1}})(\frac{S_i + S_{i+1}}{2}) + \frac{S_n}{T_n}$$

The last term in the previous equation is an underestimation of the contribution to the risk from damages larger than S_n (the value associated with the highest return period).

Table 6.5 presents the risk value results for the different reaches of the Dender based on return periods ranging from 1 year to 500 years. To derive these values, an approximation proposed and applied by WL (Vanneuville et al., 2003a) is used.

Climate scenario	low	Mean	high
Walloniё - Geraardsbergen	6 884	23 541	62 453
Geraardsbergen - Idegem	7 218	22 032	42 294
Idegem – Pollare	3 625	8 328	13 878
Pollare - Denderleeuw	15 547	46 756	123 020
Denderleeuw - Teralfene	7 267	18 902	64 914
Teralfene - Aalst	1 982	5 050	14 041
Aalst - Denderbelle	141 910	162 702	174 992
Denderbelle - Dendermonde	30 554	39 028	44 072

*Table 6.5 Risk in the Dender catchment for the 3 climate change scenarios (*25 Euro/year).*

For the different return periods, the mentioned values should be multiplied by:

- T1 : 0.92859
- T20 : 0.05765

- T100 : 0.00975
- T500 : 0.00401

6.4 Conclusion: Climate change impact analysis: the Dender case

The influence of changing rainfall and potential evapo(transpi)ration patterns on river discharges due to climate change has been examined in this chapter for the Dender basin. The lumped conceptual hydrologic model NAM was used to conduct hydrological simulations for future climate scenarios.

A serious decrease of summer rainfall together with an increase of evapo(transpi)ration result in more extreme low flow discharges (for almost all the predicted climate scenarios). The summer base flow can decrease with more than 50% during dry summers. This increases the chance on water deficits, with adverse consequences for drinking-water production, shipping, agriculture, industry, nature …

Being frequently associated with climate change, the increase of flood probabilities is clear for the predicted high climate scenario. Peak discharges in the Dender could rise more than 25% in the most extreme scenario while their mean trend is even diminishing a few percents. They could as well decrease in the low scenario to reach a factor of -30% indicating that large uncertainty remains in the future flood probabilities investigations.

The impact results for the Dender basin seem to be very sensitive to the balance between the precipitation increase vs the potential evapo(transpi)ration decrease ratio and between the winter rainfall increase vs summer rainfall decrease ratio. The results seem also to depend on non-climatic factors as regional differences are seen between the 12 sub-basins of the Dender for the variables of runoff, overland flow and potential evapo(transpi)ration.

The evolution of water extremes and their corresponding flooded areas and damage risk depend on the chosen climate scenarios, on the hydrological model and on sub-basin characteristics.

Chapter 7

Regional differences analysis for entire Scheldt River Basin District

7.1 Introduction

The hydrological impact analysis applied in chapter 6 for the river Dender basin, has been extended to all hydrographic sub-basins of the Scheldt River Basin District in order to investigate the regional differences across this district.

The Scheldt River Basin District combines variations in population, development and natural resources; it is likely that different regions will experience differing levels of vulnerability to climate change. The coastal area is receiving lower rainfall volumes. The major towns, infrastructure and resorts in these areas are located in low-lying coastal areas that could become increasingly vulnerable to higher flood or storm surge levels. Consequently, it is very important to investigate each regional condition apart through the different sub-basins of the Scheldt River Basin District in order to have a general overview of the patterns of hydrological changes due to climate change.

As stated in the introduction of this PhD dissertation text, the catchments of Flanders (containing Scheldt River Basin District) will act as case study depending on the availability of data and hydrological/ hydro-dynamic tools which are applied in the current water management practices. An interpolation of climate impacts is made for the areas suffering from absence of data or inexistence of gauged stations.

This chapter assesses the impacts of climate change on the hydrological extremes along rivers in the Flanders region with its regional differences. The degree to which the hydrological system will respond to a given change in climate, including both beneficial and harmful effects will be discussed. Under this chapter, it is possible also to assess whether regional hydrological systems would be highly sensitive to modest changes in climate, whether the sensitivity includes non-climatological factors as the degree of urbanization and the changes in land use.

A number of quantitative estimates of impacts of climate change are cited below in this chapter. Such estimates are dependent on the specific assumptions employed regarding future changes in climate, as well as upon the particular models applied in the analysis. For this purpose, the hydrologic, hydrodynamic models, tools and data were fully provided by the WL, (Ms. Erika D'haeseleer: the Demer and the Ijzer basins modelling tools and data (~35 years hourly data), Mr. Hans Vereecken provided the Leie-Bovenschelde basin modelling tools and Mr. Patrik Peeters provided the Sigma model covering the Dijle, Nete and Zenne basins).

This chapter applies the same methodology mentioned before on the total Scheldt River Basin District area with investigations on sub-basin scale.

7.2 Interpolation procedure

Some Flemish areas suffer from data limitations. In order to reach an overall understanding of the variation of the hydrological climate change impact of all the Scheldt River Basin District sub-basins, an interpolation procedure has been followed for the un-gauged areas in order to estimate their hydrological behaviour in response to climate change. The interpolation procedure considers that the hydrological answer of the un-gauged areas is considered to be similar to:

- The closest neighbor gauged sub-basin to the studied area (un-gauged sub-basin) for which the surface area is more or less the same while being included at the same catchment. This ensures that the studied area falls into the same hydrological system. It is obvious that many neighboring sub-basins might be chosen;
- The closest neighbor gauged sub-basin to the studied area (un-gauged sub-basin) for which the geotechnical parameters are more or less the same (soil type, soil layers depth, hydraulic conductivity...);
- The closest neighbor gauged sub-basin to the studied area (un-gauged sub-basin) for which land use and topographical slope more or less the same.

If the un-gauged area is located in between neighboring sub-basins presenting different hydrological answers with respect to the geotechnical parameters and land use, an average value is taken for the un-gauged area.

7.3 Results for the Scheldt River Basin District

Climate change impact on the hydrological extremes has been investigated for the entire Scheldt River Basin District area (see results for separate Flemish catchments in Appendix F), where the results have general agreement with the ones found for the Dender basins in terms of hydrological mass balance.

In fact, while for the mean scenario, the runoff peaks look to 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-basin (Figure 7.1).

Overland flow volume results follow the same patterns as the runoff peaks (Figure 7.2). As for actual evapo(transpi)ration volumes, a maximum of additional 17% is expected for the low scenario, while this variable shows an increase for all the applied climate scenarios (which is consistent with general warming tendencies) (Figure 7.3). Low flow decreases dramatically for the entire Scheldt River Basin District area for all climate scenarios indicating that future low flow problems might be in more concern than flood problems (Figure 7.4).

Obvioulsy the large range of uncertainty seen in the above impact values, which are induced by the climate models, enlights once again the heavy impact of the assumptions taken in these last. One of the sources of uncertainty is the assumption of stationarity of the physical processes while climate is changing along with their stabe representations inside the models, plays an important role in the overall uncertainty. Furthermore, the downscaling using RCMs (which are only an increased resolution of GCMs) does not include local scale processes strongly influencing the hydrological response. Thus, the above impact values should be regarded together with their joined uncertainties.

The results indicate also spatial heterogeneity of the hydrological answer in response to climate change scenarios forcing. Flanders embraces then different hydrological systems that react in various ways to the same changes in climate. It seems that the different Scheldt River Basin District sub-basins are separated by physico-morphological boundaries forming the reasons behind the difference in hydrological behaviour. For instance, it was expected to find the highest variation of runoff peaks for the more urbanized areas of Flanders (major Flemish cities) which was not true in some cases throughout this analysis. This emphasizes the importance of hydrologic regionalization and the identification of the specific characteristics in each sub-basin. Understanding the spatial heterogeneity of the hydrological behaviour in Flanders due to climate change will be the subject of the next paragraph.

7.4 Sensitivity of the hydrological results to the physico-morphological characteristics in the Scheldt River Basin District

Quantifying how local characteristics affect the hydrological response at a river basin scale due to climate change forcing is a current challenge in hydrological science. These impacts are significant in small scales, a fact that has been shown through the previous analysis. Understanding the relative role of natural and anthropogenic processes in the spatial hydrological heterogeneity generation is important for current management and future predictions. The objective of this paragraph is to analyze whether observed fluctuations in the runoff peaks over the Scheldt River Basin District can be attributed to differences of the physico-morphological characteristics.

We identified three physico-morphological constraints which may contribute to this heterogeneity. Using the means of statistical correlations, we investigated the implication of the processes of soil type, land use and topographical slope into the spatial heterogeneity results of high scenario runoff peaks. For every catchment of the Scheldt River Basin District, possible correlations between predicted climate change induced increase in runoff peaks and the mentioned natural processes are presented in the upcoming paragraph.

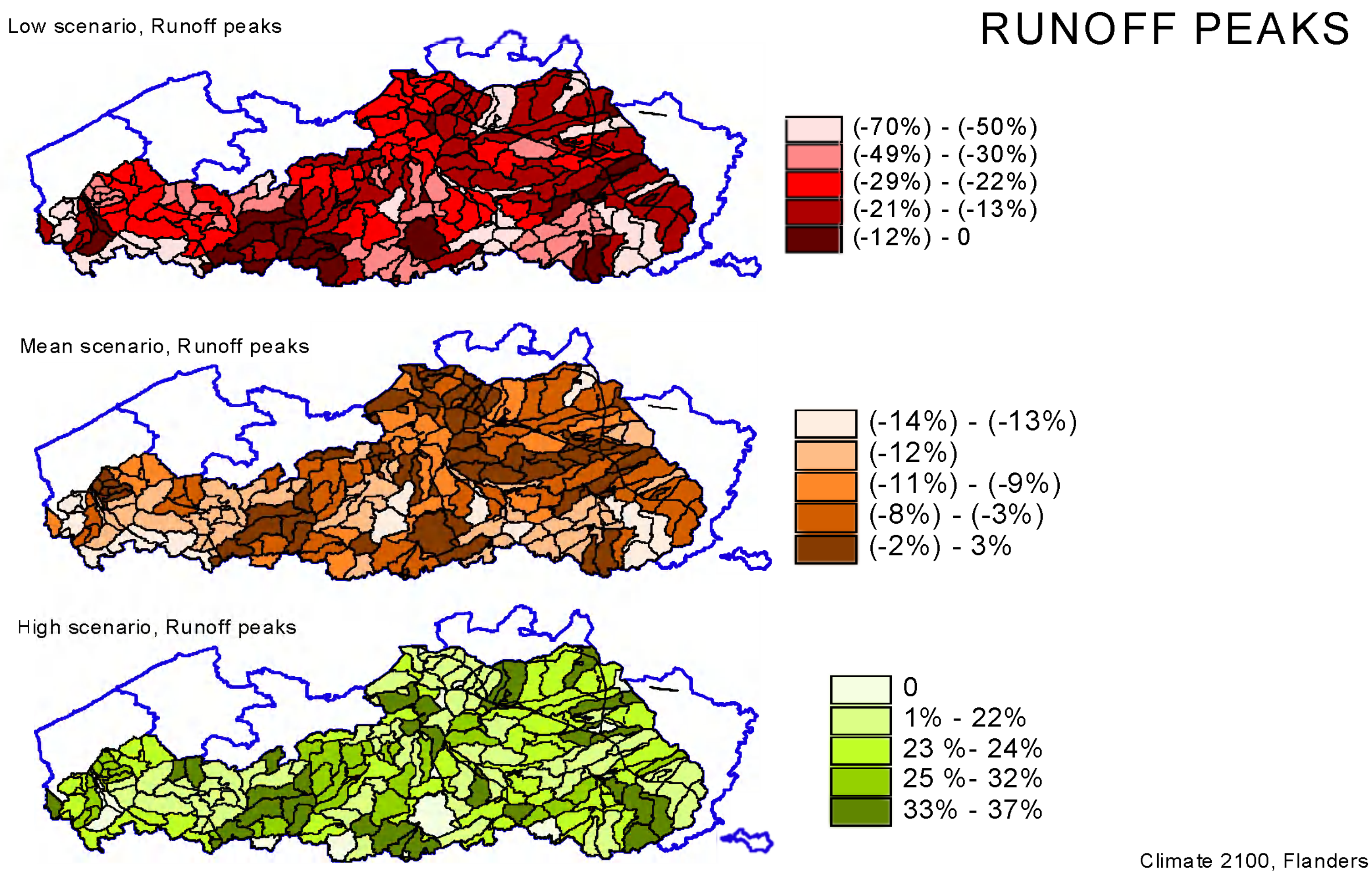


Figure 7.1 Percentage of variation of hourly runoff peaks for the low, mean and high scenarios for Flanders, regional differences.

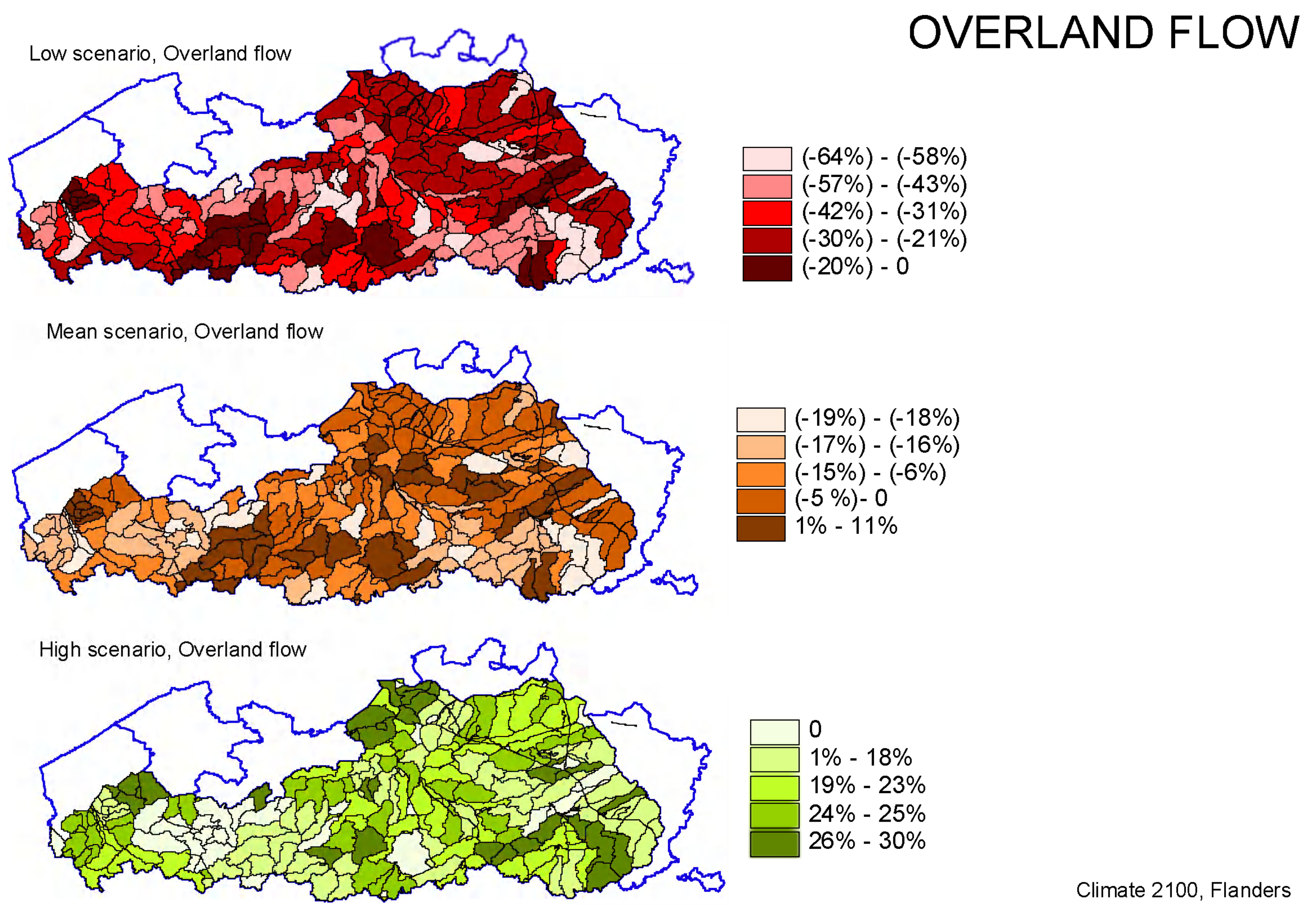


Figure 7.2 Percentage of variation of hourly overland flow volumes for the low, mean and high scenarios for Flanders, regional differences.

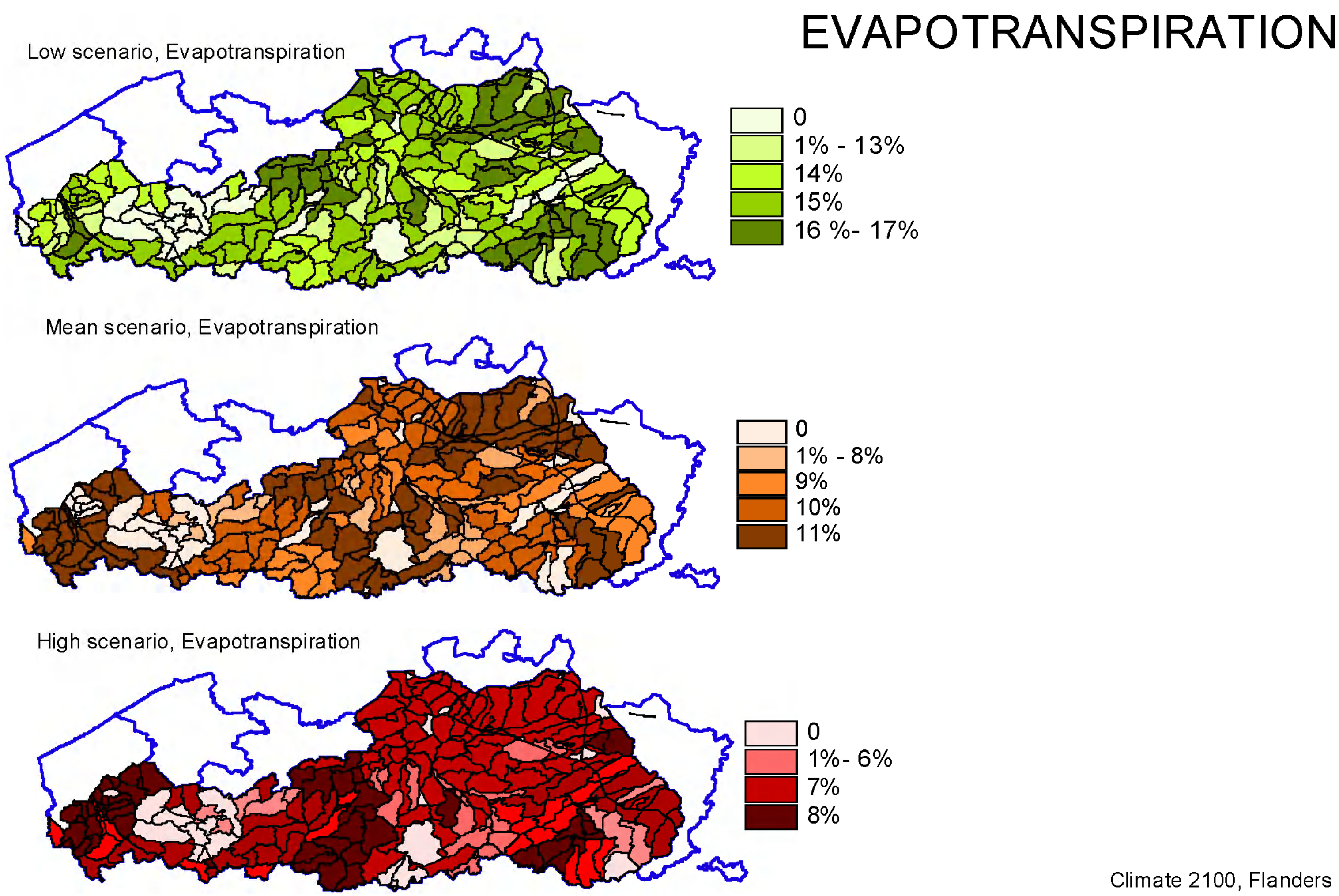
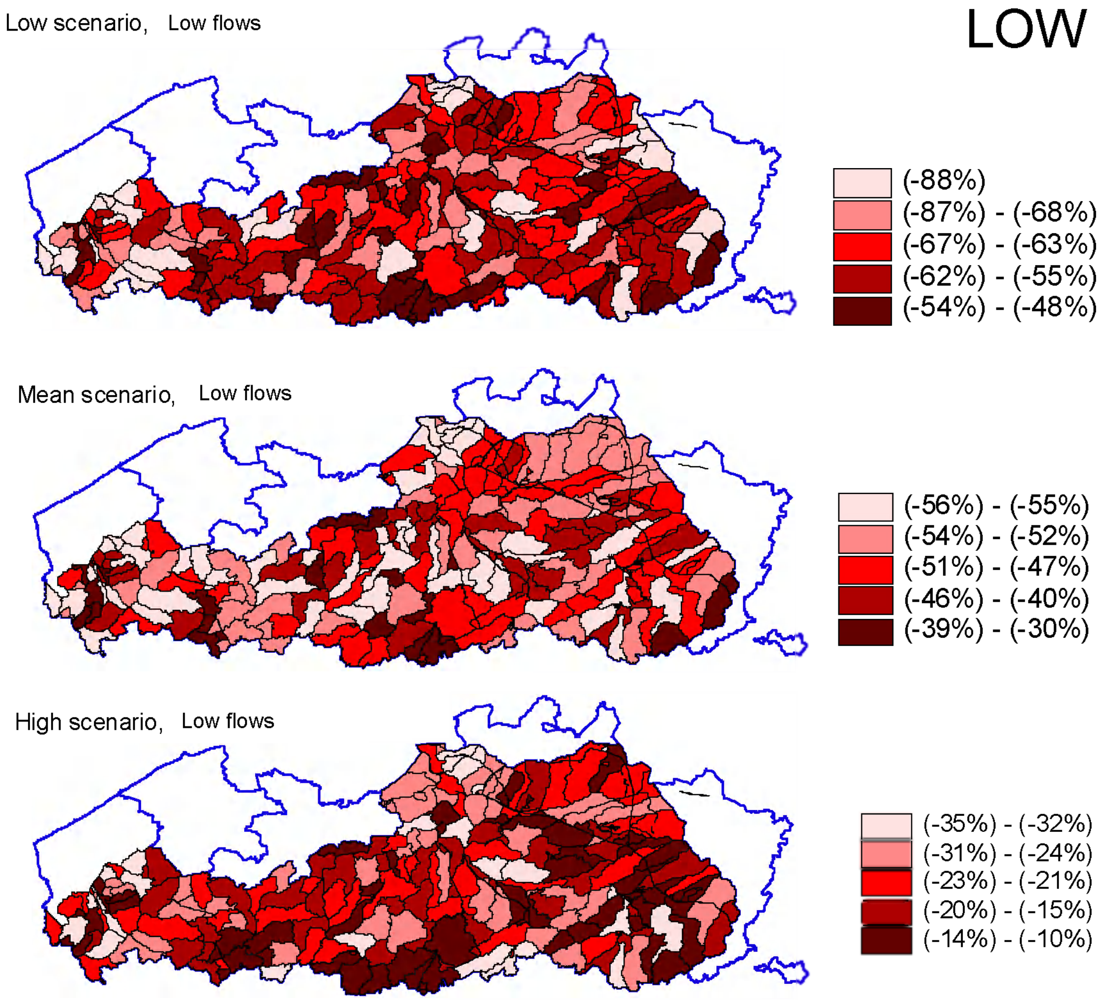


Figure 7.3 Percentage of variation of hourly ETa volumes for the low, mean and high scenarios for Flanders, regional differences.

LOW FLOWS



Climate 2100, Flanders

Figure 7.4 Percentage of variation of hourly low flows for the low, mean and high scenarios for Flanders, regional differences.

7.4.1 *Correlation results for hourly peak flows and discussion*

In a previous WL study, Willems and Rombauts (2004) derived catchment characteristics (percentage of slope, percentage of land use and percentage of soil type) for NAM model calibration needs. The work has been done primarily for the Dender catchment, then extended to all of the Flanders catchments.

While being based on a DTM (Digital Terrain Model) with a grid resolution of 50m * 50m, the slope property has been derived by comparing the percentage of grid cells with slope higher than 4 degrees in comparison with the neighbor cells.

As for the land use property, the percentages of agricultural parcels, forest parcels and urban areas have been derived based on the land use map for Flanders and Brussels of 1995 with spatial resolution of 20m.

The digitized version map of the soil association map of Belgium 1970 with a scale of 1:50000 has been used to extract the soil type properties by fraction of parcels with sandy soil, loamy soil and impermeable soil types (Willems and Rombauts, 2004).

Throughout the result panels for every catchment of the Scheldt River Basin District (see panels below), in most cases, the signature of the physico-morphological characteristics does not provide efficient explanation to the spatial hydrological heterogeneity. Indeed, there are no real strong correlations, although some tendencies can be detected.

While loamy soils would contribute to the increase of runoff peaks due to their fine texture and low permeability coefficient, sandy soils would behave totally in the opposite way. This can be seen clearly for all the basins although the uncertainties are high and no strong correlation can be concluded. The best correlation coefficient is found for the Zenne basin with a value of R^2= 0.16 between the percentage of variation of runoff peaks and the percentage of loamy soils.

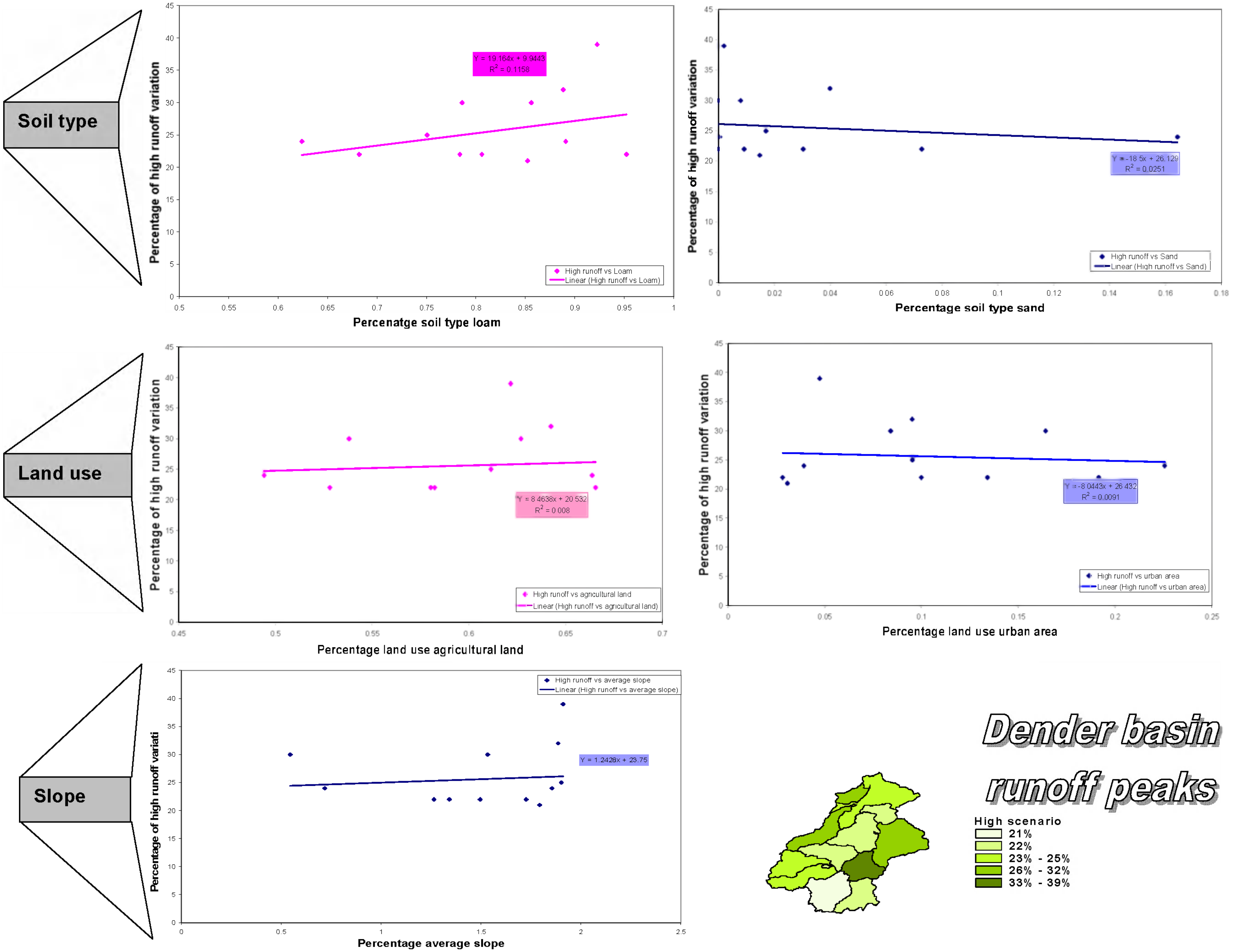
From the other side, and being totally unexpected, there is almost no correlation between the percentage of variation of runoff peaks and land use in Flanders. In all catchments, the degree of urbanization does not seem to contribute into the hydrological response although it is commonly known that hydrological responses of catchments to urbanization are increased runoff volumes and increased peak flows due to vegetation clearing and soil compaction.

As for the topographical slope, for all the basins, the correlation shows weak to moderate impact of topography on the hydrological response heterogeneity. No strong correlations are found for all the basins indicating large model uncertainty, but general tendencies are seen where with increasing topographical slope, runoff peaks increase which is very logic. This indicates that topographical slope explains part of the hydrological response heterogeneity.

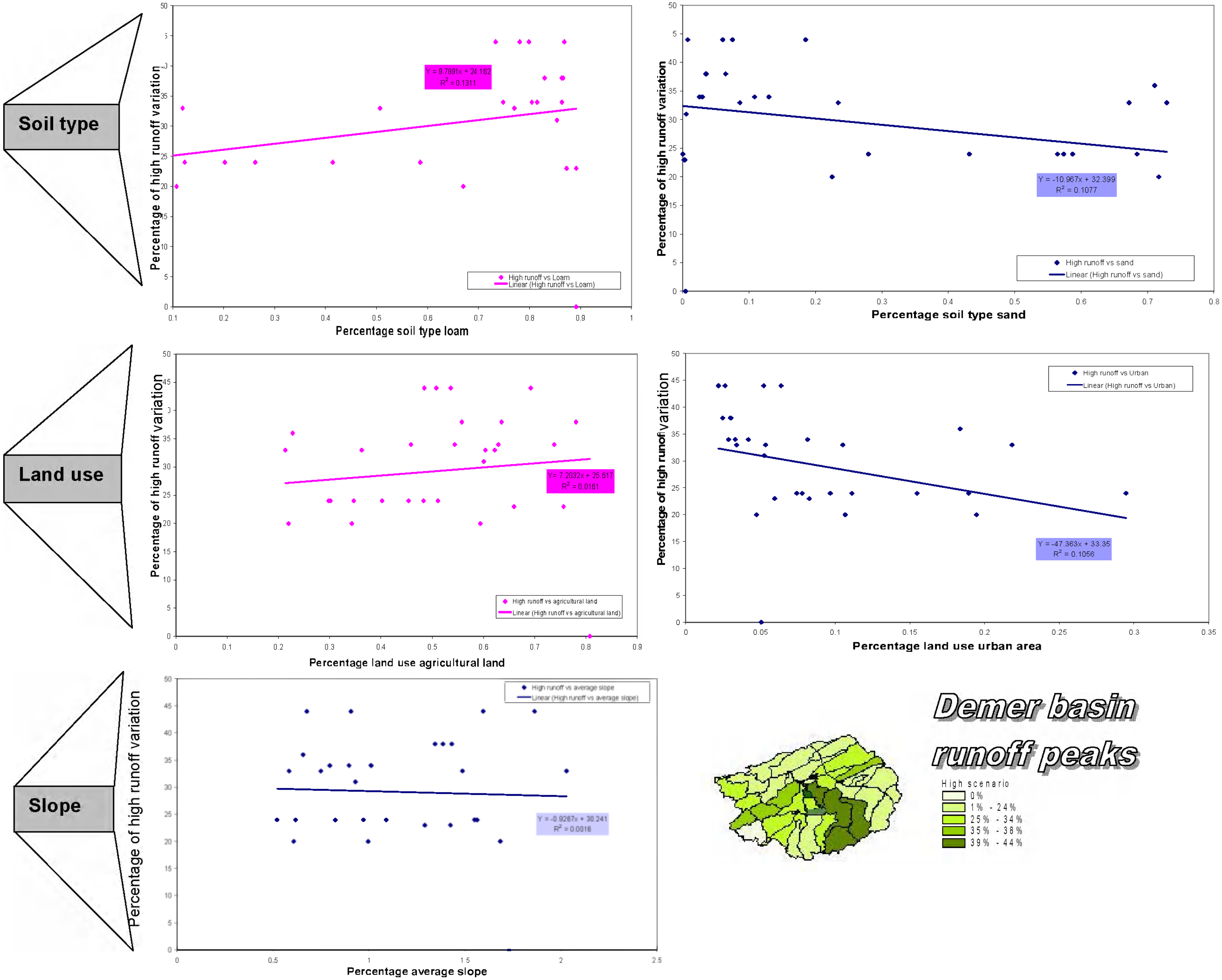
The overall results show that the difference in the hydrological response to climate change scenarios only in part can be explained by soil type and topographical slope however the uncertainty remains very high.

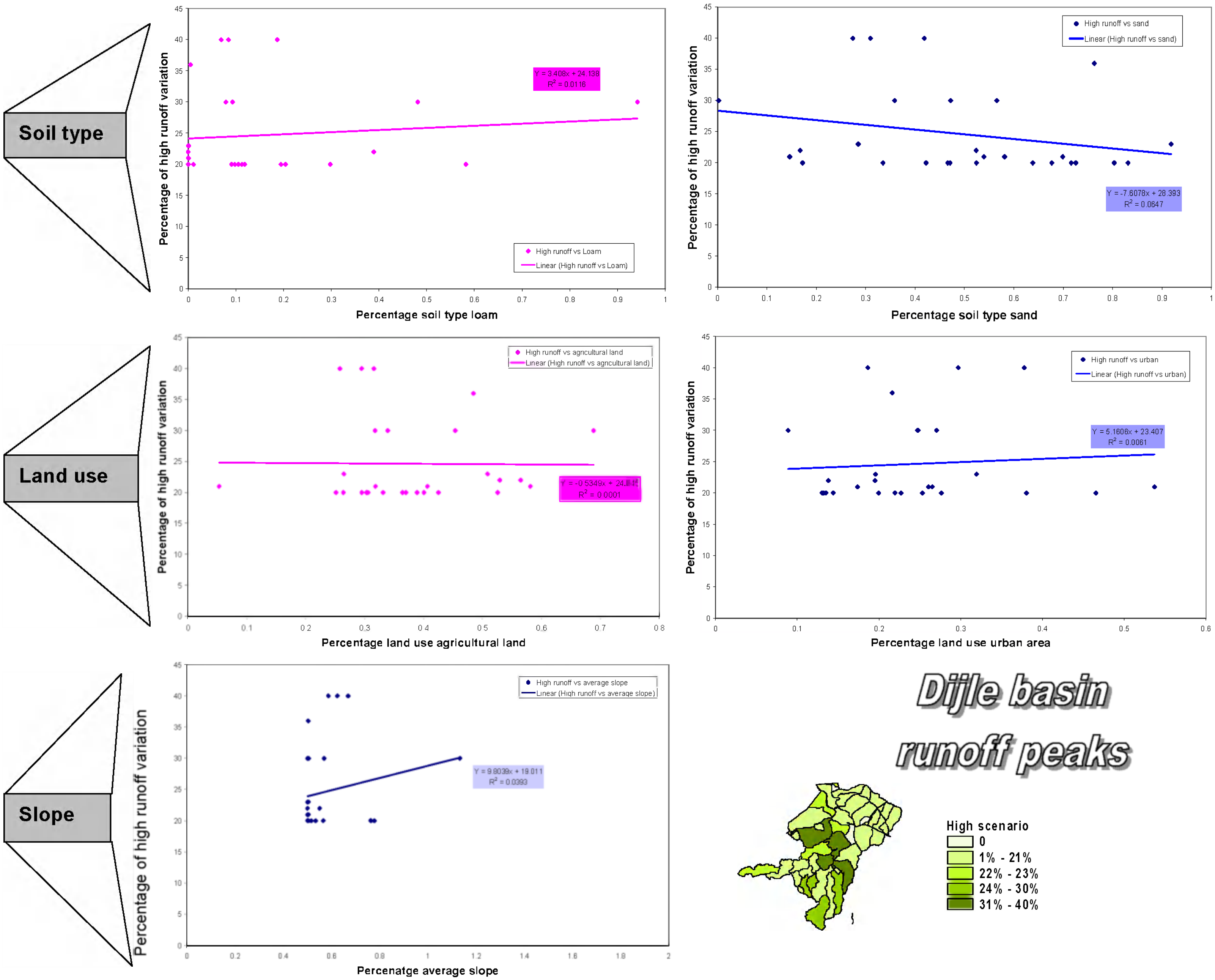
Possible explanation of the additional heterogeneity in hydrological response is related to the hydrological model uncertainty. Although reaching acceptable accuracy, the hydrological models for every basin are still providing considerable uncertainty. The calibration of hydrological models furthermore is subject to inconsistencies and subjectivities due to calibrations done by different persons and (consultancy) agencies in Flanders. The inaccuracy of meteo-hydrological data used as inputs of the hydrological models would add further uncertainty. It moreover should be mentioned that the generated climate scenarios were based on the PRUDENCE project data extraction to the closest grid point to the Uccle station, making the assumption that this station is the most representative of the Belgian area. This assumption brings additional uncertainty as, for instance, precipitation shows considerable spatial distribution variation between the coast and the eastern part of Flanders. Thus, upon processing other PRUDENCE grid points covering Flanders, new climate scenarios can be generated for each specific region. This work is currently under progress in the CCI-HYDR project.

The un-expected result of absence of contribution of the land use into the hydrological responses differences should be taken with high caution as land use is continuously changing and is predicted to show high fluctuations in the shadow of the long term climate change.

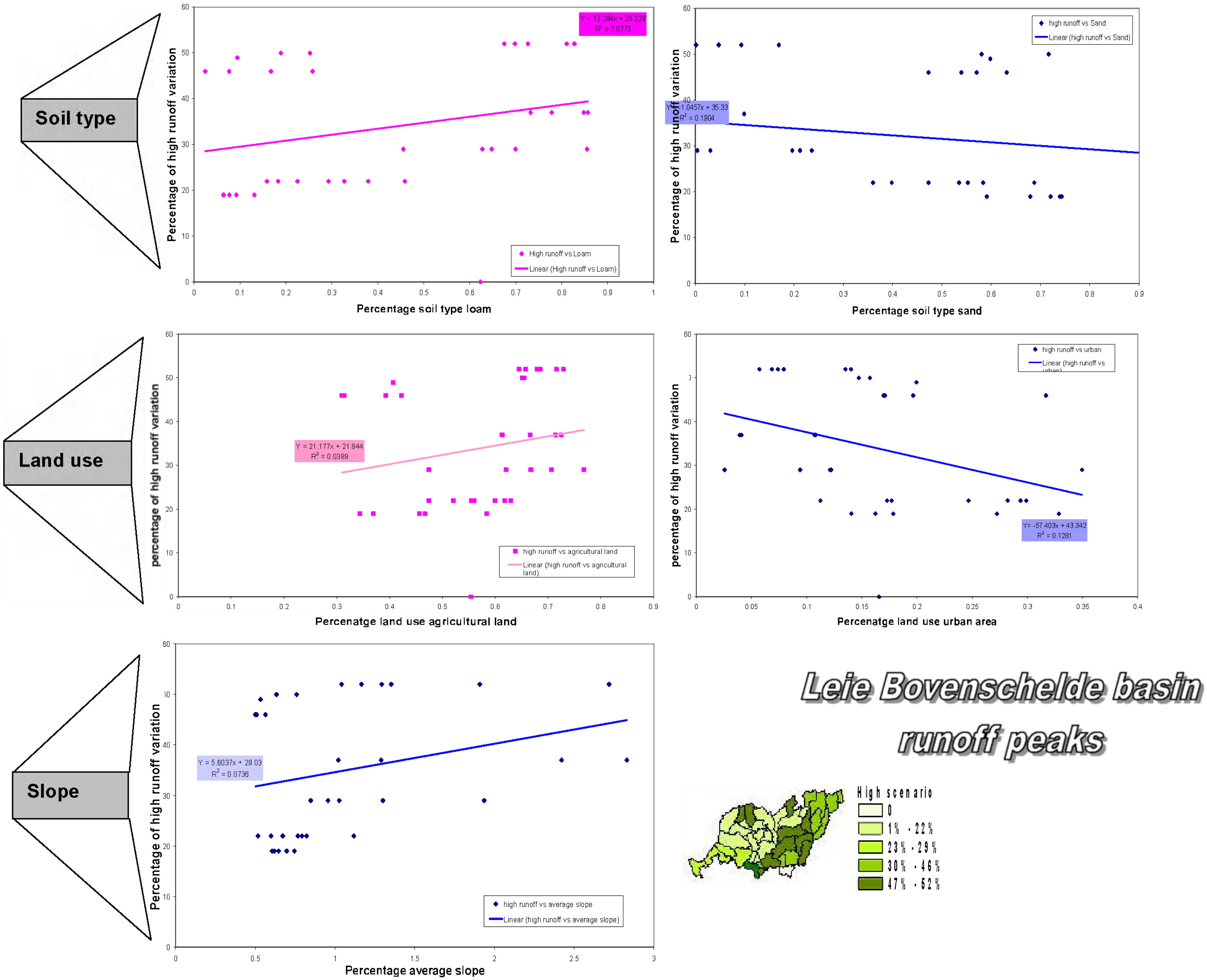


Soil type
Land use
Slope
Percentage of high runoff variation
Percenatge soil type loam
Y = 19.164x + 9.9443
R2 = 0.1158
High runoff vs Loam
Linear (High runoff vs Loam)
Percentage soil type sand
Y = -18.5x + 26.129
R2 = 0.0251
High runoff vs Sand
Linear (High runoff vs Sand)
Percentage land use agricultural land
Y = 8.4638x + 20.532
R2 = 0.008
High runoff vs agricultural land
Linear (High runoff vs agricultural land)
Percentage land use urban area
Y = -8.0443x + 26.432
R2 = 0.0091
High runoff vs urban area
Linear (High runoff vs urban area)
Percentage of high runoff variati
Percentage average slope
High runoff vs average slope
Linear (High runoff vs average slope)
Y = 1.2428x + 23.75
Dender basin
runoff peaks
High scenario
21%
22%
23% - 25%
26% - 32%
33% - 39%

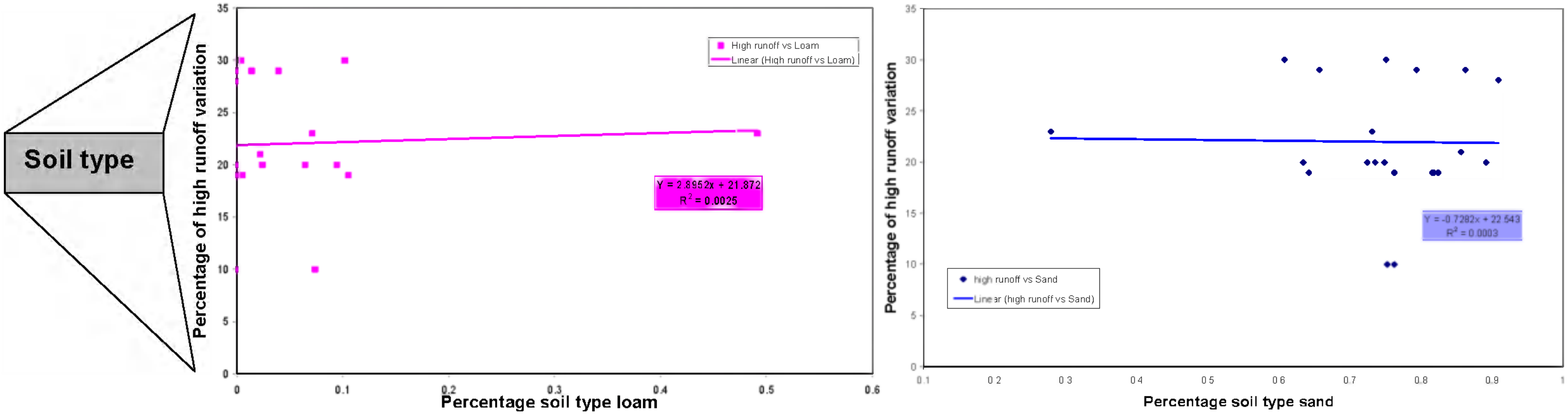

Soil type
Land use
Slope
Percentage of high runoff variation
Y = 9.7891x + 24.162
R² = 0.1311
High runoff vs Loam
Linear (High runoff vs Loam)
Percentage soil type loam
Y = -10.967x + 32.399
R² = 0.1077
High runoff vs sand
Linear (High runoff vs sand)
Percentage soil type sand
Y= 7.2032x + 25.617
R² = 0.0161
High runoff vs agricultural land
Linear (High runoff vs agricultural land)
Percentage land use agricultural land
High runoff vs Urban
Linear (High runoff vs Urban)
Y = -47.363x + 33.35
R² = 0.1056
Percentage land use urban area
High runoff vs average slope
Linear (High runoff vs average slope)
Y = -0.9267x + 30.241
R² = 0.0016
Percentage average slope
Demer basin
runoff peaks
High scenario
0%
1% - 24%
25% - 34%
35% - 38%
39% - 44%

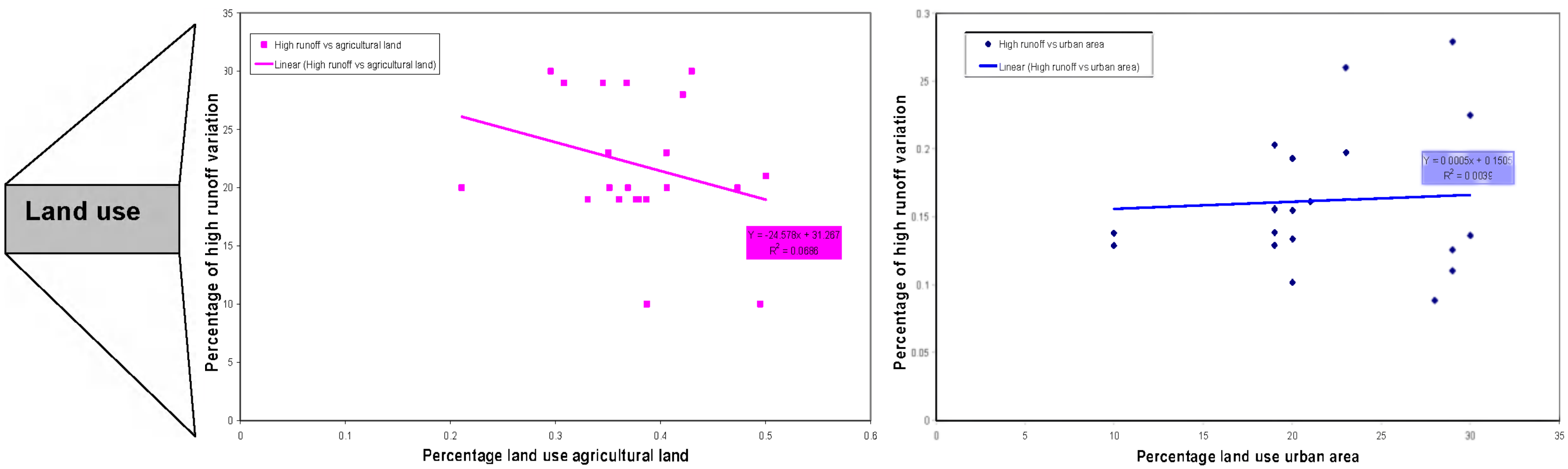


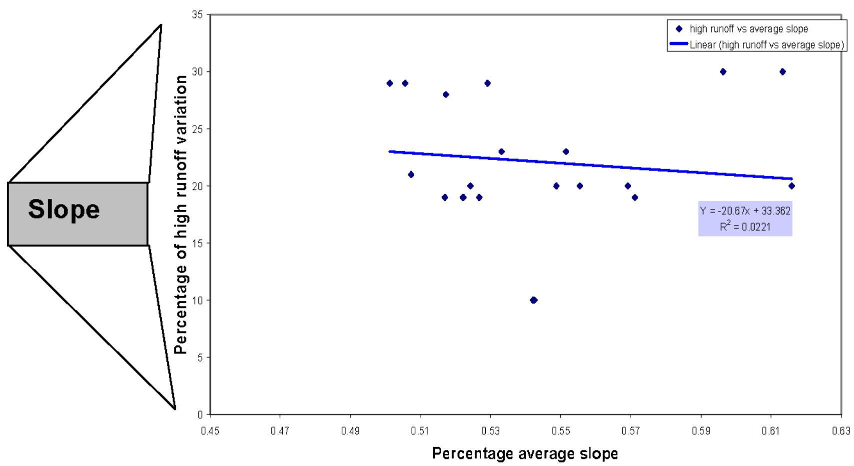
Soil type
Land use
Slope
Percentage of high runoff variation
Percentage soil type loam
High runoff vs Loam
Linear (High runoff vs Loam)
Y = 3.408x + 24.138
R² = 0.0116
Percentage soil type sand
High runoff vs sand
Linear (High runoff vs sand)
Y = -7.6078x + 28.393
R² = 0.0647
Percentage land use agricultural land
High runoff vs agricultural land
Linear (High runoff vs agricultural land)
Percentage land use urban area
High runoff vs urban
Linear (High runoff vs urban)
Y = 5.1606x + 23.407
R² = 0.0061
Percenatge average slope
High runoff vs average slope
Linear (High runoff vs average slope)
Y = 9.8039x + 19.011
R² = 0.0393
Dijle basin
runoff peaks
High scenario
0
1% - 21%
22% - 23%
24% - 30%
31% - 40%

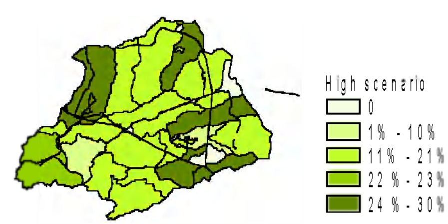


Soil type
Percentage of high runoff variation
Percentage soil type loam
Y = 13.094x + 28.229
R² = 0.0773
High runoff vs Loam
Linear (High runoff vs Loam)
Percentage soil type sand
Y = -1.0457x + 35.33
R² = 0.1904
high runoff vs Sand
Linear (high runoff vs Sand)
Land use
percentage of high runoff variation
Percenatge land use agricultural land
Y = 21.177x + 21.844
R² = 0.0389
high runoff vs agricultural land
Linear (high runoff vs agricultural land)
Percenatge land use urban area
Y= -57.403x + 43.342
R² = 0.1281
high runoff vs urban
Slope
Percentage of high runoff variation
Percentage average slope
Y = 5.6037x + 29.03
R² = 0.0736
high runoff vs average slope
Linear (high runoff vs average slope)
Leie Bovenschelde basin
runoff peaks
High scenario
0
1% - 22%
23% - 29%
30% - 46%
47% - 52%

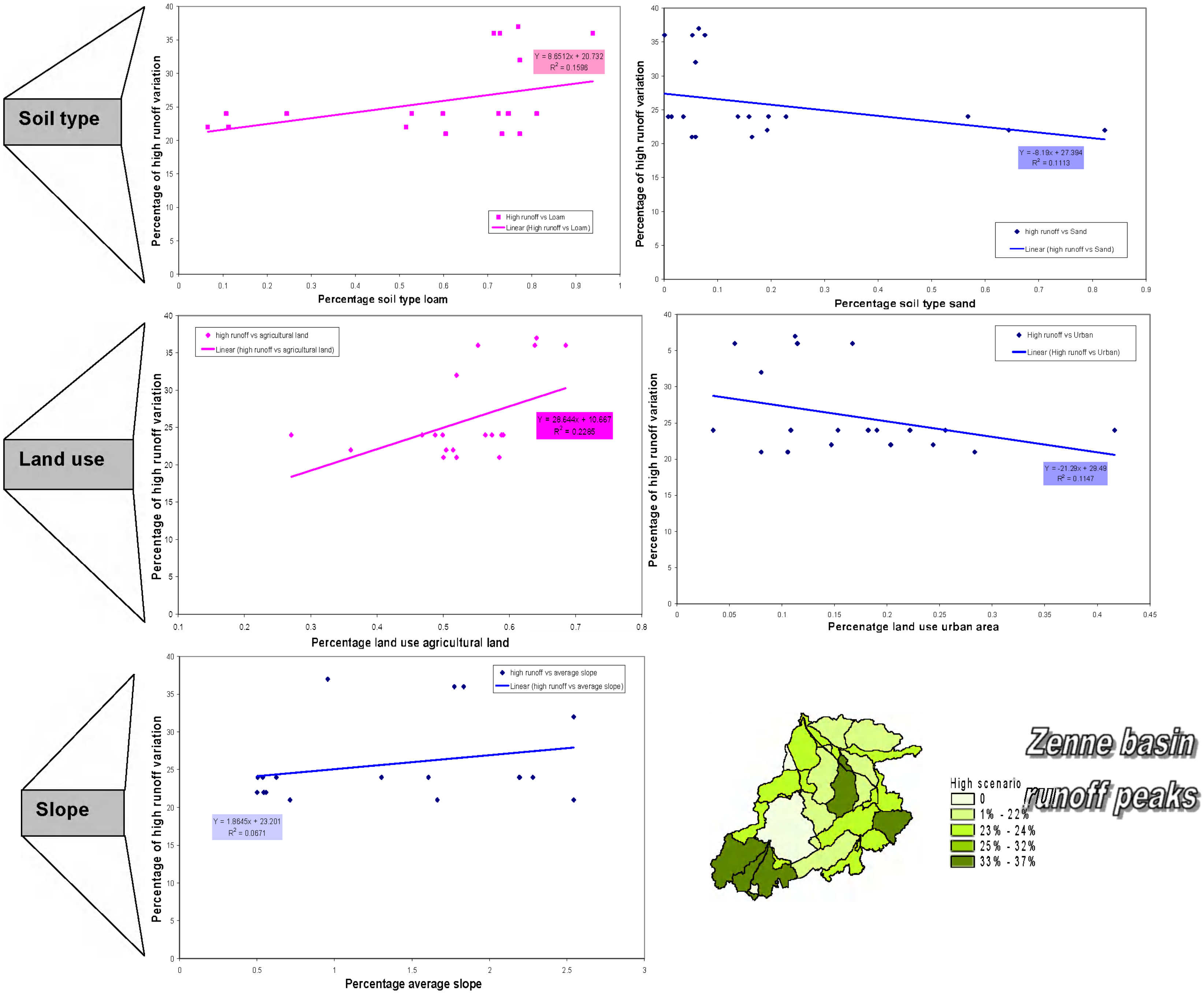








Nete basin runoff peaks



Soil type
Land use
Slope
Percentage of high runoff variation
Percentage soil type loam
Y = 8.6512x + 20.732
R2 = 0.1596
High runoff vs Loam
Linear (High runoff vs Loam)
Percentage soil type sand
Y = -8.19x + 27.394
R2 = 0.1113
high runoff vs Sand
Linear (high runoff vs Sand)
Percentage land use agricultural land
high runoff vs agricultural land
Linear (high runoff vs agricultural land)
Y = 28.644x + 10.667
R2 = 0.2285
Percenatge land use urban area
High runoff vs Urban
Linear (High runoff vs Urban)
Y = -21.29x + 29.49
R2 = 0.1147
Percentage average slope
high runoff vs average slope
Linear (high runoff vs average slope)
Y = 1.8645x + 23.201
R2 = 0.0671
Zenne basin
runoff peaks
High scenario
0
1% - 22%
23% - 24%
25% - 32%
33% - 37%

7.5 Conclusion: Climate change impact on hydrological extremes in the Scheldt River Basin District

While Flanders is concerned about climate change and the possible impacts of the predicted 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.

Facing three generated climate scenarios representing from one side extreme future conditions for precipitation and potential evapo(transpi)ration with the high and low scenarios, and from the other side an average scenario, the Scheldt River Basin District reacts very sensitively. The runoff volumes and overland flow volumes systematically increase and decrease depending on the scenario. Runoff peak changes (flood risk) show high uncertainty and can reach increases up to +35%. Actual evapo(transpi)ration remains increasing for all the scenarios as a result of temperature increase.

The local physico-morphological characteristics seem to weakly influence the differences in hydrological responses due to climate change scenarios forcing leaving their place to natural variability and to uncertainty brought through hydrological models.

One also should keep in mind that the resulted climate change impact values reflect the strong assumptions taken on the stationarity of the physical representations of the natural phenomena (e.g., ETo) while climate is changing (also at the predicted target time). This returns to the issue of the unknowable knowledge about the possible changes of the physics of these processes due to climate change.

Regardless the high uncertainty within climate and hydrological simulations the direct economic impact of climate change due to possible “water-related” damage might be significant and should be taken into account in future water management activities.

Chapter 8

Sensitivity analysis

8.1 Introduction

Uncertainty is a constant companion of scientists and decision-makers involved in climate change and related impact research and management. The uncertainty arises generally from two different sources: incomplete knowledge and unknowable knowledge about the future (Hulme and Carter, 1999). Although it is recognized that it is of major concern to treat all uncertainties in climate change impact assessments, a systematic quantification of uncertainties and uncertainty propagation is far to be performed. This has to do among other things with the complex modelling system used particularly in climate change modelling (Boorman and Sefton, 1997; Guo and Ying, 1997). The IPCC stated it very clear in their third assessment report that: "It is impossible to get a real quantification of uncertainty in climate change impact assessments" (IPCC, 2001).

An appropriate uncertainty exercise should go through different major steps:

- Definition of the major uncertainty sources including the uncertainty due to the mismatch of different processes, measurements and model scales;
- Estimation and propagation of uncertainty;
- Communication of uncertainty.

It is to be mentioned that even if the problem of quantification of uncertainties could be resolved, it would remain to communicate these uncertainties to decision and policy-makers as well as to the general public; which is not an easy issue and also falls beyond the scope of this research. Therefore, this chapter will focus on the remaining steps of definition and identification of the uncertainty sources and the possible methods of assessing the results sensitivity to the joined modelling procedure uncertainty.

8.2 Sources of uncertainty

Known as principal sources of uncertainties, Morgan and Henrion (1990) define the measurement errors, variability and model structure. Measurement errors are generally due to imprecision of instruments or mis-calibration (Bouij, 2002). Variability is a common qualification to all natural processes exhibiting systematic and random variations. The model structure along with the spatial and temporal scales employed in it introduce additional uncertainties by simplifying relations between variables and leaving out other important variables.

Lei and Schilling (1996) distinguish conceptual uncertainty due to incompleteness of a model structure and inaccuracy of formulations, parameter uncertainty and input data uncertainty.

Wu et al. (2005) stated that data uncertainty and incorrect assumptions about these data lead to additional errors. Uncertainties result also from switching model scales (both in space and time).

Uncertainties might decrease or increase with the emerging of complex models which have the challenge of being more precise and/or more accurate than simple models. Data requirements for the initialization and calibration of complex models are to be tightly controlled and need to be in the range of current field experimentation. In this context, making models more complex can increase their uncertainty and affect the overall communicability between the different models' parts. Simply by increasing the number of model parameters which are uncertain, we are increasing the model uncertainty.

Numerous other divisions of uncertainties can be found in literature where authors mostly agree about all dominant uncertainties when considering the model outputs accuracy. From his side, Bouij (2002) grouped the different sources of uncertainties along with their relation to the modelling process in the following table 8.1.

Source	Sub-source	Modelling process
Natural uncertainty	Randomness	Scales
	Scaling issues	Scales
Data uncertainty	Measurement errors	Scales
	Inadequacy of data	Scales
Model parameter uncertainty		Scales/ formulations
Model structure uncertainty	Model incompleteness	Processes
	Model inaccuracy	Formulations

Table 8.1. Different sources of uncertainty and their relation to the modelling process (Bouij, 2002).

8.2.1 Climate models and climate change scenarios uncertainties

The uncertainty in future climate simulated by climate models is particularly large, especially for a variable like precipitation where temporal and spatial distributions vary very much (Bouij, 2002).

Hulme and Carter (1999) consider four sources of uncertainty in climate models: the global system predictability (future emission), the climate sensitivity, the climate system predictability and the sub-grid scale climate variability. For them, the second and third sources are closely related to model structure but the fourth refers to scaling issues.

As for Dickinson (1989), he concluded that the atmospheric composition and the calculation of the radiative forcing are the main sources of uncertainties in a climate model. Visser et al (2000) analyzed the uncertainty sources presented by Dickinson and concluded that the key uncertainty source remains in the radiative forcing models. Strictly speaking, this is representing the different scenarios run by IPCC corresponding to the different emission scenarios.

One other major source of uncertainty poorly represented into climate models is the notion of surprises and rapid non-linear responses of the climate system to anthropogenic forcing. The slow reorganization of the thermohaline circulation and the rapid deglaciation are some of those surprise issues, for which our scientific comprehension is still unable to understand the phenomena drivers and to predict future behaviour.

Throughout this research and while dealing with the different RCMs of the PRUDENCE project, several other sources of uncertainty appeared, which are resumed below:

- The different physical concepts of climate models. Although high reliability is reached by the climate models, the equations building the models are still far to fully represent the entire complexity of the climate system. Very often, important components and parameters are neglected due to poor scientific understanding;
- The climate models structure and data exchange between the different climate model components;
- The temporal and spatial scales on which the model operates. Some natural processes require specific resolutions, which might end up with neglecting some processes or poorly represent them;
- The uncertainty in the future emission scenarios. A factor that ends up to a large uncertainty in the climate model outputs (Figure 8.1 presents the range of variation of global surface warming due to different emissions). Analysis of the PRUDENCE climate model simulation results for A2 and B2 emission scenarios covered this uncertainty only partly (explains partly the high, mean and low climate change scenarios differences obtained in chapter 5);
- The downscaling from GCMs to RCMs, called dynamical downscaling, where climatologists are in fact attempting to increase spatial and temporal resolution without introducing several local regional natural processes that should have great impact on the local climate and on the local hydrological response. This was shown in previous chapter with the impact of soil type and topography slope in the overall hydrological answer of every catchment in Flanders;
- The assumption of stationarity in the transient climate. In fact the PRUDENCE RCMs predict the climate situation in 2071-2100 based on the baseline condition of 1961-1990. It is however clear that along the time gap between these two periods, the climate would not remain the same, and the conditions in 2071-2100 would be very dependent on the conditions in the 2020s, 2050s... Furthermore, several new natural processes might show up as a result of changes in atmospheric composition and current natural processes would surely change the total behaviour of the climate. This is an important source of uncertainty that is totally neglected in climate models;
- The areal factors issues. Actually, the climate models provide an output as an average value on a specified grid cell with certain spatial resolution. This areal value is compared and/or applied upon a point measurement value. Such action needs areal reduction factors so the comparison should be based on the same scale. Those areal

factors are poorly known and dependent on the location, on the output variable intensity, frequency;

- The perturbation approach applied within this research. Transferring the climate signal into the hydrological model requires perturbing the variable (e.g., precipitation) intensity and as well perturbing the frequency (adding and removing storms). The latter is not considered in the hydrological impact investigation, which would introduce part of the overall uncertainty (only in summer, thus mainly on the low flows impact).

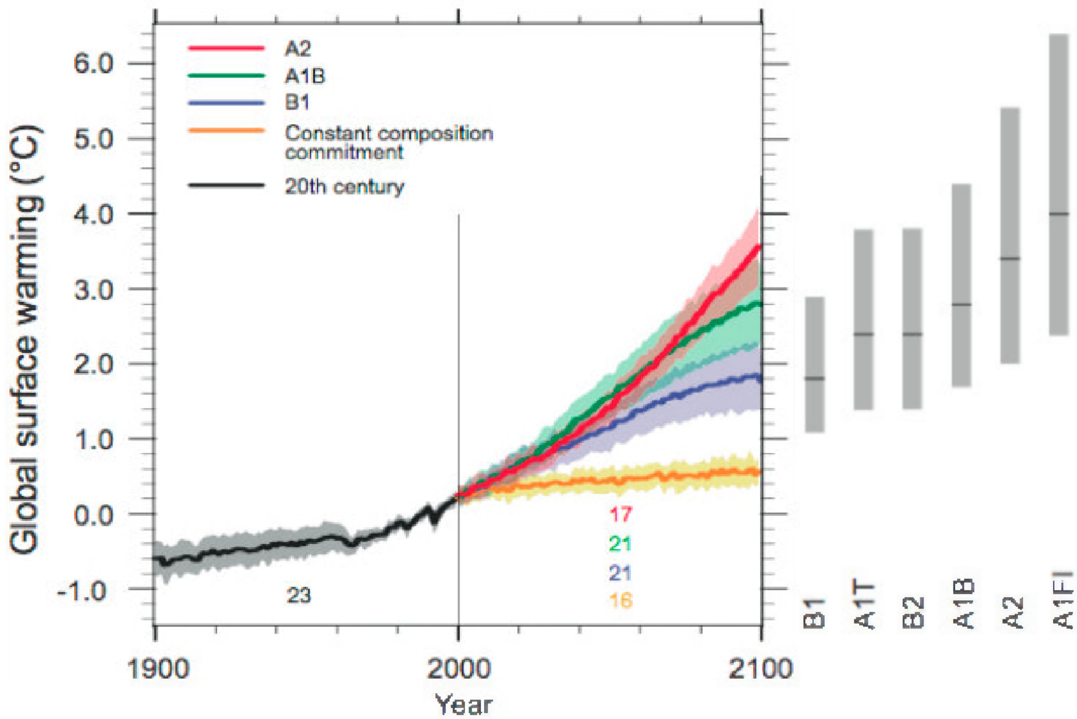


Figure 8.1 Predicted global surface warming due to different emission scenarios (the colored numbers present the number of climate model runs) (Vimont, 2007).

All previous points show that the bigger part of uncertainty in climate impact assessments comes from climate models and are imposed upon the hydrological models.

8.2.2 Hydrological impact model uncertainties

The use of rainfall-runoff models (lumped or distributed) to assess the response of a catchment to climate change inevitably introduces additional uncertainties (Bouij, 2002). In practice, it is common to estimate model output uncertainty by means of calibration. In this way, the model structure uncertainties are not included as they are in practice very difficult to estimate (can be assessed by validation or model inter-comparison). Willems (2000) quantified these uncertainties for rainfall runoff models applied to Flemish hydrographic catchments. Timbe (2007) extended this investigation towards uncertainties in the hydrodymanic river modelling and the flood mapping. These appear to be an order of magnitude lower than the uncertainties in the climate change scenarios.

8.3 Sensitivity analysis of the climate change impact on hydrological extremes in Flanders

As previously mentioned in this study, transferring the climate impact to the hydrological field has been made through means of perturbation factors which helped creating climate scenarios (high, mean and low) for Flanders. The differences between the high and low scenarios cover part of the climate model related uncertainties (through comparison of outputs from the different RCMs) and part of the emission scenario uncertainties (through involving A2 and B2 emission scenarios).

The perturbation factors scenarios were built empirically based on two criteria (see chapter 5 'climate models selection', section 5.6.1).

However, sensitivity of these perturbation factors, which is depending on the methodology of creating them, might influence in turn the hydrological response to climate change. In this chapter we look to perform a sensitivity analysis on the hydrological response to the possible variations in the created climate scenarios. By doing so, it becomes possible to evaluate the degree of sensitivity (percentage of variation) of the perturbation factors to the process used to generate them (empirical process/statistical process). It also allows assessment of the degree of sensitivity of the hydrological response in turn.

To do so, the control RCM precipitation values are mapped to the real measurement record (Uccle precipitation). Then the climate models baselines that meet closely with the record are considered accurate/accepted to create climate change scenarios. However, even when the RCM control run represents the real historical climate in an unbiased way, we are not expecting perfect match with the record because of randomness (natural variability) by which the rainfall distributions might deviate. This leads to use statistical techniques (Monte Carlo simulations) to build confidence intervals. In order to be accurate/accepted for future climate scenarios, the difference between any RCM baseline (control precipitation) and the record (Uccle precipitation) should lay within the chosen confidence interval.

8.3.1 The two-component exponential distribution

In several case studies, the exponential distribution has been suggested as presenting the best approximation to the distribution of precipitation intensities in Belgium. Willems (1998) presented a systematic methodology which derived the type of the distribution and the optimal threshold. Willems (2000) used the two component exponential distribution to represent storms of two different types (airmass thunderstorms and cyclonic/frontal storms). This was done for each duration in the range from 10 min to 15 days. He found that for different time aggregation levels (at least up to 15 days), the tail of the distribution for Uccle precipitation series behaves in an exponential way when an optimal threshold is selected. Since the exponential distribution can be solved explicitly, the random sampling for the Monte Carlo simulations is not complicated.

The two component distribution is defined as:

$$G(X) = p_a G_a(X) + (1 - p_a) G_b(X) \quad (8.1)$$

in which $G_a(x)$ and $G_b(x)$ are two different exponential distributions and subscripts *a* and *b* represent the thunderstorms and frontal storms respectively.

$$G_a(X) = 1 - \exp(-\frac{X - X_t}{\beta_a}) \quad (8.2)$$

$$G_b(X) = 1 - \exp(-\frac{X - X_t}{\beta_b}) \tag{8.3}$$

β is considered to be the scale parameter (slope of the Q-Q plot) while X and X_t are the variable and the threshold respectively.

8.3.2 Defining the Monte Carlo confidence intervals

Random samples are generated from the two-component exponential distribution known for the Uccle precipitation data (Willems 2000). Using Monte Carlo (MC) simulations, confidence intervals were defined for the Uccle precipitation empirical quantiles (reflecting the sampling uncertainty). Based on these confidence intervals, through statistical hypothesis testing, the hypothesis was tested whether the control values of the RCMs were from the same statistical population as the observed Uccle precipitation, taking into account the randomness due to natural variability in the 30 years rainfall series of RCM control values and their corresponding sampling uncertainty.

Defining confidence intervals requires selection of rank values which represent the confidence level. These rank values are estimated based on the number of samples that have been generated. It was decided to reduce the number of simulations to 250 for reasons of computational constraints.

For example, the 95% confidence interval contains a region where 95% of the possible values would lie due to randomness. Therefore given 250 random samples the 95% confidence limits were identified by the 243rd and 7th ranked values in the series. The procedure for obtaining these critical values is achieved through the following steps (assuming there are 250 random generated samples each with 10804 data points (30 years daily data):

- Each of the 250 random samples contains 10804 randomly generated observations. The synthetic data is sorted in descending order for each of the 250 samples with the highest having a rank of 1 and lowest rank 10804;

- A new set of data is then got from the ranked sample data. All similarly ranked values are grouped into new series. For instance all the highest values from each sample are extracted to form a unique series of highest points. Similarly all 2nd highest values are extracted from the different series to form a new collection containing the 2nd highest values from all the 250 samples. The process continues until the 10804 values are also extracted from each series. This process is aimed at obtaining values with the same exceedance probability (same rank), the so-called quantiles;

- The quantiles extracted consequently represent a range of variability. By default each of the 10804 new extracted series now contains 250 values (number of samples used). A 95% confidence interval can now be defined for each exceedance probability after ranking the values.

Little information is provided by the scientific literature regarding the most appropriate confidence interval to choose. The IPCC (TAR, 2001) uses the 90% confidence interval without any argumented reason. In this study we decided to proceed with different threshold regions or levels to decisive acceptance or rejection of climate models, which correspond with different levels for the confidence intervals (80%, 85%, 90%, 95% and 99%) for each data time scale (daily, weekly and monthly). Obviously some climate model results (control simulations) will not meet closely with the real measurement (Uccle data) and will fall outside the confidence interval for certain quantiles or exceedence probabilities and thus will be rejected.

In the opposite side, the accepted ones will serve to create statistical low, mean and high scenarios (factors) for precipitation. These statistically generated factors (new factors) are therefore compared to the empirically generated ones (old factors) which provide their degree of sensitivity.

8.3.3 Areal reduction factor (ARF)

As mentioned in chapter 4 ‘downscaling methods’, section 4.4.2.1, when comparing RCM grid precipitation with Uccle empirical data, the Uccle precipitation data need to be corrected by an areal reduction factor (ARF). Two constant ARFs having the values of 1 and 0.85 will be used in this study together with different precipitation time scales ranging from daily, weekly to monthly.

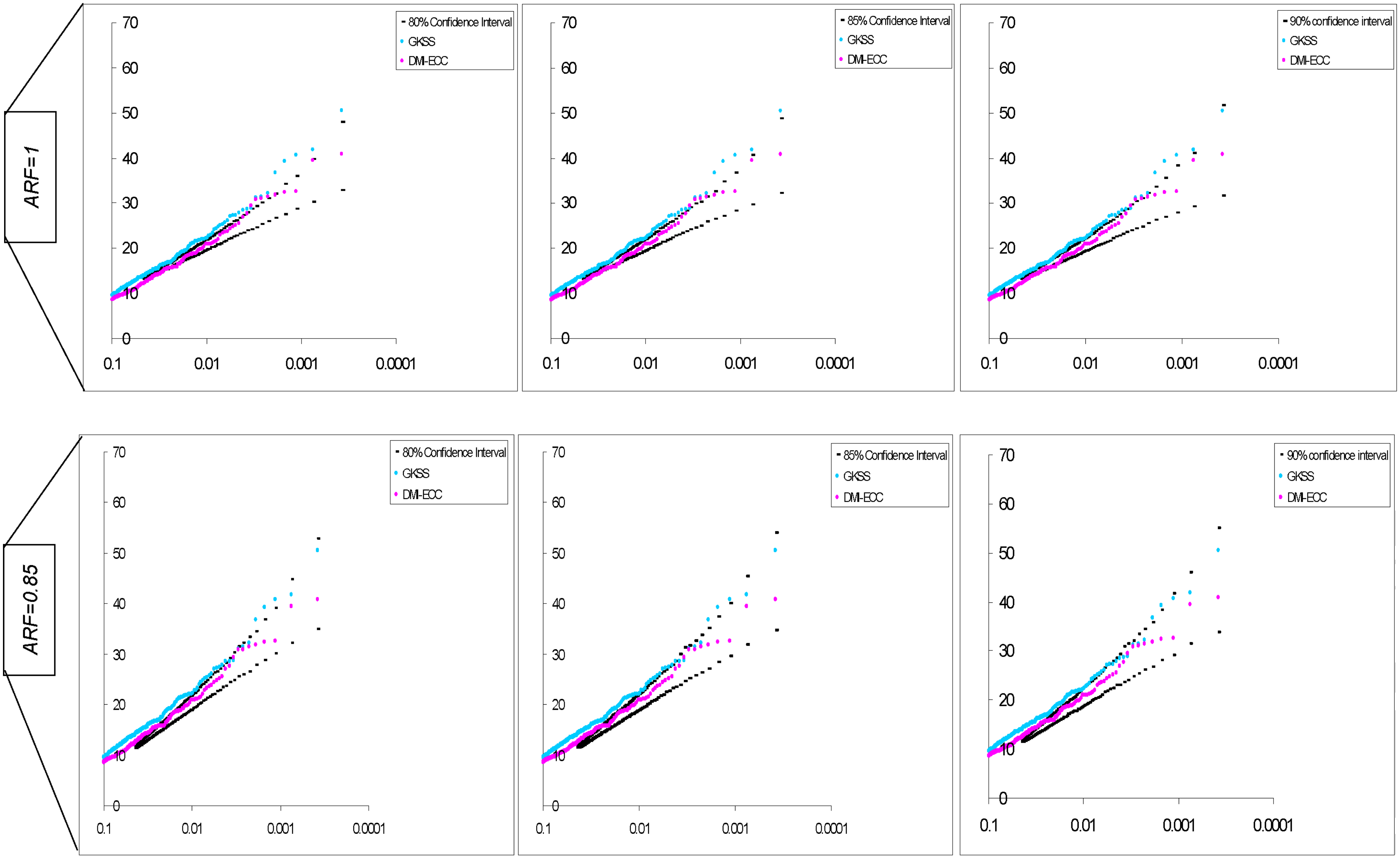
8.3.4 Results and discussion

The Monte Carlo simulation based sensitivity analysis has been performed for RCMs control precipitation for every season and for the different areal factors. It appears that the selection/rejection of climate models mostly depends on the ARFs, in opposite to their weak dependency on the confidence level. An example is given in Figure 8.2 where Monte Carlo simulation results for daily precipitation data are shown for the models DMI-ECC and GKSS, while the same procedure has been applied for all the RCMs. Table 8.2 presents the results.

	80% confidence interval	**85% confidence interval**	**90% confidence interval**	**95% confidence interval**	**99% confidence interval**
Winter daily precipitation (ARF =1)	ETH DMI-ECC KNMI METNO-Had DMI-HC1 DMI-HC2 DMI-HC3 GKSS-sn	ETH DMI-ECC KNMI METNO-Had DMI-HC1 DMI-HC2 DMI-HC3 GKSS-sn	ETH DMI-ECC KNMI METNO-Had DMI-HC1 DMI-HC2 DMI-HC3 GKSS-sn	ETH DMI-ECC KNMI METNO-Had DMI-HC1 DMI-HC2 DMI-HC3 GKSS-sn/ GKSS	ETH DMI-ECC/ DMI-F25 KNMI METNO-Had DMI-HC1 DMI-HC2 DMI-HC3 GKSS-sn CNRM
Summer daily precipitation (ARF =1)	CNRM DMI-F25 DMI-ECC GKSS-sn DMI-HC1 SMHI-MPI KNMI	CNRM DMI-F25 DMI-ECC GKSS-sn DMI-HC1 DMI-HC3 SMHI-MPI KNMI	CNRM DMI-F25 DMI-ECC GKSS-sn DMI-HC1 DMI-HC3 SMHI-MPI KNMI	CNRM / ETH DMI-F25 DMI-ECC GKSS-sn DMI-HC1 DMI-HC3 SMHI-MPI KNMI	CNRM / ETH DMI-F25 DMI-ECC GKSS-sn DMI-HC1 DMI-HC3 SMHI-MPI KNMI ITCP METNO-Had
Winter daily precipitation (ARF =0.85)	DMI-F25 GKSS-sn DMI-HC2	DMI-F25 GKSS-sn DMI-HC2	DMI-F25 GKSS-sn DMI-HC2 DMI-HC3	DMI-F25 GKSS-sn DMI-HC1 DMI-HC2 DMI-HC3 KNMI	DMI-F25 GKSS-sn DMI-HC1 DMI-HC2 DMI-HC3 KNMI
					KNMI

Summer daily precipitation (ARF =0.85)	ETH DMI-F25 DMI-ECC GKSS-sn DMI-HC1	ETH DMI-F25 DMI-ECC GKSS-sn DMI-HC1 CNRM	KNMI ETH DMI-F25 DMI-ECC GKSS-sn DMI-HC1 CNRM	KNMI ETH DMI-F25 DMI-ECC GKSS-sn DMI-HC1 CNRM	ETH DMI-F25 DMI-ECC GKSS-sn DMI-HC1 DMI-HC3 METNO-Had CNRM

Table 8.2 Accepted models after MC simulation for different confidence interval levels and different ARFs.


ARF=1
ARF=0.85
80% Confidence Interval
85% Confidence Interval
90% confidence interval
GKSS
DMI-ECC
0
10
20
30
40
50
60
70
0.1
0.01
0.001
0.0001

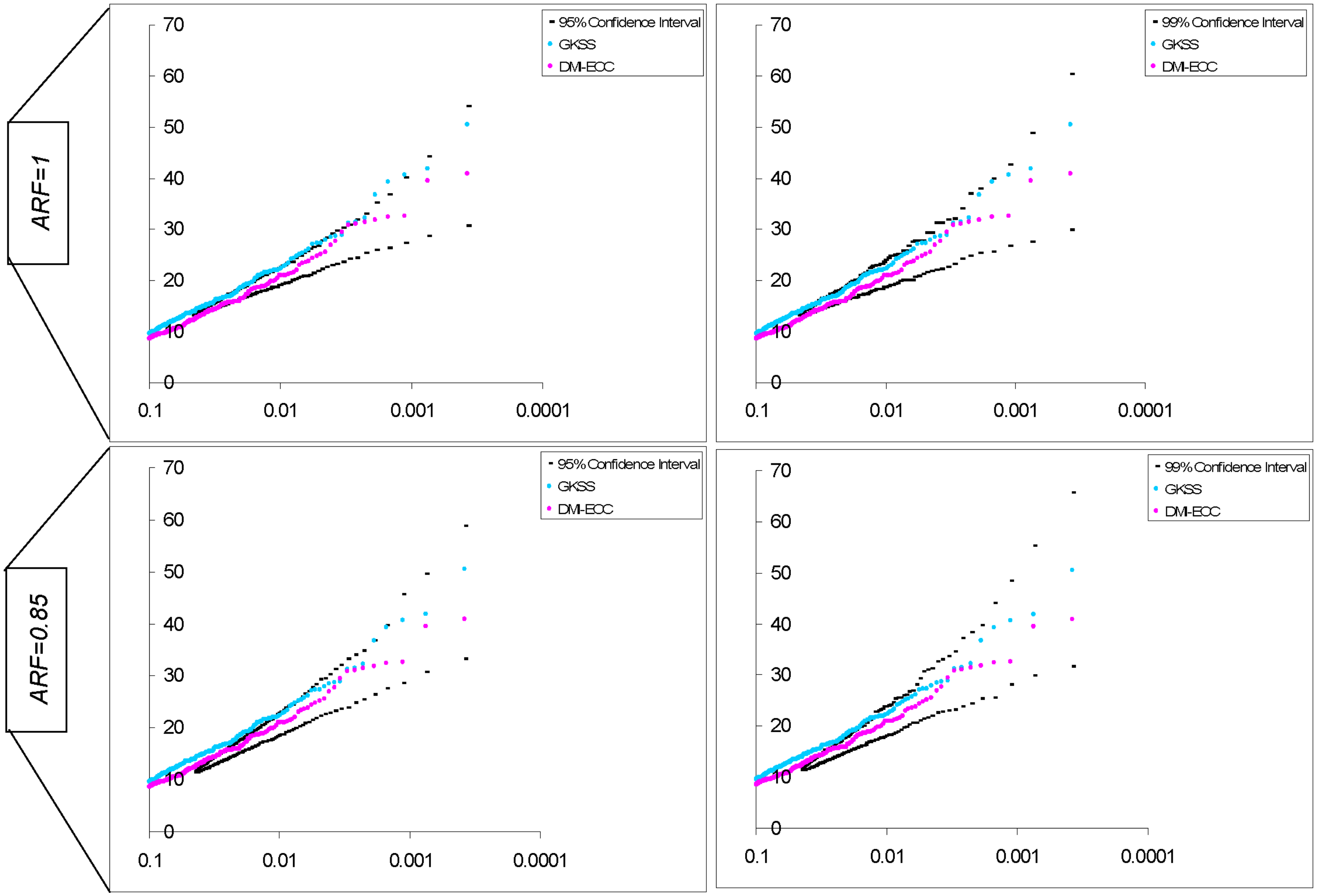


Figure 8.2 Confidence intervals on Uccle daily precipitation quantiles after MC runs for different ARFs, and comparison with the DMI-ECC and GKSS control runs.

The new scenarios are presented and compared to the old ones in the table 8.3 below.

The results show that for the daily data, the calculated percentage sensitivity, which is the difference between the new factors and the old factors reported to the old ones, (equation (8.4) below) is small around the low and mean scenarios, in opposite it grows around the high scenario (~12% in winter precipitation) (Table 8.3). When we go towards higher time scales, the sensitivity grows around the low precipitation scenario (~16% for the low scenario for monthly data) (Table 8.5).

$$S = \left| \frac{F_{Newscenario} - F_{Oldscenario}}{F_{Oldscenario}} \right| \% \qquad (8.4)$$

where S refers to the percentage sensitivity of the perturbation factor and $F_{New\ scenario}$ presents the perturbation factors generated statistically after Monte Carlo simulations for the variable of precipitation. $F_{Old\ scenario}$ are the perturbation factors empirically generated previously in this study for the same variable (see chapter 5, section 5.6.1).

The same analysis has been made for the weekly and monthly time scales and the results are shown in tables 8.4, 8.5 below

It is thus possible to create envelope curves around each scenario for the winter and summer precipitation presenting the range of uncertainty around the old scenarios (degree of sensitivity for the low, mean and high factors). Figures 8.3 and 8.4 present respectively the scenario envelope curves for winter and summer precipitations.

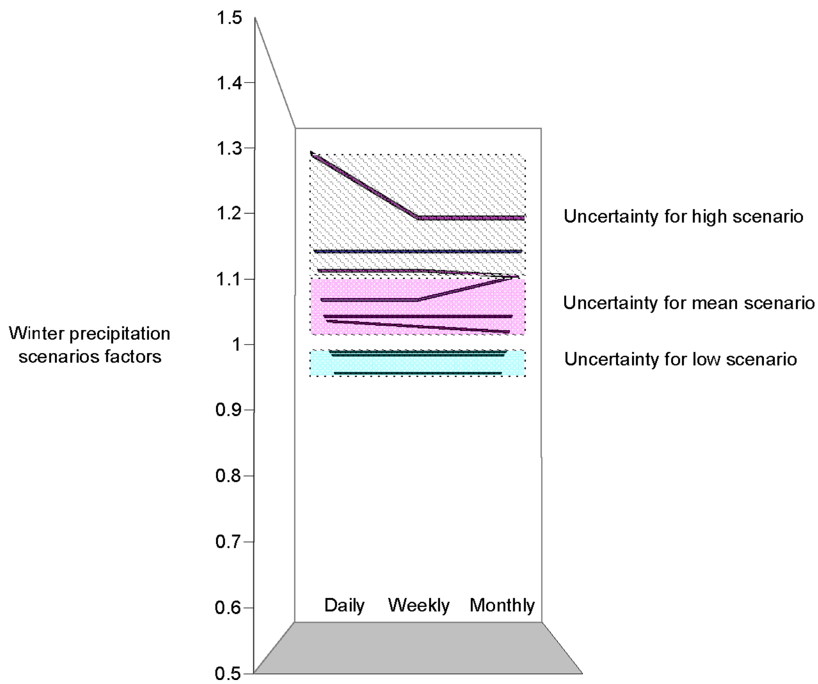


Figure 8.3 Range of variation of the high, mean and low scenarios for winter precipitation after MC runs reflecting sampling uncertainty and sensitivity of the ARF value.

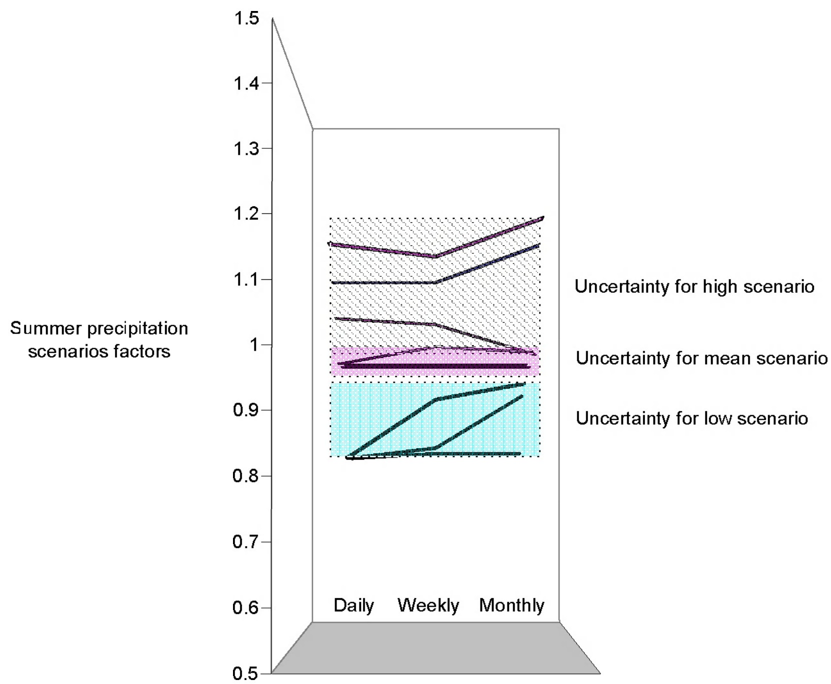


Figure 8.4 Range of variation of the high, mean and low scenarios for summer precipitation after MC runs reflecting sampling uncertainty and sensitivity of the ARF value.

The percentage of sensitivity is then transferred to the hydrological model for daily data and is applied to the Dender basin in a tentative of assessing the sensitivity of the hydrological impact including flood maps. Only the high scenario percentage was chosen to be applied as it shows the biggest range of variation and would present the highest flood risk. Figure 8.5 shows the Q-Q plot for the VHA zone 410 of the Dender basin where the blue area present a quantification of the range of variation of runoff peaks for the high climate scenario. Note that the variation grows with the return period. Hydrological model evaluation shows that 12% percentage variation in the daily winter precipitation factor (for the high climate change scenario) results to an average of 50% variation in the hourly runoff peak flows (width of the blue area in Figure 8.5) for the range of extremes (events with return period higher than 0.1 year). Clearly, the hydrological model is very sensitive to variations in climate scenarios.

Similar to the previous procedure, the upper and lower boundaries of the variation zone of the runoff peaks (for the high scenarios) (blue zone in figure 8.5) served to calculate factors to perturb the composite hydrographs for producing flood maps. Table 8.6 presents these new factors for both upper and lower limits of the uncertainty zone.

VHA zones	**400**	**401**	**410**	**411**	**420**	**421**	**422**	**423**	**430**	**431**
Upper limit factor	44.42	43.37	53.39	50.28	46.38	60.60	63.48	59.98	50.34	62.55
Lower limit factor	14.56	14.24	15.22	14.8	14.24	23.82	21.38	14.68	15.69	18.00

Table 8.6 Uncertainty around the composite hydrograph factors corresponding to the variation of runoff peaks in the Dender basin.

DAILY DATA	80% confidence interval			85% confidence interval			90% confidence interval			95% confidence interval			99% confidence interval		
Scenario	**Low**	**Mean**	**High**	**Low**	**Mean**	**High**	**Low**	**Mean**	**High**	**Low**	**Mean**	**High**	**Low**	**Mean**	**High**
NEW Winter daily precipitation (ARF =1)	1.03	1.10	1.30	1.03	1.10	1.30	1.03	1.10	1.30	1.03	1.10	1.30	1.03	1.09	1.30
NEW Summer daily precipitation (ARF =1)	0.83	0.99	1.16	0.83	0.99	1.16	0.83	0.99	1.16	0.83	0.99	1.16	0.83	0.99	1.16
NEW Winter daily precipitation (ARF =0.85)	1.03	1.08	1.14	1.03	1.08	1.14	1.03	1.08	1.14	1.03	1.08	1.14	1.03	1.08	1.14
NEW Summer daily precipitation (ARF =0.85)	0.95	1.00	1.06	0.83	0.95	1.06	0.83	0.96	1.06	0.83	0.96	1.06	0.83	0.97	1.10
OLD Winter daily precipitation	1.00	1.08	1.16	1.00	1.08	1.16	1.00	1.08	1.16	1.00	1.08	1.16	1.00	1.08	1.16
OLD Summer daily precipitation	0.83	0.99	1.11	0.83	0.99	1.11	0.83	0.99	1.11	0.83	0.99	1.11	0.83	0.99	1.11
***S* (%) for ARF =1 (Winter)**	3	1.85	12	3	1.85	12	3	1.85	12	3	1.85	12	3	0.92	12
***S* (%) for ARF =1 (Summer)**	0	0	4.5	0	0	4.5	0	0	4.5	0	0	4.5	0	0	4.5

Table 8.3 Percentage sensitivity for the precipitation perturbation factors for different ARFs & different confidence intervals (Daily data).

WEEKLY DATA	80% confidence interval			85% confidence interval			90% confidence interval			95% confidence interval			99% confidence interval		
Scenario	**Low**	**Mean**	**High**	**Low**	**Mean**	**High**	**Low**	**Mean**	**High**	**Low**	**Mean**	**High**	**Low**	**Mean**	**High**
NEW Winter daily precipitation (ARF =1)	1.03	1.10	1.20	1.03	1.10	1.20	1.03	1.10	1.20	1.03	1.10	1.20	1.03	1.09	1.20
NEW Summer daily precipitation (ARF =1)	0.87	0.99	1.11	0.87	0.99	1.11	0.87	1.02	1.12	0.87	1.02	1.12	0.87	1.02	1.12
NEW Winter daily precipitation (ARF =0.85)	1.03	1.07	1.14	1.03	1.07	1.14	1.03	1.07	1.14	1.03	1.07	1.14	1.03	1.07	1.16
NEW Summer daily precipitation (ARF =0.85)	0.94	0.99	1.05	0.94	0.99	1.05	0.92	0.98	1.05	0.81	0.96	1.05	0.81	0.96	1.05
OLD Winter daily precipitation	1.00	1.07	1.14	1.00	1.07	1.14	1.00	1.07	1.14	1.00	1.07	1.14	1.00	1.07	1.14
OLD Summer daily precipitation	0.85	0.98	1.09	0.85	0.98	1.09	0.85	0.98	1.09	0.85	0.98	1.09	0.85	0.98	1.09
***S* (%) for ARF =1 (Winter)**	3	3	5.26	3	3	5.26	3	3	5.26	3	3	5.26	3	2	5.26
***S* (%) for ARF =1 (Summer)**	2.5	1	2	2.5	1	2	2.5	4	3	2.5	4	3	2.5	4	3

Table 8.4 New Percentage sensitivity for the precipitation perturbation factors for different ARFs & different confidence intervals (Weekly data).

MONTHLY DATA	80% confidence interval			85% confidence interval			90% confidence interval			95% confidence interval			99% confidence interval		
Scenario	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
NEW Winter daily precipitation (ARF =1)	1.03	1.14	1.23	1.03	1.14	1.23	1.03	1.14	1.23	1.03	1.14	1.23	1.00	1.10	1.23
NEW Summer daily precipitation (ARF =1)	0.84	0.99	1.20	0.84	0.99	1.20	0.84	0.99	1.20	0.84	0.99	1.20	0.84	0.99	1.20
NEW Winter daily precipitation (ARF =0.85)	1.00	1.06	1.13	1.00	1.06	1.13	1.00	1.06	1.13	1.00	1.09	1.13	1.00	1.09	1.13
NEW Summer daily precipitation (ARF =0.85)	0.95	0.97	1.00	0.95	0.97	1.00	0.95	0.97	1.00	0.93	1.01	1.20	0.93	1.01	1.20
OLD Winter daily precipitation	1.00	1.09	1.17	1.00	1.09	1.17	1.00	1.09	1.17	1.00	1.09	1.17	1.00	1.09	1.17
OLD Summer daily precipitation	1.00	1.09	1.17	1.00	1.09	1.17	1.00	1.09	1.17	1.00	1.09	1.17	1.00	1.09	1.17
S (%) for ARF =1 (Winter)	3	5	5	3	5	5	3	5	5	3	5	5	0	1	5
S (%) for ARF =1 (Summer)	16	10	3	16	10	3	16	10	3	16	10	3	16	10	3

Table 8.5 Percentage sensitivity for the precipitation perturbation factors for different ARFs & different confidence intervals (Monthly data).

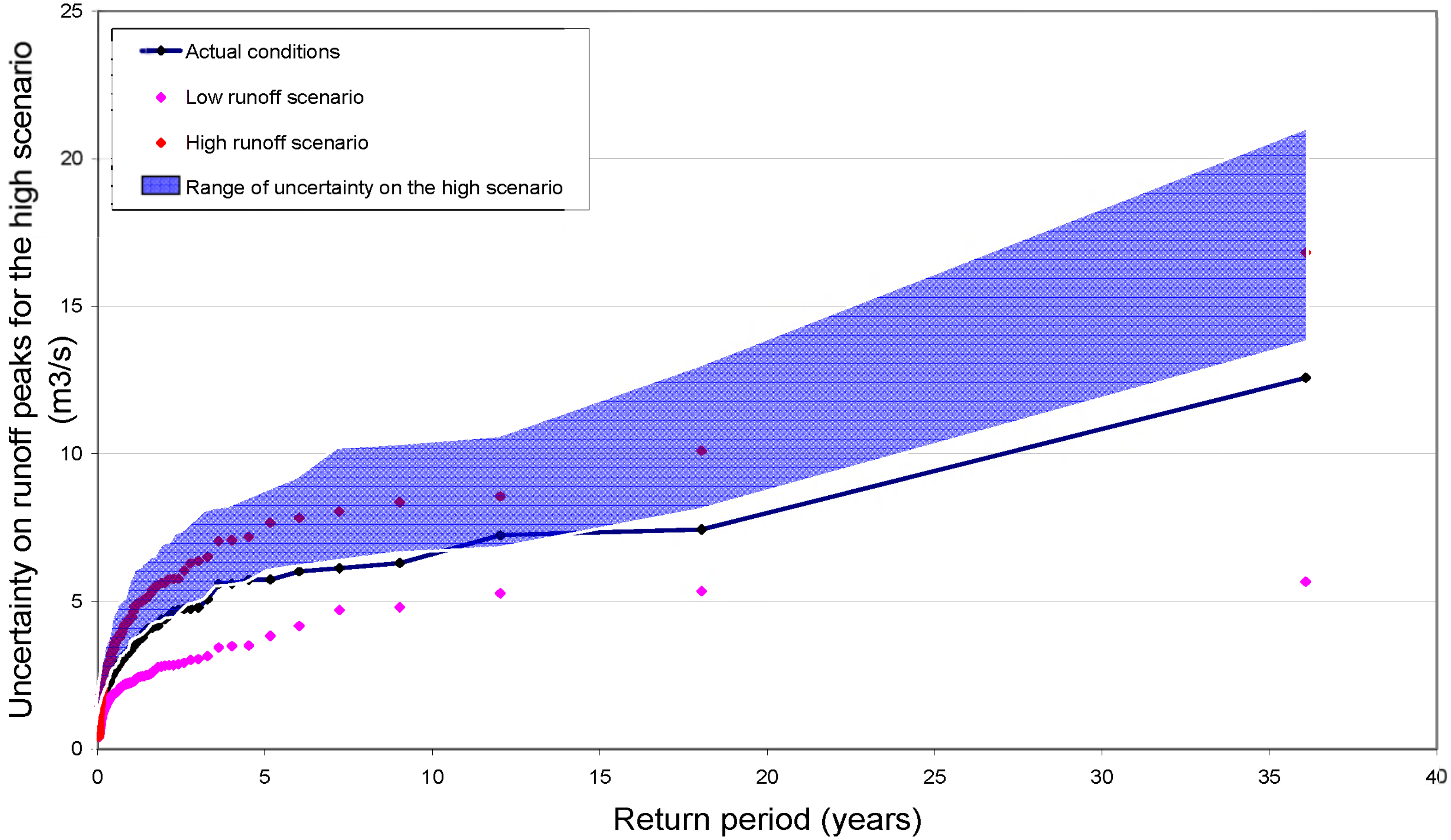


Figure 8.5 Q-Q plot for the VHA zone 410 of the Dender basin showing the range of variation of the high climate scenario.

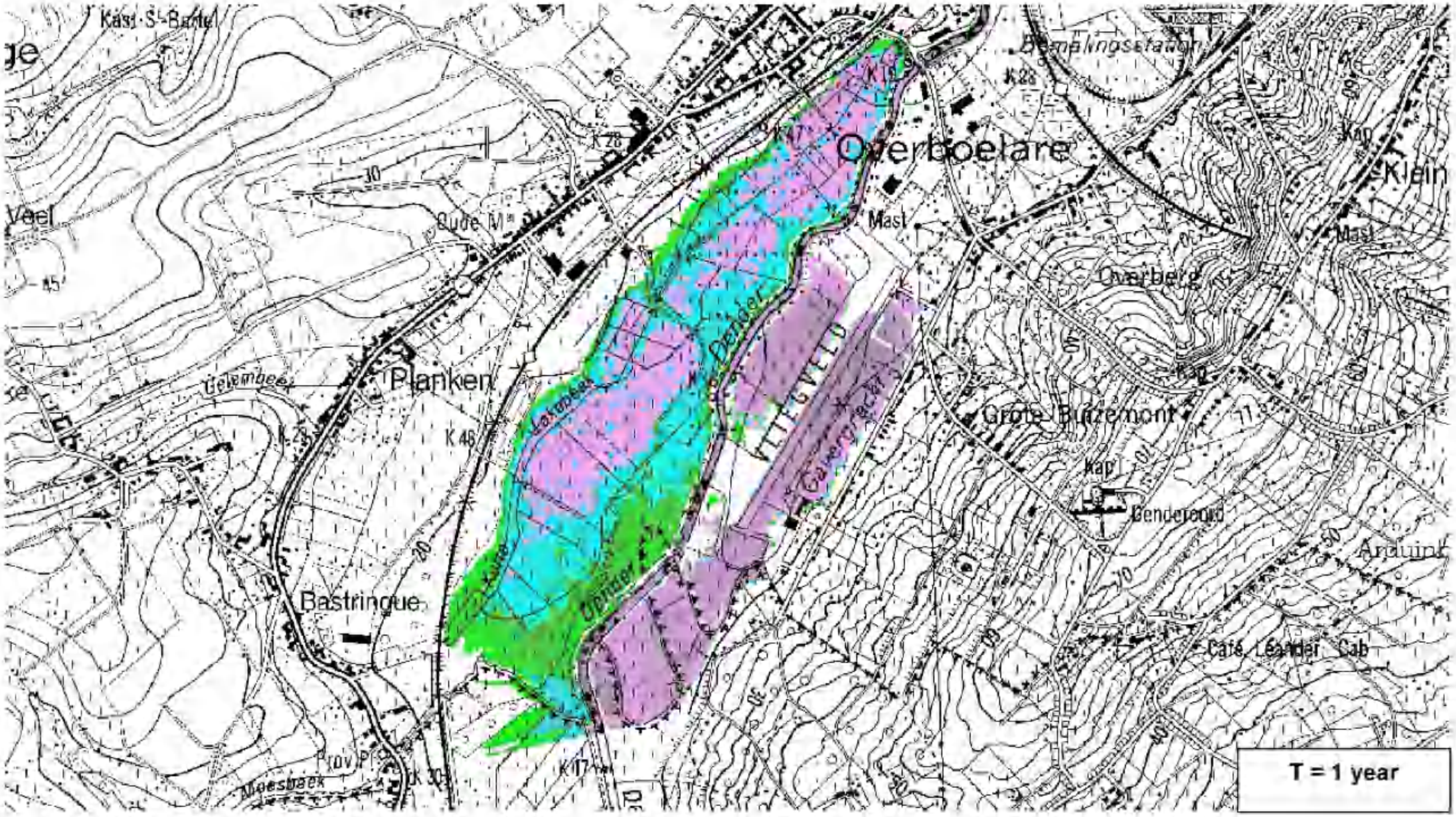


Figure 8.6 Extension of the flooded area due to variations in high scenario for the Dender basin (Overboelare region; T=1year).

Original high scenario.

Upper variation limit for high scenario.

Lower variation limit for high scenario.

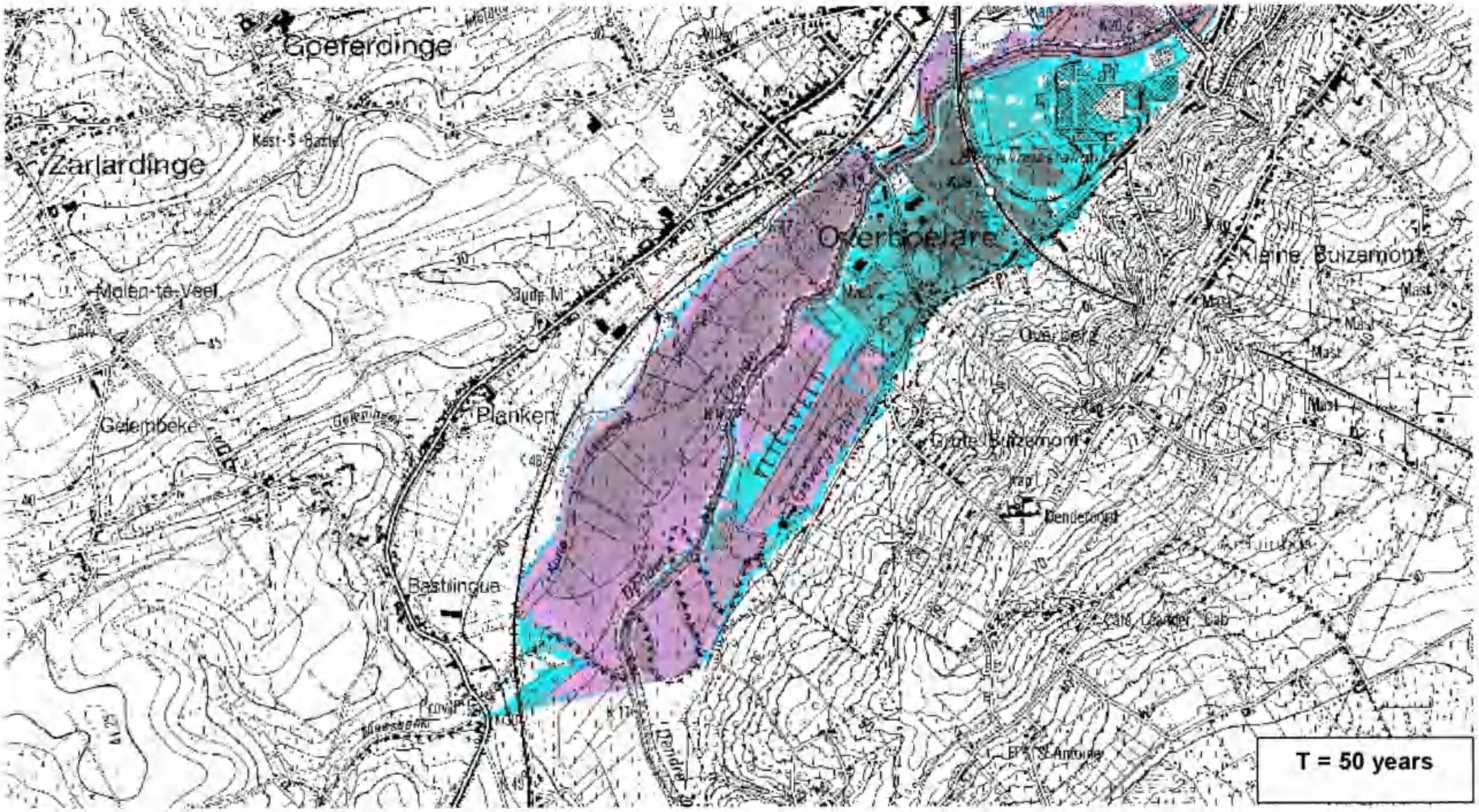


Figure 8.7 Extension of the flooded area due to variations in high scenario for the Dender basin (Overboelare region; T=50 years).

Original high scenario.

Upper variation limit for high scenario.

Lower variation limit for high scenario.

The figures 8.6 and 8.7 show respectively the extension of the flooded area for the Dender basin due to the range of variation of the high scenario for return periods of 1 and 50 years. The flood extent varies largely depending on the coefficient of sensitivity showing that the uncertainty of the hydrological model results strongly depends on climate input data brought through the generated climate change scenarios.

For T = 1 year, the difference of variation of the flooded area is rather high emphasizing once again the importance of prediction uncertainty and the extension of damage that might be caused. As for T = 50 years, this difference is less significant, because once the floodplains are filled with water, the variation of flooded areas will decrease.

8.4 Conclusion: Sensitivity analysis

"If we had perfect climate change evolution predictions, we could predict their impact on our environment". This kind of statement is actually the key driver for several climate change impact studies on hydrology and on other environmental fields. This returns to the fact that the ultimate factor in such studies is our ability to precisely predict the future climate.

The results of this chapter confirm the statement above. Indeed uncertainties are unavoidable in scientific researches. Moreover in climate change impact studies where uncertainties come in various forms (data uncertainty, parameter uncertainty, model uncertainty, emission uncertainty…etc). In most of these studies it is clear that, while the sign of the impact is often clear, there remains less knowledge about the size of the impact; the size can cover a range of possible magnitudes.

Focusing only on the generated climate scenarios, in chapter 5 it was shown that different RCMs and different emission scenarios produce highly different climate change (reflected by the range from high to mean to low scenarios). In this chapter, investigation was made for the additional variation due to random sampling or variation in the selection of ARFs when acceptance of RCM based climate change scenarios is based on the consistency check with historical meteo-station data (daily Uccle rainfall intensity in this case). The results show that generated climate scenarios and the hydrological impacts are sensitive to the variations considered.

The results show that a percentage sensitivity of 12% in the daily high scenario perturbation factor for precipitation result in 50% variations in hourly runoff peaks for the range of extreme events (events with return periods higher than 0.1 year) and therefore large variations in the possible flooded areas.

This enhanced the hypothesis that we could predict the hydrological evolution if the climate models would do a better job in terms of modelling future climate and in terms of taking into account all the possible changes that might happen upon the physical processes. Reporting and communicating the range of variations, uncertainties in the climate change scenarios and hydrological impact result, therefore should be seen as an important aspect of the analysis.

Chapter 9

Conclusions

9.1 Recapitulation

This study addresses climate change impact assessment on the hydrological extremes in Flanders. It aims to ensure that the needs of the Flemish climate impacts community for scenarios of hydrological extremes as floods and low flows along rivers are taken into account and that outputs from the most recent climate model simulations are available for use.

The scientific evidences regarding climate change are now overwhelming, the changes are already occurring, a fact that leaves small rooms for doubting this issue. The IPCC mentioned with high confidence, in the Fourth Assessment report, that warming observed during the last 50 years is attributable to human activities.

Moreover, changes in the frequency and intensity of extreme events are surely having more impacts on environment and human activities than changes in the mean climate. Losses of life and very high economic damages have been experienced during recent flooding events in the last decade in Belgium. A vital question for Belgium is, therefore, whether such events will occur stronger and more frequently in the future.

Modelling science offered scientists with the best tool for understanding climate and predict its future variations through the General/Global Circulation Models (GCMs). Unlikely, GCMs spatial and temporal resolutions make the barrier to use their results into specific applications as in hydrology where fine resolutions are needed. Hence, several developments have been made in this issue while producing high resolute regional climate models (RCMs).

The European project PRUDENCE provided the best option with 24 climate simulations highly resolute produced with different time scales, including estimates of precipitation and potential evapo(transpi)ration till 2100 and covering the studied area, but mainly focusing on the A2 emission scenario. PRUDENCE was chosen to be the climate support data for this study.

Transferring the climate change signal to the hydrological field requires downscaling techniques. This study identified a robust downscaling technique; the frequency perturbation approach, as being a combination of dynamical and statistical techniques and applied it to regional historical data to provide reliable and plausible future scenarios of precipitation and potential evapo(transpi)ration for Flanders. The developed future climate scenarios take into account changes in the extremes intensities together with changes in extremes frequencies. These scenarios consist of sequences of low, mean and high factors, accounting for the uncertainty in the climate model results.

The results show that scenarios differ from winter condition to summer condition and are time scale dependent. But mostly, scenarios differ depending on variable frequencies and affect as well the number of extreme events, which are for the summer season highly different from the frequency or rainfall intensity class.

A methodology for assessing climate change impacts on hydrological extremes in Flanders has been therefore set and applied to high and low flow river discharges along the sub-catchments and rivers of the Scheldt River Basin District.

The hydrological and hydraulic simulations show that water balance variations are very sensitive depending on the balance between the summer perturbation effect (less rainfall) versus the winter perturbation effect (more rainfall), and on the balance between the rainfall perturbation effect versus the evapo(transpi)ration perturbation effect.

The high flow peaks and flood risk have potential tendency to increase up to 35%, or decrease to -70% depending on the scenario while low flows show systematical reduction, indicating that low flow problems become more severe in the future and are probably more important than the increase in flood risk.

The other important results consist in the regional differences, where it was clearly shown that climate change does not impact lonely, but in combination with the local conditions (up to some extents), while natural variability and models uncertainty still count considerably.

Furthermore, the sensitivity in the hydrological impact results was shown for a number of uncertainty sources leading to uncertainties in the climate change scenarios for rainfall and potential evapo(transpi)ration.

The results of this study come to confirm those of several other studies regarding the impacts of climate change on hydrology. However, due to high uncertainties, taking actions against climate change would be early until more scientific issues are known. Taking potential climate change into account for future hydrological studies is important rather than focusing on the guarantee that climate change will cause more floods.

This study made clear that climate change impact assessment is an extremely complex issue, hence, encouraging more research on this topic in order to increase awareness and to help improve further investigations and predictions is very important.

9.2 Own contributions

Several original contributions to climate change impact assessment studies have been emphasized throughout this thesis. They are cited as follows:

- This thesis brought and joined together knowledge from several scientific fields: climate modelling science, hydrological/hydrodynamic modelling science, topographic information systems modelling science and risk analysis modelling;
- In this thesis, we assured the statistical analysis of results processed (by RMI) from a large climate database for Belgium (in small scales), a processing that has been based on the PRUDENCE results;
- An efficient downscaling method has been developed through the combined dynamical-statistical downscaling method based on perturbations which count for changes in rainfall intensity and frequency in a combined way;
- Climate change scenarios for the variables of precipitation and potential evapo(transpi)ration have been generated for Belgium;
- A methodology has been set up for assessment of climate change impact on hydrology that has been implemented and applied already by end-users;
- Climate change regional impact analysis on hydrology has been done for the entire Flanders area of Belgium of the Scheldt River Basin District;
- A sensitivity analysis has been performed to quantify the hydrological results sensitivity related to the selection of climate change scenarios.

9.3 Further research

Climate change impact on the hydrological extremes in Flanders is still in its early stages. Additional researches are needed to reach a high understanding level of the processes laying behind the changes in frequencies and intensities of extreme events due to climate change and the local conditions. In the following lines, some analysis points are described for further research:

- Following and using the latest developments and results in respect to regional climate models which are continuously improving in spatial and temporal resolutions for the better benefits of hydrological impact simulations;
- Simulating a wider range of emission scenarios (e.g., A1, A1B, B1…scenarios of IPCC);
- Inter-comparison of improved statistical, dynamical and statistical-dynamical downscaling methods using long term data and identification of the more robust ones. In this respect methods based on probabilistic weather generators, multiple regression, neural networks...etc, should be taken into account;
- Incorporation of additional predictor variables (e.g., humidity, low-level thermal advection) in order to address the problem of stationarity (e.g., the underlying assumption of statistical downscaling that observed climate relationships remain valid under changed climate);
- This would lead to a reconstruction of scenarios of extremes for selected regions;

- Analyzing the recent historical trends in extremes and their causes and impacts, over a wide variety of regions, not only in rainfall but also in river flow, where also other non-climate related factors play a role, as land use change and trends in water management;

- Comparing Flanders results with those of specific European regions with similar local conditions using the same GCMs/RCMs and same emission scenarios;

- Use of distributed hydrological models where the basin is described in a more detailed spatially-variable way, to investigate whether the use of lumped conceptual or fully distributed and more detailed physically based hydrological models lead to same conclusions. These models also would allow other land-phase related and climate change interrelated physical processes to be taken into account.

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Curriculum Vitae

PRESENT FUNCTION

- **Sep 2005- March 2008**: Scientific researcher at the Civil Engineering Department, Hydraulics Laboratory of the K.U.Leuven, Belgium & the Waterbouwkundig Laboratorium of the Flemish government.
    - Methodology for climate change impact analysis on hydrological extremes. Research project for the Waterbouwkundig Laboratorium of the Flemish government, 2005-2006. (http://www.kuleuven.be/hydr/CCI-HYDR.htm)
    - Climate change impact on hydrological extremes along rivers and urban drainage systems: Research project for the Belgian Federal Office for Scientific Research (BelSPO) - Research program Science for a Sustainable Development (SSD), 2006-2009. (http://www.kuleuven.be/hydr/CCI-HYDR.htm)
    - Climate change impact calculation on hydrological extremes in Flanders, flood and flood risk assessment, and analysis of regional differences. Research project for the Waterbouwkundig Laboratorium of the Flemish government, 2007-2008.

EDUCATION

- **Jan 2003**: **PhD** study at the civil engineering department of **Laval University, Quebec, Canada**. "Flow balance modelling analysis in different scales, modelling using the genetic programming technique, global change and water resources use";
- **2002-2003**: Master project at the civil engineering department of **the University of Louisiana at Lafayette (ULL), USA**. Project title: "**Developing a Comprehensive Flood Management Hydrologic Computer Model**". It is a project collaboration between the Swiss Federal Institute of Technology of Lausanne & Zurich (**EPFL, ETHZ, Swiss)** and the University of Louisiana at Lafayette **(ULL)**;
- **2001-2003**: **Master** in hydrology, hydrogeology and water resources management at **the Swiss Federal Institute of Technology of Lausanne, Zurich - Switzerland. EPFL, HYDRAM; ETHZ**: hydrology, hydrogeology and water resources management;
- **1997-2000**: Engineering studies at **the National Agronomic Institute of Tunisia (NAIT)**, Rural Engineering Department for Water and Forestry. Award: **Principal engineer** (Engineering Diploma) speciality: Rural Engineering Water and Forestry; option: Rural Infrastructures and Buildings;
- **1995-1997**: Preparatory Biology cycle at (**NAIT**). Award: Second best score at the national Tunisian scale. Admitted at the "National exam of access to the Engineering studies";
- **1995**: Bachelor of sciences.
- **April 2007:** International conference within ESPACE project: **European Spatial Planning: Adapting to Climate Events**. Conference title: "Planning system in Germany and adaptation to climate change, what more can be done". Tutzing, Munich, April 18th, 2007.
- **Dec 2006:** Visit to Qatar University, Department of Humanities, College of Arts and Sciences. International seminars on climate change and climate change impact estimations. "Current conditions and future risks of the Qatar area".
- **July 2006:** International conference participation. International conference on climate and water issues and appropriate adaptation strategies at EU level to be held during the German EU Presidency in February 2007. Title: "**Impacts of climate change on water resources and adaptation strategies in Europe"**;

- **May 2006: International Seminar: CIWEM (**The Chartered Institution of Water and Environmental Management) annual seminar titled: Climate Change Current Risks-Future Actions". Swindon, UK. Participation of several research & consulting agencies (e.g. ATKINS, ABE engineering, Thames Water, HR Wallingford, Hal crow, Environment Agency...);

Projects in the past 5 years

- Climate change impact calculation on hydrological extremes in Flanders, risk & economical damage assessment. Research project for the Waterbouwkundig Laboratorium of the Flemish government (& the Hydraulics Laboratory of the K.U. Leuven), 2007-2008.
- Climate change impact on hydrological extremes along rivers and urban drainage systems: Research project for the Belgian Federal Office for Scientific Research (BSLPO) - Research program Science for a Sustainable Development (SSD), 2006 – 2009, (http://www.kuleuven.be/hydr/CCI-HYDR.htm).
- Methodology for climate change impact analysis on hydrological extremes (AWZ – WL Borgerhout , Flemish Water Authority, Belgium), 2005-2006.
- Flow balance modelling analysis in different scales, modelling using the genetic programming technique, global change and water resources use (Laval, Quebec), 2003.
- Stochastic Modelling - Hydrologic Forecasting and Flood Risk, Zurich, 2002.
- Climatology - Hydrometeorology and Large Scale Hydrology, Zurich, 2002.
- Developing a Comprehensive Flood Management Hydrologic Computer Model (Louisiana, USA), 2002.
- Dams structures, automatic structural calculation of sustaining walls, Tunisia Concept, 2000.

PUBLICATIONS

- Boukhris O., Willems P., Baguis P., Roulin E. 2008. Rainfall and evapotranspiration climate change scenarios for impact analysis on hydrological extremes in Belgium. International conference on "Water resource systems management under extreme conditions", Moscow, 4-5 June, 2008. Published in conference proceedings.
- Boukhris O., Willems P. 2008. Climate change impact on the hydrology in highly urbanized Belgian areas. International conference on "Urban water", Leuven, 15- 19 September 2008. Accepted for publication in proceedings.
- Boukhris O., Willems P., Baguis P., Roulin E. 2008. Climate change impact on hydrological extremes along rivers in Belgium. International conference on "Floodrisk 2008", London, 30 September-2 October 2008. Accepted for publication in proceedings.
- Willems P., O. Boukhris, J. Berlamont, K. Van Eerdenbrugh, P. Viaene, J. Blanckaert (2007), 'Impact van klimaatverandering op Vlaamse rivieren', Het Ingenieursblad, 29, januari 2007, 28-33 + uitgebreid artikel in pdf formaat op www.hetingenieursblad.be, 8 p. (www.kviv.be/hetingenieursblad/images/07-1%20Klimaatverandering%20-%20lange%20versie.pdf).
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- Willems P., Boukhris O. (2007), 'Climate change impact on hydrological extremes along rivers in Belgium', EGU General Assembly 2007, Vienna, 15-20 April 2007, EGU2007 Session HS41: 'Statistical concepts in understanding and modelling hydro-climatic change'.
- Willems P., Boukhris O. (2007), 'Climate change impact on hydrological extremes along rivers in Belgium', Conference 'Variations climatiques et hydrologie', Lyon, 27-28 maart 2007, Congrès de la Société Hydrotechnique de France / 29e Journées de l'hydraulique.
- O.Boukhris, P.Willems & J.Berlamont (2006), "Opstellen van een methode voor het inrekenen van de klimaatsverandering in de composiethydrogrammethode - Algemeen rapport", rapport MOD 706/10-1 Waterbouwkundig Laboratorium Vlaamse Overheid, december 2006, 74 p. (watlab.lin.vlaanderen.be/ned/documentatie/2006.htm).
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