Effect of climate change on the hydrological regime of navigable water courses

SUBREPORT 1 - LITERATURE REVIEW OF THE CLIMATE RESEARCH IN BELGIUM
Effect of climate change on the hydrological regime of navigable water courses

Subreport 1 - Literature review of the climate research in Belgium

Vansteenkiste, T.; Pereira, F.; Willems, P.; Vanneuville, W.; Van Eerdenbrugh, K.; Mostaert, F.

September 2011

WL2011R706_18_rev2_0
Deze publicatie dient als volgt geciteerd te worden:

Abstract

Over the past decennia many studies on the impacts of climate change on water resources have been carried out for the Belgian territory. This inventory attempts to provide a summarized literature review of these studies and tries to find an answer to the question what role hydrological models have in climate change impact modelling. Many different hydrological models have been developed with different characteristics and purposes. For Belgium, conceptual rainfall-runoff models like NAM and PDM are commonly used due to their significant advantages regarding parameter estimation and computational time, when compared to physically based models. Physically based, distributed models require a large amount of high quality spatially-explicit input data. They are often difficult to parameterise and have extended simulation times. Only a limited number of studies with these models are known for Belgian catchments. Intermediate physical-conceptual models also exist and have some applications in Belgium (e.g. WetSpa, SWAT). Investigation of the model performance showed that all hydrological model types are able to simulate the overall hydrological regime for Belgian catchments in an acceptable way.

The 3 different types of hydrological models have been used recently to simulate the climate scenarios for Belgium and to assess the impact on hydrological extremes. All models simulate similar trends in the future flow extremes: higher as well as lower winter discharges can be expected for future winter periods; while summer discharges are expected to decrease (and will continue to decrease till 2100) due to climate change. When comparing the high and low flow changes between the models major differences were found for low flow minima, while the differences in high flow changes were rather limited. One reason is that precipitation is the dominant factor in high flow estimation, while for low flow modeling the model structure plays a more important role. The physically based MIKE SHE model envisages a considerable smaller decrease of the low flows than other models (HBV, NAM, WetSpa). This difference might be a consequence of the higher physical detail of the MIKE SHE model, which has a mechanism that more realistically accounts for groundwater flow. Simplifying the representation of the groundwater system by the (semi-)conceptual models might lead to discrepancies in the climate projections.
However, it is not clear if the more complex and detailed models will lead to better hydrological predictions. In spite of the uncertainties among the applied models, the results indicate a wide range of changes in the discharge regime by 2100. The results should therefore be interpreted as trends and not as an accurate quantitative prediction of hydrological changes.

In climate research in neighbouring countries, the importance of considering the uncertainties related to the hydrological model has been reported. While uncertainty due to climate modelling and scenarios has been well documented, little research has been conducted on the uncertainty in climate change impact assessments due to limitations in impact models.
Table of contents

Table of contents ................................................................. I
List of tables ........................................................................... II
List of figures .......................................................................... III
Introduction ............................................................................. 1
1 Hydrological impact modelling ............................................. 2
   1.1 Review on the classification of hydrological models .......... 2
   1.2 Dynamic modelling .......................................................... 5
   1.3 Hydrological models applied to Belgian catchments ......... 5
      1.3.1 Hydrological models available at Flanders Hydraulics Research .......... 6
      1.3.2 Other hydrological models ................................................. 9
2 Climate change impact research in Belgium ...................... 14
   2.1 CCI-HYDR climate change scenarios ................................. 14
   2.2 Review on the climate change impact methodology .......... 17
   2.3 Review of the climate change impact studies and results ... 18
      2.3.1 Overview of the climate change impact studies ............... 18
      2.3.2 Role of hydrological models in the climate change impact research .......... 24
   2.4 Other climate change studies for Belgium ....................... 26
3 Climate change impact research in neighbouring countries .... 28
   3.1 Hydrological models ......................................................... 28
   3.2 Climate change impact analysis and methodology ........... 32
4 Conclusion .............................................................................. 34
   4.1 Recapitalizations ................................................................. 34
   4.2 Suggestions ......................................................................... 34
Referenties .................................................................................. 36
List of tables

Table 1: Available NAM-models at Flanders Hydraulic Research ............................................................. 6
Table 2: Seasonal correlations and scenario definitions (adopted from Ntegeka et al., 2008) ................. 16
Table 3: Overview of the climate impact research at Flanders Hydraulic Research .............................. 23
Table 4: Averaged variation in nearly independent peak and low flows for the low, mean and high climate scenarios assessed by different hydrological models ......................................................... 24
Table 5: List of hydrological models applied in European basins ........................................................... 28
Table 6: Main characteristics of hydrological models used in neighboring countries (AMICE, 2010) ...... 31
List of figures

Figure 1: Main hydrological model types, (a) empirical models, (b) lumped conceptual models, (c) semi-distributed conceptual models and (d) fully distributed, physically-based models (based on Velner et al., 2008) ................................................................. 4

Figure 2: Comparison of the hydrographs reproduced by SWAT and SWAT–MODFLOW (adopted from Kim et al., 2008) ............................................................................................................................................. 10

Figure 3: Diagram of the SCHEME model with model parameters (adopted from Baguis et al., 2010) .................. 12

Figure 4: Rainfall series perturbations (adopted from Ntegeka et al., 2008) ......................................................... 16

Figure 5: Relevance and interpretation of the CCI-HYDR scenarios (adopted from Ntegeka et al., 2008). ................................................................. 17

Figure 6: Percentage of variation of hourly runoff peaks for the low, mean and high CCI-HYDR climate scenarios (adopted from Boukhris et al., 2008) ................................................................................................ 19

Figure 7: Percentage of variation of hourly low flows for the low, mean and high CCI-HYDR climate scenarios (adopted from Boukhris et al., 2008) .................................................................................................. 20

Figure 8: Nearly independent hourly peak flows versus empirical return period for the low, mean and high climate scenarios simulated in the (a) MIKE SHE and (b) WetSpa models .......................................................... 22

Figure 9: Nearly independent hourly low flows versus empirical return period for the low, mean and high climate scenarios simulated in the (a) MIKE SHE and (b) WetSpa models .............................................................................. 23

Figure 10: Model complexity control for hydrologic prediction (adopted from Shoups et al., 2008) ............. 30

Figure 11: Relative changes in high and low flow quantiles (adopted from Ducharne et al., 2010) ............. 33
Introduction

The global climate is changing. It has changed in the past, is changing presently and will change in the future (IPCC, 2007). Climate change, which is expressed by an increase in global average temperature, is also observed in Belgium (Baguis et al., 2008; Baguis et al., 2009; Ntegeka and Willems, 2008; Ntegeka et al., 2010). Although increases in temperature may be the clearest indicator of the ongoing climate change, changes in the amount and variability of rainfall and evapotranspiration might have the largest impact on hydrological systems. These changing rates of rainfall and evapotranspiration will directly affect the magnitude and timing of run-off and the water availability. It will significantly influence the hydrological (water) cycle. Over the past decennia many studies into the impacts of climate change on water resources have been carried out for the Belgian territory (Bultot et al., 1988; Gellens and Schädler, 1997; Gellens and Roulin, 1998; Boukhris et al., 2008; Ntgeka et al., 2008; Baguis et al., 2009). These studies all have used a common basic methodology to estimate the potential impact of climate change to hydrological systems in Belgium. This standard impact methodology (IPCC, 2007) consists of three steps:

1. development of hydrological models using current climate conditions and observed river flows;
2. adjusting historical series of model input variables to the climate change scenarios;
3. run the model with the current and future climate variables and analyse the impacts by comparing the hydrological model results with the reference period (current conditions).

However, the impact studies have employed different climate scenarios to present the climate change, different hydrological models to simulate the climate scenarios, different impact methodologies to assess the impact,... as a result of which an overload of results is available. This inventory gives insight in the climate impact research for Belgium and tries to find an answer to the question to what kind of hydrological model, with what level of complexity, is most suitable for climate change impact assessment. This report ‘Inventory on the climate impact research for Belgium’ will summarize past researches with special focus on the hydrological modelling and impact results. The report is developed in the framework of the study ‘Effect of climate change on the hydrological regime of navigable water courses’ by the Hydraulics Section of the University of Leuven, VITO and the research group BIOMATH of the University of Gent for Flanders Hydraulics Research in Borgerhout.

The report is organised in 4 chapters. A first chapter deals with the hydrological model codes for impact analysis. A review on the classification of hydrological models is given, followed by the model codes which are commonly applied to Belgian catchments. A second chapter summarizes the climate change impact research in Belgium. First, the climate scenarios and the impact methodology are clarified. Next, the impact studies are highlighted and their impact results examined. In a next chapter a short overview of the climate change impact studies for neighbouring countries is given with focus on the hydrological models and impact results. In conclusion of this report, we bring together and summarize all information of the review. Suggestions are formulated for future climate research for Belgium.
1 Hydrological impact modelling

Hydrological models provide a framework to conceptualise and investigate the relationships between climate and water resources. It is an assemblage of mathematical descriptions of components of the hydrological cycle and they are employed to understand dynamic interactions between climate and land-surface hydrology (Singh and Woolhiser, 2002). All climate change impact studies for Belgium have used these kinds of models to translate the assumed climate changes into hydrological responses. There is a wide variety of hydrological models with different levels of complexities. They can be classified in categories, which are given in section 1.1. However, no model is perfect in characterising the real physical interactions. It is often unclear if the assumptions made by the models are likely to be limiting in terms of what we know about the response of the catchments of interest. This is where the idea of conditioning of models might become very important. Dynamic models are modular modelling tools and allow us to adjust the model structure according the modelling purposes. This dynamic way of modelling is clarified in section 1.2. A final section 1.3 of this chapter summarizes the research among (available) hydrological models at Flanders Hydraulics Research.

1.1 Review on the classification of hydrological models

Hydrological models can be basically classified as either deterministic or stochastic (Chow, 1988; Abbott and Refsgaard, 1996; Beven, 2001). Deterministic models only permit one possible outcome from a simulation with one set of inputs and parameter values, whereas stochastic models allow for an element of randomness in the outcomes due to uncertainties associated with the input and parameter variables. Most hydrological models are deterministic, but some consist of one or more stochastic components (Singh and Woolhiser, 2002).

Within deterministic models, two main approaches to modelling may be adopted, the lumped approach or the distributed approach (Chow, 1988; Abbott and Refsgaard, 1996; Beven, 2001; Breuer et al., 2009). Lumped hydrological models consider the whole system (catchment, sub-catchment, aquifer, etc.) as a single unit and typically represent state variables, such as average storage in the saturated zone, as an average over the entire catchment. A limitation of the lumped approach is that the models are not able to consider the spatial diversity of hydrological processes over large spatial domains, associated with heterogeneity in land cover/use and soil properties, for example. The parameters used in the lumped models represent spatially averaged characteristics of the hydrological system and are often unable to be directly compared with field measurements. In contrast, distributed hydrological models typically incorporate spatial variable datasets (e.g. land use, land and soil characteristics). They are able to represent spatial heterogeneity of catchments and to generate outputs at interior locations (Singh and Woolhiser, 2002), which allow them to provide a more representative description of catchment-scale processes than lumped models (Abbott and Refsgaard, 1996). However, despite their extended capacities, these models feature a range of complexities. Calibrating of such a distributed model is challenging so much so that a less powerful lumped model is often preferred (Singh and Woolhiser, 2002).

Distributed models typically discretize the catchment into sub-units (e.g. grid cells). Fully-distributed models divide the catchment into a uniform grid and are the most complex. However, less complicated models which do not consider every individual point separately also exist. These simplified or semi-distributed models offer an intermediate way between lumped and fully distributed models. This separate strand of models attempts to maintain a distributed description of catchment responses but which does in a much simpler way. This type of models defines its spatial resolution based on a distribution of functional hydrological responses in the catchment. In these models the distribution function component is an attempt to make allowance for the fact that not all of the catchment can be expected to respond in an exact similar way. Points in the catchment need to be classified in terms of their hydrological similarity. Different approaches exist that have been used in attempting to use such a distribution of different responses in the catchment to model rainfall-runoff processes (Beven, 2001):
The first is a statistical approach, based on the idea that the range of responses in a catchment area can be represented as a probability distribution of conceptual stores without any explicit consideration of the physical characteristics that control the distribution of responses. This is a purely statistical and does not require any formal definition of similarity for different points in the catchment. An example is PDM.

A second type of distribution function model that attempts to define similarity more explicitly is that based on the idea of hydrological response units or HRUs. These are parcels of the landscape differentiated by overlaying maps of different characteristics, such as slope, soil, vegetation,… Models of this type differ in the type of conceptualization used for each HRU. An example is SWAT in which HRUs are formed by areas that shares soil type and land use.

The third approach to be described is based on an attempt to define the hydrological similarity of different points in a catchment based on simple theories. TOPMODEL is an example using topography and soils information for the definition of the hydrological identical cells.

One of the advantages of this distribution function approach is that some important nonlinearities of the runoff generation process can be reflected in the distribution function but without introducing the large numbers of parameters values needed for fully distributed models (Beven, 2001). This will make model calibration much easier.

Next to the spatial variation, the hydrological models are often classified according their representation of catchment water processes. Empirical or black box models use simple empirical equations such as linear regression equations (response function models) between input and output variables. They are developed using the measured time series instead of utilising mathematical expression describing the physical processes. They do not explicitly take into account physical processes. Several types of empirical models are observed (Govindaraju and Rao, 2000):

- models using statistical methods such as ARIMA (Autoregressive Integrated Moving Average);
- models based on the unit hydrograph (or applying its principles);
- models using data-driven methods such as artificial neural networks, model trees, nearest neighbour, evolutionary algorithms,…

An alternative to these empirical models are the conceptual models. These models describe the transformation of rainfall to runoff by means of rather simple concepts and parameters that need to be calibrated (Chow, 1988; Abbott and Refsgaard, 1996; Beven, 2001). The equations used are semi-empirical, but still with a physical basis. The structure of conceptual models is often based on several but interrelated storages representing physical elements in the catchment. The different reservoirs are linked to each other by these semi-empirical laws (Varado et al., 2005). The mode of operation may be characterized as a system that is continuously accounting for the moisture contents in the storages.

Conceptual models usually treat the entire catchment or subcatchment as one unit (spatially lumped); although they can be also partially distributed (semi-distributed) in case the models are related and form a collection of units. The main data to run conceptual models are the precipitation and potential evapotranspiration. The advantage of these models is that the parameterization of the models is simple and computation is efficient. Parameters of such models are defined at catchment scale by calibration but are not easily linked to measured physical properties. Therefore the predictive power of these models is questionable in case of climate or catchment changes (Varado et al., 2005). Nevertheless these kinds of models have been widely used to model hydrological processes in climate and meteorological impact studies. Other disadvantage is that these models cannot be easily applied on ungauged catchments. They are generally valuable and employed for operational water management such as flood forecasting or dam management (Varado et al. 2005). IHACRES, NAM, PDM are lumped examples; CLASSIC, SWAT are semi-distributed modelcodes.

A third manner to represent the catchment water processes is given by the physically-based models. Contrary to the empirical and conceptual models, these models use theoretical concepts in terms of sets of complex differential equations derived from fundamental physics and usually represent the characteristics in a catchment in a spatially-explicit way. The individual components of the hydrological cycle are dealt on a physical basis. Model parameters and variables are distributed in time and space and have a physical meaning. They are directly related to observable characteristics and can be measured in the field, which makes the calibration of these models redundant. However, it will never in practice be possible to obtain sufficient data to give a fully correct description in all details.
The representation of physical processes in the model is often too crude and the scales of measurement for many hydrological parameters are incompatible with the scales used in the models. Calibration will be crucial. It will not be a straightforward task due to high amount of parameters. MIKE SHE is an example of this kind of models.

Based on the spatial variability and the presentation of the physical processes, 4 main hydrological model types are distinguished. These are presented in figure 1 and include the empirical models, lumped conceptual models, semi-distributed conceptual models and fully distributed, physically based models. The physically-based, distributed models give a detailed and potentially more correct description of the hydrological processes in the catchment than do the empirical and conceptual model types (Abbott and Refsgaard, 1996; Refsgaard and Knudsen, 1996; Boyle et al., 2001; Ajami et al., 2004; Carpenter and Georgakakos, 2006). Runoff is a spatially distributed process that depends on several influencing factors including slope, soil type, surface roughness, imperviousness, surface storage as well as distribution of rainfall and initial conditions. The aspects could be incorporated into the distributed models. These models, however, require a high amount of spatially-explicit input data and show relatively high computational requirements, which limit their applicability.

Next to these main model types intermediate approaches are developed, combining the advantages of different model types. These model strategies aim at a combination between the trends of physical models and conceptual ones depending on the processes described by the objectives of the study and the state of knowledge of the catchment. In these models, such as the TOPMODEL (Beven and Kirkby, 1979), WetSpa (Wang et al., 1996), DPHM-RS (Biftu and Gan, 2001), WATBAL (Knudsen et al., 1986) attention is given to the hydrological processes at certain level through a distributed, physically based approach whereas other processes are simulated in less detailed way by use of a lumped, conceptual approach. These models try to overcome the limits of the usual types, while keeping their advantages by simplifying the dynamic approach and discretization using new concepts (Ambroise, 1999).
1.2 Dynamic modelling

Dynamic models find their origin in the interdisciplinary nature of water- and environmental-resource problems. These problems require the use of modeling approaches that can incorporate knowledge from a broad range of scientific disciplines (Leavesley et al.; 1996). Dynamic models can meet these requirements. A dynamic model is not a specific model but it is actually a flexible framework in which a variety of physical processes can be developed. The framework itself consists of a module library for various water resource applications. A module is a set of computer source code used to simulate a variety of physical processes related to water, energy, chemical and biological situations. A given process can actually be represented by several different library modules, each representing an alternative means to conceptualize a solution to a given problem. A model is created by coupling the most appropriate modules together to develop the most optimal application for a given situation (Shultz, 2007). Where existing modules are not appropriate, new algorithms can be integrated by the user.

For hydrological modelling purposes, a library consisting of water resource modules need to be applied to simulate the various components of the hydrological cycle. These module components may include temperature, precipitation, solar radiation, impervious area, interception, soil-moisture accounting, evapotranspiration, infiltration, overland flow, subsurface flow, ground water, channel flow, reservoir routing, sediment, and snow (Leavesley, 1996). The relevant module components for the desired application will be coupled to compose an integrated hydrological model. The user has wide latitude in choosing the level of rigor or detail required of an individual component model. The number of applied subsystems, the amount of state variables and the selected mathematical equations of the processes in the model will determine the complexity of the composed model. The model building itself is accomplished using an interactive model builder interface. The different modules are coupled by using the output from one module as the input to other process modules. Users might view inputs and outputs for each module. A GIS interface is used to characterize topographic, hydrologic parameters; visualize spatially and temporally distributed model parameters and variables; and validate model results.

Dynamic modelling shows some advantages above the usual model types. They provide flexibility and allow the user to adjust the representation of physical catchment characteristics and hydrological subprocesses in accordance with the available data and the particular application. The user might develop the most desirable modelling approach given a set of user needs and water resource conditions (Shultz, 2007). Dynamic modelling is a fast way of modelling as it uses a high-level scripting language, which can express complex ideas in simple statements. It is also open source software. This facilitates the direct and indirect sharing of resources, expertise, knowledge, and costs. However, next to these advantages there is one major disadvantage. It is difficult to determine the optimum level of complexity (optimum number of subsystems and state variables and the level of process description) for an acceptable level of accuracy. Examples of dynamic modelling systems are PCRaster language by Van Deursen (1995), the Modular Modeling System (MMS) by Leavesley et al. (1996) and the Catchment Modelling Framework (CMF) by Kraft et al. (2011).

1.3 Hydrological models applied to Belgian catchments

Many hydrological model codes with different complexity have been applied on Belgian catchments. This section gives an overview of the modelling studies and research done by the Flanders HydraulicS Research. Additionally some other modelling projects for Belgian catchments are mentioned with their main findings. This inventory of existing models might help in the selection of an appropriate hydrological model for future climate impact research.
1.3.1 Hydrological models available at Flanders Hydraulics Research

For their modelling studies on navigable water courses Flanders Hydraulics Research applies the NAM lumped, conceptual hydrological model of DHI. NAM is a rainfall-runoff model that operates by continuously accounting for the moisture content in three different and mutually interrelated storages, which represent physical elements of a catchment (snow storage, surface, root zone and groundwater storages). Being a lumped model, it treats each sub-catchment as one unit, therefore the parameters and variables considered represent average values for the entire sub-basins. Detailed descriptions of the modelling procedures and mathematical formulation can be found in the MIKE user’s manual (DHI, 2008) and associated publications at Flanders Hydraulics Research.

NAM-models have been developed for many catchments; spread over the 11 basins in Flanders. Table 2 lists the references in which the development of these models is described. The set up and parameterisation of the models are extensively reported in these references.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dijle –Zenne bekken</td>
<td>IMDC et al. 2003</td>
</tr>
<tr>
<td>Bekken Gentse Kanalen</td>
<td>Fobe and Vereecken, 2005</td>
</tr>
<tr>
<td>Leiebekken</td>
<td>Sorsema, 2002</td>
</tr>
<tr>
<td></td>
<td>Fobe and Vereecken, 2004</td>
</tr>
<tr>
<td>Bovenschelde</td>
<td>Fobe and Vereecken, 2005</td>
</tr>
<tr>
<td>Brugse Polders</td>
<td>Fobe and Vereecken, 2004</td>
</tr>
<tr>
<td>Demerbekken</td>
<td>Smets, 2003</td>
</tr>
<tr>
<td>Benedenschelde</td>
<td>IMDC et al. 2003</td>
</tr>
<tr>
<td>Netebekken</td>
<td>IMDC et al. 2003</td>
</tr>
<tr>
<td>Denderbekken</td>
<td>Willems et al., 2002</td>
</tr>
<tr>
<td>IJzerbekken</td>
<td>IMDC, 2001</td>
</tr>
</tbody>
</table>

The NAM models are mainly developed for gauged catchments in these basins. The models represent the hydrology of the area upstream the monitoring stations and are calibrated against hourly discharge series monitored at these stations. All models, except for the Heulebeek (Soresma, 2002), were calibrated based on the General Guideline for the modelling of the navigable watercourses in Flanders (‘Algemene methodologie’) (Willems, 2000). During the model set up difficulties with the rainfall input were often reported (Fobe and Vereecken, 2004, 2005). Rainfall series lack data, hourly series systematic underestimate or overestimate daily measurements, measurements stopped and data are no longer available,… Also good and continuous calibration data was sometimes limited (IMDC et al., 2003, Fobe and Vereecken, 2005). The calibrated models were overall able to simulate the discharges of the catchments in an acceptable way. However, some modelling studies reported difficulties in modelling the interflow (Fobe and Vereecken, 2004). Other remarks were made on the influence of many discharge series by regulation of hydraulic structures (Fobe and Vereecken, 2004, 2005). Also difficulties were experienced in these studies to model large catchments in which interacties between the (natural) hydrological system and canals take place.
NAM models were also built for ungauged catchments in Flanders. The parameters for these models were based on correlations between parameters and physico-morphological characteristics. However, in the hydrological modelling study for the Leie and Bovenschelde basin (Fobe et al., 2004; 2005), no (clear) correlation could be found between the model parameters and the physico-morphological characteristics of the different modelled subbasins. In these reports (Fobe et al., 2004; 2005) one concluded that this is due to the fact different modellers calibrated the models. Calibration by different modellers will lead to another set of parameters, although they used the same General Guidelines to calibrate the models. Van Steenbergen et al. (2010) quantified this influence of the modeller by recalibrating hydrological models with the original data set and analysed this effect on the high flows extremes. He concluded that the high flows can be 10% to 20% higher/lower estimated due to parameter sets defined by other modellers. This confirms the findings of Fobe and Vereecken (2004) that the subjective choices made by the modeller play an important role in the calibration process.

In the hydrological modelling study for the Dender, Willems et al. (2002) highlighted the importance of a consistent approach in the calibration of the hydrological models. Only in this way uniform parameter sets for the models of the different sub-basins of the Dender can be achieved. In Willems et al. (2002) it is suggested to first investigate the correlation between discharges series and the characteristics in the basin by means of the subflows rather than the correlation between parameters and basin characteristics. This is more accurate and led to the following logical findings:

- a negative correlation between the recession constant for overland flow and percentage urban area;
- a positive correlation between the interflow and groundwater flow and percentage clay;
- the percentage rainfall contributing to the total runoff depends on the soil type and land use;
- the percentage rainfall contributing to overland flow depends mainly on the land use; while the percentage rainfall contributing to interflow and groundwater flow mainly is more related to the soil type.

Next the correlations between NAM parameters and basin characteristics can be examined, making use of the above correlations with the discharge series.

Research to the applicability of the NAM hydrological model in low flow and high flow conditions has been done respectively by Deschamps et al. (2006) and Van Steenbergen et al. (2010). Deschamps et al. (2006) concluded that the NAM model was not able to model low flows with a high efficiency. He stated that the model might be used for low flow modelling although they give not very reliable and clear results. It is better to enclose them in a larger modelling system for low flow modelling. Several techniques were applied in his study to improve the low flow model capacity of NAM, although none of them were very successful. The research focused on the sub-basins of the Leie.

Van Steenbergen et al. (2010) compared the high flow modelling performance of three model codes, i.e. PDM, NAM and VHM. These model codes are commonly used for hydrological modelling purposes in Belgium. The comparative analysis was conducted for two small catchments, i.e. Molenbeek and Herk which are respectively sub-basins of the Rupel and the Demer. The different models were built using the same rainfall and evaportranspiration data. The study focused on real-time flood forecasting applications. The PDM hydrological model is commonly used in the flood forecasting models of the Flemish Environment Agency (VMM) for unnavigable water courses, while NAM is used as input for the flood forecasting models of the navigable rivers at Flanders Hydraulics Research. The third model in the comparison is the generalized lumped conceptual rainfall-runoff model. This model is not actively used for flood modelling purposes in Flanders but it offers a generalized model structure framework. The model structure building is done in a transparent, step-wise way, where separate parts of the model structure are identified and calibrated based on multiple and non-commensurable information derived from river flow series by means of a number of sequential time series processing tasks (Willems, 2011). The VHM model is often applied in research at the K.U.Leuven (Pagliero, 2009; Salazar, 2010; Mulleman, 2010).

The study of Van Steenbergen et al. (2010) tested an innovative technique by which the predictive power of hydrological models on high flows can be evaluated. The technique is based on a cumulative frequency analysis of the change in peak flows, considered for different rainfall classes. Additionally, relations between the surface runoff coefficient and the relative soil moisture content were evaluated and adjusted. Results indicate that the models show large differences in their surface runoff coefficients.
The PDM model tends to simulate higher flows during extreme wet conditions due to their exponential relation between the surface runoff coefficient and the soil moisture content, while the NAM model considers a linear relation. VHM will identify the best equation (linear or exponential) based on the available data.

In this study of Van Steenbergen et al. (2010), the sensitivity of the different parameters in the three models was also analysed. After the model calibration, a sensitivity analysis was carried out to investigate the uncertainty in the calibrated model caused by the uncertainty in the estimation of various parameters. The sensitivity analysis was conducted by evaluating the high flow extremes in response to various parameter disturbances of the calibrated parameters. The analysis involved perturbing the values of the parameters with respect to the best estimates and examining how the simulated high flows change. The common approach is to evaluate one parameter at a time; all other parameters are kept unchanged while a given parameter is being evaluated. The outcome of the analysis gives very valuable information for future model development (see Van Steenbergen et al., 2010).

For the hydrological modelling of the Meuse, the HBV model code is used. HBV is a water balance-based mathematical model code used to simulate the runoff properties using rainfall, temperature and potential evaporation data. The model consists of different routines representing snow by a degree-day method, soil water and evaporation, groundwater by three linear reservoir equations and channel routing by a triangular weighting function. The model operates at a daily time scale. HBV is known to model the high flows well, but the low flows are moderately modelled. A few studies which have been carried out using the HBV models of the Meuse confirm this and state that HBV has difficulties to represent extreme low flows (De Wit et al., 2007; AMICE, 2010).

Next to the above mentioned lumped conceptual hydrological models, some research on distributed model codes was done at Flanders Hydraulics Research. Vansteenkiste et al. (2010) gave an overview in the distributed model codes and suggested codes which could be applied for the climate impact research in Flanders. So far, two model codes were tested: MIKE SHE and WetSpa.

MIKE SHE is a spatially distributed, physically based, hydrological model (Abbott et al., 1986). It simulates the terrestrial water cycle including evapotranspiration (ET), overland flow, unsaturated soil water, and groundwater-surface water movements. ET is calculated using the Christiansen and Jensen (1975) method based on potential evapotranspiration, leaf area index, root depth for each vegetation type, and a set of empirical parameters. Overland flow is described using the diffusive wave approximation of the Saint-Venant equations. Movement of water in unsaturated zones is assumed to be vertical. The unsaturated soil water infiltration and redistribution processes can be modelled using Richard’s equation, the gravity flow method or a simple soil water balance equation. Saturated water flow (i.e. groundwater) can be simulated by a linear reservoir or a 3-D groundwater flow model. Channel flow and upland groundwater-surface water interactions are controlled by the MIKE 11 model. MIKE 11 is a one-dimensional model that tracks channel water levels using a fully dynamic wave version of the Saint-Venant equations. The MIKE SHE model code can also be applied for water quality purposes. It has been widely used worldwide (Refsgaard, 1997; Sun et al., 1998; Thompson et al., 2004; Sahoo et al., 2006, Zhiqiang et al., 2008) for a wide range of applications. MIKE SHE also has been applied a number of times in Belgian catchments: for the Gete (Christiaens et al., 1998; Vázquez et al., 1999; 2002) and the Grote Nete catchment (Rubarenzya, 2007).

WetSpa is a grid-based distributed hydrological model for water and energy transfer between soil, plants, and atmosphere (Liu et al., 2003; Liu, 2004). It considers the hydrological system composed of a canopy layer, a root zone, a transmission zone and a groundwater reservoir. A mixture of physical and empirical relationships is used to describe the hydrological processes in the model. The processes are set in a cascading way, starting from a rainfall event. Evapotranspiration from the soil and vegetation is calculated based on the relationship developed by Thorntwaite and Mather (1955), as a function of potential evapotranspiration, vegetation type, stage of growth and soil moisture content. The surface runoff (overland flow and channel flow) is calculated using a soil-moisture modified rational method with a potential runoff coefficient depending on land cover, soil type, slope, magnitude of rainfall and antecedent soil moisture. It is routed by the diffusive wave approximation (Liu et al., 2003). Percolation and interflow are assumed to be gravity driven. Interflow is determined by Darcy’s law and a kinematic wave approximation in function of hydraulic conductivity, moisture content, slope angle and root depth. The groundwater component is simplified as a lumped linear reservoir. The groundwater discharge is proportional to the groundwater storage and inverse proportional to the recession coefficient.
Total runoff is the summation of surface runoff, interflow and groundwater discharge. The WetSpa model has been applied to several watersheds in- and outside Flanders (Liu et al., 2006; Nurmohamed et al., 2006; Bahremand et al., 2006; Bahremand et al., 2007).

Vansteenkiste et al. (2011) report on the application of these distributed model codes, MIKE SHE and WetSpa, to the Grote Nete catchment in order to compare their model performance and impact by climate scenarios on peak and low flows. Both models were calibrated and validated based on hourly river flow data downstream the basin. MIKE SHE was additionally evaluated on groundwater heads and internal discharges in the basin. The model results and the comparison of the different modelling approaches indicate that both models perform well in their simulation of the catchment hydrology. Overall good model efficiencies were achieved, and the MIKE SHE model was found capable of simulating groundwater heads and their dynamics with reasonable accuracy. The extreme peak and low flows were well modelled as well. However, external discharges from wastewater treatment plants and industrial activities had to be taken into account. The models were afterwards used to estimate the impact of the climate scenarios for Belgium with special focus on the changes in low flows. This is discussed further in section 2.3.1 Even though these distributed models are more difficult to parameterise; they show major advantages in the generation of runoff (Abbot and Refsgaard, 1996).

1.3.2 Other hydrological models

This section reports on some other (mainly distributed) hydrological modelcodes, which have been applied to catchments in Belgium. These modelcodes might form an alternative in the climate impact research as expertise is available at different institutes in Belgium. Some of these modelcodes were already briefly described in Vansteenkiste et al. (2010).

GSFLOW

GSFLOW is a coupled Groundwater and Surface-water FLOW model. It is based on the integration of the U.S. Geological Survey Precipitation-Runoff Modeling System, PRMS (Leavesley et al., 1983) and the well known USGS Modular Groundwater flow model MODFLOW-2005 (Harbaugh, 2005). GSFLOW is a relatively new model which is initially released on May, 2008. It provides mass balances and exchange rates among different hydrological zones, including surface, soil, unsaturated and saturated zones. The input data of this model includes: topography, land use and soil maps, timeseries of precipitation and evapotranspiration, maximum and minimum temperature, solar radiation, hydrogeological description of the area, and pumping and observation wells.

The area of the watershed is discretized into a network of homogeneous units (hydrologic response units - HRUs). It is assumed that, for each HRU, the hydrological and physical processes and its hydrologic response is homogenous. The model operates on both daily and storm time scale. In the hydrological PRMS model, the watershed is conceptualized as a series of reservoirs: the impervious zone, the soil zone, subsurface and groundwater zone. The response of these reservoirs provides the total watershed response. MODFLOW-2005 (Harbaugh, 2005) is a finite difference, three dimensional groundwater flow model. After pre-processing of the data, the PRMS and MODFLOW models were developed independently. After calibration of the PRMS and MODFLOW model separately, the GSFLOW model was run. Calibration of the GSFLOW model was done using parameters that influence the flows between PRMS and MODFLOW. This modelcode is useful for the analysis of groundwater-surface water interactions. GSFLOW is used at the department of Hydrology and Hydraulic Engineering of the Vrije Universiteit Brussel and has been applied to a case study in Flanders by Yiman (2010).

SWAT

SWAT or the Soil and Water Assessment Tool (Arnold et al., 1993) is a semi-distributed hydrological model that operates on a daily time step. This coarse time step is a strong limitation when the model is used for high flow or flood studies. The model is physically based, computationally efficient, and capable of continuous simulation over long time periods.
Major model components include weather, hydrology, soil temperature and properties, plant growth, nutrients, pesticides, bacteria and pathogens, and land management. Data needed for model development are: topography, land cover, soil map, rainfall, air minimal and maximal temperature, solar radiation, wind speed, relative humidity and streamflow data. SWAT models can be applied for water quality purposes, where additional sediment and nutrient delivery data, fertilizer and pesticide data and/or point sources of pollution are needed.

In SWAT, a watershed is divided into multiple sub-watersheds. These are further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management, and soil characteristics. The HRUs represent percentages of the sub-watershed area and are not identified spatially within a SWAT simulation. SWAT was calibrated a.o. for catchments that are part of the sub-basins of the Scheldt river basin (Heuvelmans et al., 2004), the Grote Laak (Nossent and Bauwens, 2007), the Grote Nete catchment (Rouhani, 2008), Kleine Nete (Shrestha et al., 2010). SWAT models in Belgium are often developed in the framework of water quality modelling studies (van Griensven and Bauwens, 2005; Vandenberghhe et al., 2005, 2006, 2007; Cools et al., 2007).

In the different modelling studies, SWAT is able to simulate the runoff regime well. High flows are modelled well (but limited to the daily time step), but difficulties arise in the modelling of low flows. Low flows are normally derived from groundwater discharge (Smakhtin, 2001). The SWAT model has its own module for the simulation of groundwater discharge, which is lumped and therefore distributed parameters could not be represented. The groundwater component in SWAT is oversimplifying the description of the interaction between groundwater and streamflow and the simulation of baseflow. Therefore the SWAT model was combined with the MODFLOW groundwater model code to better represent the physical processes of the underground water movement (Perkins and Sophocleous, 1999; Kim et al., 2008). Figure 2 compares the model results of SWAT with and without this extra component for a 2-year period in the Musimcheon basin in South Korea.

![Figure 2: Comparison of the hydrographs reproduced by SWAT and SWAT–MODFLOW (adopted from Kim et al., 2008).](image-url)

The SWAT model was in that basin not able to correctly reproduce the streamflow dynamics during low flow conditions. This difference in low flows was due to insufficient baseflow simulation resulting from the limitation of the SWAT groundwater module. An improved correspondence of measured and simulated streamflow in the low flow season was achieved by the combined SWAT-MODFLOW model. Specifically, gradual or rapid variations of groundwater flow could be determined mainly by the river-aquifer exchange flow rate in SWAT-MODFLOW.
**WetSpaSS**

WetSpaSS is the acronym for Water and Energy Transfer between Soil, Plants, and Atmosphere under quasi-Steady State. It is a steady state spatially distributed water balance model for simulating yearly or seasonal averages of groundwater recharge, evapotranspiration (soil evaporation and transpiration also as separate outputs), runoff, and interception (Batelaan and De Smedt, 2007).

The groundwater recharge output from WetSpaSS can be used as input for MODFLOW in a steady state or seasonal varying groundwater model. The resulting groundwater depth of the MODFLOW head output is then used as input to WetSpaSS for refining the estimation of recharge. This process continues until a desirable groundwater head is achieved.

WetSpaSS uses detailed information on soil, land use, slope, groundwater depth, and hydro-climatological distributed maps with associated parameter tables. The surface runoff depends on the land use, soil, slope and precipitation intensity in relation to infiltration capacity of the soil. The model has been applied in different areas in Belgium e.g. the Dijle, Demer and Nete catchments (Batelaan and De Smedt, 2007), and including the more specific Grote Nete catchment (Woldeaamlak et al., 2007), Kleine Nete catchment (Dams et al., 2008.) and several other locations. Generally, the simulated total discharge and the simulated recharge showed a good fit with the observations (Batelaan & De Smedt, 2007). This proves that the WetSpaSS model is able to capture the long term average discharges and recharges at catchment level. However, the time scale is a serious drawback to apply this model for the climate change impact research on extreme flows.

**Lumped rainfall-runoff model based on effective rainfall**

Poelmans (2010, 2011) applied a lumped model to the Molenbeek, a small-scale suburban catchment in the Dijle catchment. The model includes two sub-models: (1) a water balance model that assesses the effective rainfall (Chow et al., 1988) and (2) a conceptual routing model that transfers the effective rainfall into surface runoff. The first sub model assesses the proportion of the total catchment rainfall that becomes effective rainfall based on potential runoff coefficient and soil moisture deficit. The effective rainfall is the volume of rainfall which is neither retained on the land surface and evaporated nor infiltrated in the soil, and equals the total volume of surface runoff. The potential runoff coefficients were assessed on catchment scale using averaged land use and soil type. Next, the effective rainfall was transformed into a flow hydrograph by means of a conceptual routing model. The routing model is based on a cascade of two linear reservoirs.

**EPIC-Grid**

For the Walloon region of Belgium a set of other hydrological models were developed and commonly used. One of these is the EPIC-Grid conceptual-physical distributed model, which has been developed at the Université de Liège (ULG) and is derived from the EPIC software (Williams, 1995). The EPIC-Grid model is made up of several modules dealing respectively with climate, hydrology, crop growth, tillage, erosion, nutrient cycle, pesticide movement, soil temperature, crop management and economical aspects (Bauwens et al., 2010). It takes into account, inside every surface element (1 km × 1 km), the balanced values of land use, slope, weather and soil characteristics (root zone and vadose zone), growing culture and agricultural practices like fertilization, ploughing, . . . Simulations can be realized at hourly or daily time step. They can be based upon water fluxes and solute towards surface water and groundwater. The EPIC-Gid model is mainly used for water quality modelling (agro-environmental modelling,…).

The model requires temperature and rainfall observations, a map of the land use, topography and soil, information about the thickness of the unsaturated zone, a meteorological database, a database with derivative data such as hydrodynamic and chemical properties of soils, a database with agronomic data such as cultural types and agricultural practices. Finally, discharges are needed for model calibration and validation. EPIC-Grid models for Belgium are reported for the Vesdre and Lesse catchment in Wallonia, which are tributaries of the Meuse (Bauwens et al., 2010). In AMICE – Adaptation of the Meuse to the Impacts of Climate Evolutions (2011) - it is found the EPIC-Grid model is able to simulate high flows good, while low flows can be simulated quite well according the Nash Statistics for extremes.
However, from groundwater perspective EPIC-Grid uses a simplified approach. To have a better simulation of the baseflow a more reliable estimate of groundwater flow to streams is necessary. This requires an accurate and physically consistent simulation of all the interactions existing between the different parts of the hydrological cycle. To overcome this limitation the hydrological model MOHISE (Brouyère and Dassargues, 2004) is developed, which include the EPIC-Grid model.

MOHISE is a deterministic spatially distributed, physically-based model, composed of three interacting submodels: a soil-model (EPIC-Grid), a surface water model and a groundwater model (SUFT3D), dynamically linked and operated on a multi-node parallel workstation. These models can be relied better on when predictive computations are performed. MOHISE was successfully applied to the Geer basin in Belgium (Brouyère and Dassargues, 2004).

SCHEME

Another hydrological model often used in the Walloon region of Belgium is the SCHEME model (SCHEldt-MEuse) model, which is the distributed version of the IRMB hydrological model (Bultot and Dupriez, 1976). The IRMB (Integrated Runoff Model) hydrological model is a conceptual model working at a daily step and developed to simulate the water balance of catchments ranging from 100 to 1000 km². The SCHEME model considers grid cells of 7 by 7km² in which the hydrological processes are lumped. The SCHEME model structure comprises 9 different land covers and there is a snow accumulation and melting module. The (actual and potential) evapotranspiration are calculated on the base of the water intercepted by the vegetation and the water content of two soil layers. Surface water is simulated with a unit hydrograph and the underground water is represented with two reservoirs. The streamflow produced on each grid cell is routed to the outlet with a 1D submodel taking into account the river network. A sketch of the SCHEME model mechanisms for a grid cell is presented in figure 3.

![Figure 3: Diagram of the SCHEME model with model parameters (adopted from Baguis et al., 2010).](image-url)
With this design, the SCHEME model has been successfully applied to simulate a variety of basins and hydrological conditions in the river Scheldt and Meuse Basins in Belgium and upstream in France (Roulin et al., 2001, 2002).

Other models

The model applications in Belgium reported above, were found in literature. It gives an overview of the different model codes currently being used, although it is possible that more examples can be found for Belgium. All model codes in this chapter have a fixed framework to simulate the runoff. The concept of dynamic modelling is not yet fully operational for case studies on Belgian territory. No reported case studies were found in literature; although the concept is currently being applied and tested by VITO.
2 Climate change impact research in Belgium

The climate is changing. The earth is warming up. While the global climate has been remarkably stable for the past 10,000 years, there are now clear signs that the climate system is warming, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level. The Intergovernmental Panel on Climate Change (IPCC), a group of climate experts from across the world, concluded that most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas (GHG) concentrations.

Although the rise in temperature may be the clearest indicator of the ongoing climate change, it is not the only manifestation of climate change. The rise in temperatures has had, and will continue to have, serious impacts on various parts of the climate system. A warmer atmosphere contains more water vapor and results in changed rainfall patterns. The changes in the amount and variability of rainfall and evapotranspiration will have the strongest impacts on hydrological systems. This might have potentially major consequences for the use and water management of rivers. Water management planners are facing considerable challenges in future demands and availability of water. They will need to incorporate measures to cope with climate change. The dimension of the problem and the need to improve our understanding of the processes, impacts and the mitigation and adaptation strategies required has led to a large number of research efforts worldwide, but also in Belgium.

An early focus on the climate change impact research on hydrological systems in Belgium was put by the Royal Meteorological Institute (RMI). Their impact research, initiated by Bultot et al. (1988) aimed to quantify the response of basins in case of doubling the CO₂ conditions. The sensitivity of the various terms of the water cycle was investigated by comparing their values in the present runs and under double CO₂ conditions. That study gave a first insight into the direction of the expected climate change impacts for Belgium. However, there were serious limitations linked to the climate scenarios.

In the 1990s, when climate change research has proliferated in size and complexity, the results of early impact studies for Belgium were updated by Gellens and Roulin (1998). Through better insights in the complex climate processes and the development of a number of very coarse resolution climate models by the IPCC, improved scenarios became available. These scenarios include perturbation of time series of hydrometeorological input data relevant to simulate the water cycle. The impact analysis was done for a set of catchments belonging to the Scheldt and Meuse river. These catchments were spread over the country in order to represent the main types.

Later, through improved understanding of the atmospheric processes the uncertainty in climate modelling reduced. The data accuracy increased and impact studies could be performed with increased confidence. As a result climate change and its impacts have been intensively investigated during recent years. In the next section an overview in these climate change impact studies is presented with respect to the hydrological model, analysis techniques and the climate change scenarios adopted. But first we start with a short revision on the climate change scenarios for Belgium and the impact methodology used at Flanders Hydraulics Research.

2.1 CCI-HYDR climate change scenarios

As mentioned in the introduction, climate change was mainly triggered by the increase of GHG concentrations from human activities. Projections for the 21st century can only be made if a picture of the future emission of greenhouse gases is available. However, future emissions of these gases depend on many assumptions and uncertain factors such as population growth, the use of carbon fuel as an energy source, technological development, economic development, policy and attitudes towards environment, etc. For this reason, climate scenarios have been developed by the IPCC based on these factors. The IPCC Special Report on Emissions Scenarios (SRES) identifies four families of story lines (Nakićenović et al. 2000): A1, A2, B1 and B2. The A1 storyline assumes a world of very rapid economic growth, a global population that peaks in mid-century and rapid introduction of new and more efficient technologies.
B1 describes a convergent world, with the same global population as A1, but with more rapid changes in economic structures toward a service and information economy. B2 describes a world with intermediate population and economic growth, emphasizing local solutions to economic, social, and environmental sustainability. A2 describes a very heterogeneous world with high population growth, slow economic development and slow technological change. Six illustrative scenarios were drawn from these four families: A1FI (fossil intensive), A1T (predominantly non fossil), A1B (balanced across energy sources), A2, B1 and B2 (Nakićenović et al. 2000). The marker scenarios were employed by climate modelers as input to drive their climate models and develop a range of climate scenarios. All emission scenarios were designated as equally valid and probable.

Climate models try to mimic the complex natural dynamic processes of the climate. They can simulate the response of the climate system to the emission scenarios and produce a large number of variables. These output variables may serve as input to impact models to define the consequences of the future climate conditions. For hydrological modeling purposes, the spatial and temporal resolution of the climate model output is generally considered too coarse. General circulation models (or GCMs) are typically operating at about 150-300 km resolution; Regional Circulation models (or RCMs) have a typical spatial horizontal grid resolution in a range between 20 and 50 km. To use the climate model output for the hydrological impact analysis simulation results from GCMs and RCMs need to be downscaled to a smaller, hydrological scale. This can be done on dynamical or statistical bases. Dynamical downscaling uses a limited-area, high-resolution RCM driven by boundary conditions from a GCM to derive smaller-scale information. Statistical downscaling is based on statistical relationships between observed small-scale variables and larger GCM or RCM scale variables.

The statistical downscaling of the (RCM and GCM) climate model results for Belgium has been done in the CCI-HYDR project by Ntegeka et al. (2008). The scenarios are developed within the four SRES emission families (A1B, A2, B1 and B2). The climate model simulations with the A2 and B2 regional scenarios were extracted from the PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects) database, the A1B and B1 scenarios were extracted from the IPCC AR4 database. These GCM experiments were included to account for the extra uncertainty related to the emission scenarios and better reflect the range of possible future climate change by considering a larger set of GCM results for Belgium. Of these SRES scenarios, A2 has the highest emissions, A1B and B2 have emissions between the low and high end range and B1 has the lowest emissions (IPCC, 2007).

A procedure of combined dynamical-statistical downscaling was followed to combine the climate model outputs into only three scenarios for Belgium, which reliably represent the overall range of expected impacts. The dynamical downscaling was considered in the PRUDENCE project and provided a set of simulations derived from 11 RCMs nested in two main coarse scale GCMs. The results comprise a series of high-resolution simulations of the European climate for a control period (1961–1990) and for a future time period (2071–2100). The results over the control period are validated against observed trends in the past. Only the RCM runs which are consistent with the past and which do not deviate strongly from the other climate model runs are retained for further statistical downscaling. The statistical downscaling transferred these RCM projections to local observations. The method applied by Ntegeka et al. (2008) is based on perturbation factors, which are determined as the change in meteorological variables obtained from the climate model runs between the reference period (1961-1991) and the scenario period (2071-2100). The perturbation factors are derived based on their dependency on the time scale (different aggregation levels) and the intensity level or return period and are mainly considered for the number of wet days and the intensities of the events. Based on the entire set of RCM and GCM runs the high, mean and low scenario cases were defined to represent the overall range of changes. It was found that during winter the wet days will generally increase in intensity, while the number of wet days will not significantly increase. The number of wet days in summer will decrease.

The perturbation factors are then probabilistically applied to the original series for impact analysis. The changes are being made in a variable way, depending on the month in the year, and on the return period or storm frequency. In a first step, the number of wet days to be added or removed is determined for the high, mean and low wet day frequency perturbations. When adding or removing wet days, the wet days are randomly selected from the set of empirical wet days of the observed series and replaced by dry days. In a second step, intensity perturbations are applied to the wet days in the series (figure 4).
Three final rainfall series are obtained representing the future perturbed rainfall series for the high, mean and low scenario cases. For ETo, the analysis is not different from the rainfall perturbation. However the first step is omitted given that for the ETo series the day to day variability is minimal compared to the rain series. Only intensities are perturbed, but also depending on the month and the return period.

The perturbations for rainfall and ETo have to be done concurrently to preserve the internal physics of the climate system. However, only physical meaningful perturbations of rainfall and ETo were applied. These are based on seasonal relationships between the ETo and rainfall perturbations and are presented in table 2. To deduce these relationships, the perturbations of the same models were traced across all the seasons (Ntegeka et al., 2008).

Table 2: Seasonal correlations and scenario definitions (adopted form Ntegeka et al., 2008)

<table>
<thead>
<tr>
<th>Season</th>
<th>ETo</th>
<th>Rainfall</th>
<th>Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Spring</td>
<td>Mean</td>
<td>Mean</td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>High</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Autumn</td>
<td>Mean</td>
<td>Mean</td>
<td></td>
</tr>
<tr>
<td>Winter</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
</tr>
<tr>
<td>Spring</td>
<td>Mean</td>
<td>Mean</td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>Mean</td>
<td>Mean</td>
<td></td>
</tr>
<tr>
<td>Autumn</td>
<td>Mean</td>
<td>Mean</td>
<td></td>
</tr>
<tr>
<td>Winter</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Spring</td>
<td>Low</td>
<td>Mean</td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>Low</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Autumn</td>
<td>Low</td>
<td>Mean</td>
<td></td>
</tr>
</tbody>
</table>

The relationships were used to define the high, mean and low climate change scenarios based on the expected hydrological impacts (figure 5). These scenarios might be referred to as wet, mild and dry respectively. The high scenario defines the most extreme case (among all studied climate model runs) for flood risk analysis with wet winters and dry summers (most pessimistic with respect to high flows).
The mean scenario represents the expected average scenario (mean flow impact), while the low scenario by its dry winters and dry summers (strongest low flow impact) reflects the most pessimistic change in the low flow situation. All three scenarios need to be considered in impact studies to account for the overall uncertainty (Ntegeka et al., 2008, 2010). They characterise the lower and upper ends of the expected changes (again, based on the selected climate model runs).

Future series of rainfall and evapotranspiration, following the principles described above, can be constructed through the CCI-HYDR Perturbation Tool (Ntegeka and Willems, 2009), which is a Microsoft Excel-based tool. The series to be perturbed by the tool can be daily or hourly and can have any length (typical lengths vary from a few years to 100 years). The perturbations for rainfall and ETo, but also wind speed and temperature, can be made for time horizons till 2100 (e.g., for 2020, 2030, ..., 2100).

2.2 Review on the climate change impact methodology

The basic method for assessing the impact of the climate change on catchment runoff is to run a hydrological model driven by various climate scenarios and compare the output of these runs with simulation results for the reference period (current climate). The climate scenarios for the impact analysis can be created by applying perturbation factors to the input variables of the hydrological model using the CCI-HYDR perturbation tool (Ntegeka and Willems, 2009). After perturbation, three series of rainfall and evapotranspiration are generated representing the low, mean and high climate scenarios. Together with the original series (current climate conditions), these series are run in a hydrological model and make it possible to study the impact of climate change on discharge regimes of the catchment.

Next to the changes in discharge profile, one has interest in the extreme behaviour and its alterations due to climate change. These extreme data are irregular and are particularly useful because they provide a more complete picture of flow characteristics in the catchment. Moreover, knowledge on the extreme behaviour of the catchment like flood peak discharges or drought periods is essential for water resources planning, risk management, project design, etc... They are also used to study the (changes in) frequency and magnitude of extreme events.

To study the catchment extreme behaviour, the hydrological model results need to be processed in order to extract independent flows extremes. There are several ways to extract these extreme events. In classical methods, annual maximum and minimum flows are used to define the extremes and estimate their return period. A more common, valid alternative is known under the names of peak over threshold (POT) or partial duration series (PDS) analysis. The basic idea behind this method is to extract from the series a sample of events containing more than one event per year, in order to increase the available information with respect to the annual maxima method. Different selection criteria can be applied to obtain several events per year, e.g. setting a threshold, selecting an average rate of events per year,...
Next, extreme value techniques are applied to the results to estimate the probability of the extreme discharges. The theoretical distribution function that best fits to the set of observed flow data is selected. Different distribution functions are available for statistically describing extreme flows. There are also different techniques to fit these distributions. Finally, relative changes in the magnitude of the quantiles for the scenario simulation, relative to its corresponding control simulation are calculated. Good choice and fitting of the distribution function is crucial and might influence the results, especially for events with higher return periods (Dankers en Feyen, 2008).

For the analyses of extreme discharges in the impact studies at Flanders Hydraulics Research, the approach of Willems (1998) was adopted in which independent extremes are selected throughout a peak over threshold method followed by an extremes value analysis. This method is commonly applied for high flows, but is in the impact research at Flanders Hydraulics Research also applied to low flow conditions, following the method proposed by Willems (2000). Hereo, independent low flow peaks are selected and distributions are fitted to the reciprocal values of these low flows. The impact is assessed by comparing the distributions of these reciprocal values.

In order the assess the impact on flood maps and flood risk the methodology for climate change impact analysis was enhanced by Boukhris et al. (2006).

2.3 Review of the climate change impact studies and results

Different studies at Flanders Hydraulics Research have been investigating the impact of climate change on hydrological systems in Belgium. The studies all have used hydrological models to translate the assumed climate change scenarios into hydrological responses, although different types of models have been employed. These models have different spatial and temporal scales, different model conceptualizations and parameterizations,... This section gives an overview of the modelling projects and results on the climate impact research of recent years at Flanders Hydraulics Research and analyses the role of the model on the impact results.

2.3.1 Overview of the climate change impact studies

Climate change impact for Belgium has been widely investigated by Boukhris et al. (2008). The objective of that study was to cover the whole Scheldt river basin district in order to study the evolution of the water balance on a larger scale and to find a common response to all the catchments and scenarios for Flanders. Such a large scale analysis is very useful to policy makers and other decision making communities.

The impact analysis was performed for the 67 subbasins of the Scheldt river basin district. Calibrated NAM models for these basins, as listed in table 1, were used for this impact study. The models were not recalibrated for the climate impact research as the model performance with the available parameters for the different models has been validated during their development. The meteorological input data to these models (precipitation and potential evapotranspiration) were perturbed to future climate scenarios using the CCI-HYDR climate perturbation tool (version may 2007). After perturbation of these series, hydrological model simulations have been performed with these perturbed series (long-term simulation). Finally, the series of rainfall-runoff model results are processed statistically following the method suggested in section 2.2, to quantify the hydrological change. The impact was assessed on total runoff, overland flow and evapotranspiration. Impact results are given by the variation in high and low flows above a given return period (0.1 year) and are summarized in figures 6 en 7. Impacts results for ungauged catchments were estimated by interpolation (Boukhris et al., 2008).
Figure 6: Percentage of variation of hourly runoff peaks for the low, mean and high CCI-HYDR climate scenarios (adopted from Boukhris et al., 2008)
The results of this study showed high sensitivity of the flow extremes to the precipitation and evapotranspiration changes. For all tested catchments similar impact results are noted. The results show that, while for the mean scenario, the runoff peaks experience slightly decrease reaching a maximum of -14% comparing to the current runoff peaks condition, the decrease is very large for the low scenario down to -70% (figure 6). For the high scenario, climate change acts positively where we expect an increase in runoff peaks to the order of 35% depending on the subcatchment. Uncertainties on the high flow impacts thus are very high. Depending on the ratio between the increase in rainfall versus the increase in ETo, and the ratio between the increase in winter rainfall versus the decrease in summer rainfall, the hydrological impact results might turn over from a positive trend into a negative trend.

Low flows will decrease dramatically for the entire Flanders area for all climate scenarios (up to -88% for the low scenario; figure 7). A serious decrease of summer rainfall together with an increase of ETo is responsible for these more extreme low flow discharges. This will increase the frequency of water deficits, with adverse consequences for drinking-water production, shipping, agriculture, industry, nature,... While still a large degree of uncertainty is remaining in the assessment of the climate by 2100, the study by Boukhris et al. (2008) gave an insight on the direction of the expected climate change impacts. Overland flow volumes show similar behaviour as the runoff peaks.

Other important results from the study consist in the regional differences. Spatial hydrological response heterogeneities are seen within the Flanders area with respect to climate change scenarios. These hydrological response heterogeneities have been investigated by means of statistical correlations between the high scenario runoff peaks and three local physico-morphological characteristics (soil type, land use and topographical slope). The correlation results show that the signature of the local characteristics does not provide efficient explanation to the spatial hydrological heterogeneity. No strong correlations have been found, although some tendencies could be detected, explained by soil type and topographical slope.
Additionally, the impacts on the runoff discharges were transferred to changes in flood maps. The change in synthetic flood events and flood risks was estimated by translating the change in peak flows to composite hydrographs according to the methodology described in Boukhris et al. (2008). Flow-duration-frequency (QDF) relationships for the high flow series were recalculated for each climate scenario after which synthetic rainfall-runoff hydrographs (composite hydrographs) for given return periods were constructed. These hydrographs were then implemented in detailed river hydrodynamic models (full hydrodynamic models considering river cross-sections approx. each 50m and most bridges, weirs, culverts and hydraulic regulation structures) to simulate floodplains. The floodplains were modeled using the quasi 2D flood modelling approach with the MIKE11 modelling software (DHI, 2007) and a GIS mapping tool. Models currently in use at Flanders Hydraulics Research for flood management in the river basin are applied in order to construct flood maps and flood risk maps. The flood modeling shows that the flood risk will increase or decrease depending on the hydrological changes on high flows.

Vansteenkiste et al. (2009a) repeated the impact modelling of Boukhris et al. (2008) for the sub-basin of the Leie and Bovenscheldt river basin. In that analysis, an updated version the CCI-HYDR climate perturbation tool for Belgium (version december 2008) was applied. The update, based on further insights in the climatic processes, better accounts for the correlation between the rainfall and ETo perturbations. In the scenarios used by Boukhris et al. (2008) worst case combinations of these perturbations were applied. The improvements in the climate scenarios did not affect the impact tendencies, although small changes in impact results were noticed. The change in peak flows under the high and low scenario is less extreme, as a result of which the range between the impact factors between these upper and lower scenario is smaller.

To complete the impact modeling for Belgium, the impact has been quantified for the Meuse and is reported in Vansteenkiste et al. (2009b). For that analysis the HBV model (Bergström et al., 1973) has been applied to the catchments upstream of the Meuse border with the Netherlands at Borgharen. In contrast to the NAM, PDM and VHM conceptual rainfall runoff models HBV also require temperature. So, to explore the impact of future climate conditions on the discharge regime of the Meuse, precipitation, evapotranspiration and temperature data were perturbed by the CCI-HYDR perturbation factors (version december 2008) and simulated by the HBV models (Vanneuville and Holvoet, 2009; de Keizer and Kwadijk, 2009; Vansteenkiste et al., 2009b). The simulation results were compared with the reference run and the impact of the scenarios was assessed by the variation of discharge extremes and flood risk maps. The direction of obtained impacts did not differ significantly from the impact results obtained for the sub-basins in the Scheldt river basin district, which gave some confidence in the projected trends in the hydrological response. Projected changes in peak flows were found to be highly uncertain. Depending on the climate scenario an increase as well as decrease of the winter discharges were found. In contrast, significant decreases were found for low flow extremes due to a decrease in total summer rainfall and increase in evapotranspiration in all climate scenarios.

Generally, conceptual models like HBV and NAM having simplified representation of the groundwater component experience problems to simulate low flow in an accurate way. Streamflow during low flow periods are derived from releases of a groundwater storage (Smakthin, 2001). The groundwater-surface water interactions behind these releases are physically driven by the differences in water levels between groundwater and surface water, hydraulic properties (conductivity and effective porosity) and the geometry of the interfering geological layers. Conceptual models with a linear reservoir and corresponding recession coefficients to simulate the baseflow, are oversimplifying the description of the interaction between groundwater and streamflow (Dassargues et al., 1999). Logically, the question arises whether these conceptual models are suitable tools to estimate the impact of climate change on low flows. A better way to simulate adequately the physics of groundwater/surface water exchanges consists in implementing three-dimensional (3D) groundwater flow models coupled with river models. Parallel runs of the groundwater and surface water models might be needed. So, for the impact studies in Belgium, in which a decrease of future low flows might be expected, more detailed physically based and spatially distributed models might form a better alternative to model the low flow alterations by climate change. Moreover, these physically based models should, in principle, reflect our understanding of hydrological systems more closely and therefore be more robust in extrapolation to other conditions. The physical base of key processes in these models gives confidence that the models will provide more reliable results under changed climate though we realise that this cannot be proven by observations (Grabs et al.; 1997).
Whether this theoretical principle is also valid in practice, obviously depends on the data availability. As discussed in section 1, when the spatial data availability is limited, the more detailed models become over-parameterized, such that their uncertainty also might be high.

In further tests, Vansteenkiste et al. (2011) applied the WetSpa and MIKE SHE distributed model codes to study the hydrological responses of climate change. The two model codes were mainly preferred for their spatial characteristics and physical process descriptions. Detailed motivation for the selection of these model codes in the climate impact research for Belgium can be found in Vansteenkiste et al. (2010c). These models could be well adapted to the catchment characteristics, such as the role of topography, evapotranspiration, land use, soil type, and groundwater flow. However this type of models has high data demands, which make it difficult to build such models for large areas, or using long reference periods. A short description of the codes was already given in section 1.3.1.

The MIKE SHE and WetSpa models in Vansteenkiste et al. (2011) were built for the same catchment using identical temporal (precipitation and evapotranspiration) and spatial (topography, land use and soil) data and were calibrated against the observed hourly discharges in the basin. In the calibration process emphasis was put on the modelling of the low flows as the climate scenarios for Belgium will significantly affect these. The calibrated models have been compared with respect to the overall performance in terms of water balance and simulation of high and low flow extremes. Both models were able to simulate the actual conditions in an acceptable way. The calibration and validation results of the WetSpa and MIKE SHE models show that both models could reproduce the runoff with acceptable accuracy for each basin. After such extensive calibration for the present climate conditions, the sensitivity of the water balance components has been examined by modifying the input data according the CCI-HYDR climate scenarios (version december 2008).

![Graph](image_url)

Figure 8: Nearly independent hourly peak flows versus empirical return period for the low, mean and high climate scenarios simulated in the (a) MIKE SHE and (b) WetSpa models

In both model results, the original distribution of the runoff peaks (current climate) shows a shift up or down depending on the applied scenario. The high climate change scenario results in higher extremes over the full range of return periods higher than 0.1 years; while for the low scenario the runoff peaks decrease compared to the current runoff peaks. Depending on the rate of increase in rainfall versus increase in potential evapotranspiration, the peak flows in winter might increase or decrease. The uncertainty in the impact results thus is high, and is mainly due to high uncertainty in the future climate trends (the wide range covered by the climate scenarios). These conclusions are consistent with what has been concluded based on the NAM models by Boukhris et al. (2008) and the HBV model by Vansteenkiste (2009b). When the impact results of both models are compared, it is found that the MIKE SHE model reacts more extreme on the altered rainfall and evapotranspiration.
This will probably be caused by differences among the model structure; although the differences between the projected peak flows are rather limited.

Figure 9: Nearly independent hourly low flows versus empirical return period for the low, mean and high climate scenarios simulated in the (a) MIKE SHE and (b) WetSpa models

Frequency analyses on the low flow minima of the WetSpa and MIKE SHE model results reveal a significant decrease in the low flows under all climate scenarios (figure 9). The scenarios point towards drier conditions, due to less rainfall and elevated evapotranspiration for future summer periods. Also these conclusions are consistent with the results found based on the NAM and HBV models. When comparing the impact results of both models, there seems a considerable difference. The WetSpa model reacts more sensitive to the projected changes in rainfall and evaporation than MIKE SHE, which lead to stronger decreases of the low flows. From this comparison, it is clear the uncertainty in the hydrological model, caused by disagreements among the model results, might be as strong as the uncertainty in the climate scenarios.

In conclusion, table 3 summarizes the climate impact researches for the Belgian territory at Flanders Hydraulics Research with their studied area, applied hydrological model, version of climate scenarios and the studied impact.

Table 3: Overview of the climate impact research at Flanders Hydraulic Research

<table>
<thead>
<tr>
<th>Reference</th>
<th>Model</th>
<th>Impact</th>
<th>Study area</th>
<th>Scenario (version)</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Boukhris et al., 2008</td>
<td>NAM (+MIKE11)</td>
<td>- Hydrology - Floodmaps</td>
<td>Sub-basins of Scheldt river basin district</td>
<td>May 2007</td>
</tr>
<tr>
<td>- Vansteenkiste et al., 2009a</td>
<td>NAM (+MIKE11)</td>
<td>- Hydrology - Floodmaps</td>
<td>Sub-basins of the Leie and Bovenscheldt</td>
<td>December 2008</td>
</tr>
<tr>
<td>- Vansteenkiste et al., 2009b</td>
<td>HBV (+MIKE11)</td>
<td>- Hydrology - Floodmaps</td>
<td>Meuse</td>
<td>December 2008</td>
</tr>
<tr>
<td>- Vanneuville &amp; Holvoet, 2009</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.3.2 Role of hydrological models in the climate change impact research

There is a wide variety of rainfall-runoff models available. The models are supposed to be chosen according to the study region and basin characteristics, available data and study purposes. Depending on these criteria, a lumped conceptual model may be all that is required for the climate change impact research. Climate change impact modelling mainly needs precipitation and evapotranspiration input. However, Ludwig et al. (2009) stated that models with a low physical complexity are inadequate for application in a climate change context. It is generally not clear what kind of hydrological model, with what level of complexity, is more suitable for climate change impact assessment and how much uncertainty is associated with the model. While uncertainty due to climate modelling and scenarios has been well documented, little research has been conducted on the uncertainty in climate change impact assessments derived from impact models. Uncertainty analysis on hydrological models has been extensively done, but without focus on the climate change impact extrapolations. However, Van Steenbergen et al. (2010) developed a method to investigate the predictive capacities for peak flow modelling in climate change impact studies.

There are many sources of uncertainty in hydrological impact studies using hydrological models (Prudhomme and Davies, 2009). Model structural uncertainty can be roughly evaluated through analysing differences in the output from different models. Another approach is to estimate the model structural uncertainty as risk uncertainty after quantifying input and parameter uncertainties.

This section aims at analyzing the effect of hydrological models in the impact research by comparing the modelled runoff changes from the different impact studies reported in the previous sections. These impact studies have been done using a variety of hydrological models with different levels of complexity, but they applied the same type of climate change scenarios. This allows a strict comparison of impact results and permits to point out the specific behaviour of the applied models. Table 4 shows the variation of hourly runoff peaks and low flows from the different impact studies (assessed following the method described in section 2.2.)

Table 4: Averaged variation in nearly independent peak and low flows for the low, mean and high climate scenarios assessed by different hydrological models

<table>
<thead>
<tr>
<th>Modelcode</th>
<th>Catchment Description</th>
<th>Variation of high flows</th>
<th>Variation of low flows</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Low scenario</td>
<td>Mean scenario</td>
</tr>
<tr>
<td>NAM</td>
<td>Catchments over Flanders</td>
<td>-28%</td>
<td>-2%</td>
</tr>
<tr>
<td>HBV</td>
<td>Meuse</td>
<td>-20%</td>
<td>+6%</td>
</tr>
<tr>
<td>WetSpa</td>
<td>Grote Nete</td>
<td>-10%</td>
<td>+5%</td>
</tr>
<tr>
<td>MIKE SHE</td>
<td>Grote Nete</td>
<td>-20%</td>
<td>+5%</td>
</tr>
</tbody>
</table>
The impact results, assessed by the WetSpa, MIKE SHE and HBV modelling represent the results from one case study, while the impact analysis with the NAM hydrological model was conducted on many sub-basins of the Scheldt river basin district. The range of these NAM impact results is very wide. For the comparison with the other models, the impact results from the NAM modelling of Vansteenkiste et al. (2009a) is taken and averaged over the different sub-basins. These NAM impact results are preferred above the NAM impact results from Boukhris et al. (2008) as the latter were quantified with an earlier version of the climate scenarios (version may 2007) (see also table 3). Although the case studies in the different impact analyses have other properties, some clear trends can be seen from the table.

When considering the variation in peak and low flows by climate change, all models simulate the same impact tendencies. The sign of projected changes to peak and low flows is similar for all hydrological models. This gave confidence that they are plausible estimates of the hydrological response of the applied scenarios. Winter discharges and peak flows might increase as well as decrease depending on the climate scenario, while summer discharges are expected to decrease, reducing water availability for various sectors. The magnitude of changes is, however, different between the models. Here, it should be emphasised that not all models are applied on the same basin, and differences in impact results might be related to basin geomorphological characteristics. Catchments in which the fast runoff components dominate over groundwater base flow are more sensitive to climate change than others (Brouyère & Dassargues, 2004). Boukhris et al. (2008) and Vansteenkiste (2009a) analyzed the relation between hydrological responses to the climate change scenarios and the local physico-morphological characteristics of the basin and found only (weak) influences (which might be due to inconsistencies in calibrated parameter values of the hydrological models, given that the models they studied were calibrated by different persons).

Next to this analysis, the magnitudes of change can be examined with respect to the level of detail with which the models represent the hydrological processes and the spatial resolution. This comparison focuses on the analysis to what extent and why different model concepts influence model results. First of all it is noticed that the range of variations in peak flows among the models is not very different. MIKE SHE simulates the strongest increase in peak flows, while NAM simulates the lowest impact of the wet, high climate scenario. Under the low scenario the decrease is smallest by the WetSpa model. The intercomparison of hydrological models in this study demonstrates differences in impact results, indicating additional uncertainty on the hydrological impact above the uncertainty by the climate scenarios. The uncertainty on the modeled peak flow changes is relatively small considered to the uncertainty by climate scenarios. These results support previous findings that climate modelling structural uncertainty is greater than hydrological modelling uncertainty with simulations of runoff under climate change scenario (Kay et al., 2009).

In contrast to the small differences in peak flow changes, the projected changes in low flows are quite different between the models. WetSpa, NAM and HBV model are more sensitive to the changes in precipitation and evaporation with a simulated decrease of lowest daily summer base flows up to 70% during dry summers, while MIKE SHE simulates maximum 35% decrease. These inter-hydrological model differences between MIKE SHE and the other models might be related to the description of the groundwater component as also discussed in section 2.3.1. Good agreement might be found between observed and modelled hydrographs by the conceptual models. This demonstrates the ability of such models to simulate the overall pattern of the flow response across the whole range of flows. However, it is not clear whether these models can be relied on when predictive computations are performed with aquifer stresses that will possibly lie out of the calibration range. But it is also not clear if the more complex and detailed physically based models will lead to better hydrological predictions. More complexity means more parameters, more parameters means more calibration problems, more calibration problems will often mean more uncertainty in the predictions, particularly outside the range of the calibration data.
In conclusion of this section we briefly summarize our findings. The hydrological models used in the climate impact research at Flanders Hydraulics Research have different sensitivity to climate change, especially for low stream flows. The reason is that in the high flow rates, the precipitation is the dominant factor in runoff estimation, while in the dry periods the model structure plays a major role. For these low stream flows MIKE SHE simulates changes significantly different from the other models (NAM, HBV and WetSpa). MIKE SHE is in comparison to the other models more detailed physically based over its components. For impact studies, in which the complete catchment hydrological system is important, more detailed physically based and spatially distributed models seem, in principle, to be favoured to simulate the hydrological behaviour. These models should reflect our understanding of hydrological systems more closely and therefore be more robust in extrapolation to other conditions (Grabs et al.; 1997). However, it is not clear if these models will lead to better hydrological predictions because of their large amount of parameters. This leaves the possibility open that other, parametrically simpler, models may have much to offer. In that context, Yu (2002) stated that for simulating the hydrological response to climate change, physically based distributed models currently offer no advantage over the traditional conceptual lumped water-balance models. Other authors, however, tend to give a greater belief to models that are considered to be physically based relative to those that are more conceptual.

2.4 Other climate change studies for Belgium

This part presents a synthesis of several published climate change impact studies carried out on Belgian catchments, apart form the research at Flanders Hydraulics Research. Impact results of these studies are not considered earlier in the inventory because of different analysis methods and/or climate scenarios were used.

Baguis et al. (2010) investigated the impact of the CCI-HYDR climate changes on the runoff regime of the Ourthe at Angleur and the Gete at Halen using the SCHEME hydrological model. The impact analysis concerns changes in mean monthly flows, the frequencies of low and high flow events, expressed by the 5th and 95th percentiles of the simulated series, and a stream flow level with return period of 100 years, defined by the fitted probability distribution of the yearly maximal values. Results indicated that mean flows by the scenario simulations will be lower than the corresponding control values. Future hydrological behaviour is signalling a reduction of low flows in summer, while the impacts are not clear in the case of the high flows frequency. Regarding the extreme stream flow level (with return period of 100 years) no significant change is expected for the Gete. For the Ourthe the extreme flow will change significantly depending on the climate scenario taken into consideration.

Poelmans (2010, 2011) investigated the potential impact of land cover change (urban expansion), climate change and the combined impact on the peak flows and the spatial extent of floods in the Molenbeek, a small-scale suburban catchment in the Dijle catchment. In that study the lumped rainfall-runoff model, described in section 1.3.2, was used to calculate the impact of land cover change and climate change. Climate scenarios by 2050 were generated on a daily basis using the CCI-HYDR perturbation tool of Ntegeka et al. (2008), including the wet summer scenario, wet winter scenario and dry scenario. After calibration and validation, the model was applied to simulate the impact of urban expansion and climate change in the near future (2050). Impact is assessed on the peak flows, which were selected by the peak-over-threshold method. The conclusion of the study was that climate change tends to have stronger impact than urban expansion. Future peak flows might increase (on average) with more than 30% under a wet summer scenario, while they will decrease with almost 18% under a dry scenario.

Bauwens et al. (2010) studied the effects of climate change on the Vesdre and Lesse catchments using the hydrological model EPICGrid. The CCI-HYDR scenarios were simulated for the two time slices (2020–2050 and 2070–2100) for only the high (wet) and low (dry) scenarios. Impact of these scenarios was focused on the changes in high and low flows and mean monthly flows. High flows are defined by the yearly maxima, low flows by the mean annual 7-days minimum flow.
After adjusting probability distributions to these extremes the impact is assessed by comparing the distributions. For the dry scenario, the low flows are expected to decrease for all return periods for the Lesse and Vesdre catchments whereas they increase for the wet scenario. High flows will be higher for the wet scenario with respect to the reference, whereas for the dry scenarios, high flows will be generally lower. In contrast to the catchments in Flanders where low flows will decrease by climate change, the effect of climate change is very unclear as well on high as low flows for these two catchments in Wallonia. Mean monthly flows experience a strong increase for the wet scenarios from December to May, whereas a strong decrease is predicted from June to November. For the dry scenarios, a decrease in mean flow rates is observed almost every month, except in late spring.

Woldeamlak et al. (2007) analyzed the sensitivity to climate change of water balance components for the Grote Nete catchment using an uncoupled water balance module (WetSpaSS). WetSpaSS computes seasonal and annual recharge, evapotranspiration and runoff. Sequentially, the simulated mean annual recharge for various scenarios was used as input to a steady-state groundwater model (MODFLOW) to simulate the impact on groundwater conditions. Climate change is modelled using wet (greenhouse), cold or NATCC (North Atlantic Thermohaline Circulation Change) and dry climate scenarios. These scenarios are based on the empirical relation between precipitation and daily mean temperature (Kors et al., 2000). The climate scenario simulations showed increases in surface runoff, groundwater recharge and evapotranspiration for all seasons and annual totals, except for the summer groundwater recharge. For future summers more water will be lost than can be replenished due to low precipitation and high evapotranspiration, especially by forests. The larger increases in winter precipitation relative to summer precipitation resulted in an increase in the proportion of annual groundwater recharge occurring during winter in the year 2100. Stronger dynamics in groundwater heads might be expected. For future studies, Woldeamlak et al. (2007) suggested the use of transient models to study seasonal variations of the groundwater components, inclusion of land use change scenarios, and an improved representation of the coupling between groundwater and surface water.

Dams et al. (2010) quantified the impact of the CCI-HYDR 27 RCM runs on groundwater for the Kleine Nete catchment using respectively the WetSpa water balance model and MODFLOW groundwater model. Dams concluded that these CCI-HYDR scenarios generally will reduce recharge and groundwater heads, especially during summer and autumn, and increase the groundwater dynamics. The impact on the groundwater level is larger on interfluves and important inter-annual changes are caused by climate change.
3 Climate change impact research in neighbouring countries

In the previous chapter an overview was given of the climate impact research in Belgium from the development of the climate scenarios to the analysis of the hydrological impact results. To gain extra information about the climate impact research, we had a look to the climate impact modeling in neighbouring countries. Rivers do not stop at the country borders, but impact results might differ up- and downstream of the borders because of differences in the approaches applied to assess the climate impact. In the following sections we focus on the hydrological models and the methodology which are commonly used across Europe to assess the impact of climate change on river flows. These might give valuable information for the research in Belgium.

3.1 Hydrological models

Many hydrological models have been developed and applied to basins across Europe. Some of them are listed in table 5. These models vary from simple reservoir-types to highly complex physically based ones. The lumped reservoir models in the list correspond to various conceptualizations of the rainfall-runoff transformation at the catchment scale. They include a soil moisture accounting procedure in their representation of the hydrological production function, but with various formulations (linear or non linear, possibly with several soil layers, etc.). It is out of the scope of this inventory to present the models. Full descriptions of each model structure can be found in the references listed in the table. All models in the table have been widely used in hydrological research.

From literature it is found that conceptual models with higher complexity gave the best simulation of daily high and low flows (Chiew et al., 1993). However, the model should not be too complex since that may lead to over-fitting and poor extrapolation, but at the same time it should not be too simple and include the dominant processes (figure 10). Hydrological model residuals have been extensively studied under current climate conditions, but little information is available on the prediction error of hydrological models under scenario investigations (Shoups et al., 2008). It is current unsatisfactory known how these models react to change in climate variables, and to what extent model structure is influencing the climate change impact predictions (see previous chapter).

<table>
<thead>
<tr>
<th>Hydrological model</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>GR3J</td>
<td>Berthet et al., 2009</td>
</tr>
<tr>
<td>Wageningen model</td>
<td>Warmerdam et al., 1997</td>
</tr>
<tr>
<td>PDM</td>
<td>Moore et al., 1981</td>
</tr>
<tr>
<td>Tank model</td>
<td>Sugawara, 1979</td>
</tr>
<tr>
<td>SMART</td>
<td>O'Connell et al., 1981</td>
</tr>
<tr>
<td>TOPMODEL</td>
<td>Michel et al., 2003</td>
</tr>
<tr>
<td>HYMOD</td>
<td>Yadav et al., 2007</td>
</tr>
<tr>
<td>Model</td>
<td>Reference</td>
</tr>
<tr>
<td>----------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>CEQUEAU</td>
<td>Girard et al., 1972</td>
</tr>
<tr>
<td>IHAC, a lumped modified version of IHACRES</td>
<td>Jakeman et al., 1990</td>
</tr>
<tr>
<td>SIMHYD</td>
<td>Chiew et al., 2002</td>
</tr>
<tr>
<td>MOHYSE</td>
<td>Fortin et al., 2006</td>
</tr>
<tr>
<td>SACRAMENTO</td>
<td>Burnash et al., 1973</td>
</tr>
<tr>
<td>MIKE SHE</td>
<td>Abbott et al.; 1986</td>
</tr>
<tr>
<td>WetSpa</td>
<td>De Smedt et al., 2000</td>
</tr>
<tr>
<td>SWAT</td>
<td>Arnold et al., 1993</td>
</tr>
<tr>
<td>the WaSIM-ETH model, which is based on the TOPMODEL</td>
<td>Beven and Kirkby, 1979</td>
</tr>
<tr>
<td>HSPF</td>
<td>Johansen et al., 1984</td>
</tr>
<tr>
<td>IRBM</td>
<td>Bultot and Dupriez, 1976</td>
</tr>
<tr>
<td>SIM</td>
<td>Habets et al.; 2008</td>
</tr>
<tr>
<td>MODCOU</td>
<td>Ledoux et al.; 2007</td>
</tr>
<tr>
<td>GR4J</td>
<td>Perrin et al.; 2003</td>
</tr>
<tr>
<td>EROS/GARDENIA</td>
<td>Thiéry and Moutzopoulos, 1995</td>
</tr>
<tr>
<td>CLSM</td>
<td>Gascoin et al.; 2009</td>
</tr>
<tr>
<td>HBV</td>
<td>Bergström et al., 1973</td>
</tr>
<tr>
<td>HYSIM</td>
<td>Manley, 2003</td>
</tr>
<tr>
<td>PDM</td>
<td>Moore et al., 1981</td>
</tr>
<tr>
<td>Tank model</td>
<td>Sugawara, 1979</td>
</tr>
<tr>
<td>SMART</td>
<td>O’Connell et al., 1981</td>
</tr>
</tbody>
</table>

A transboundary impact research is currently been executed on the Meuse within the framework of the AMICE project. Hydrological impact results of climate scenarios in the sub-basins over the different countries are combined to assess the impact on a larger scale. For the hydrological simulations each country has used its own models. Table 12 presents the main characteristics of hydrological models used in the project.
Figure 10: Model complexity control for hydrologic prediction (adopted from Shoups et al., 2008)
Table 6: Main characteristics of hydrological models used in neighboring countries (AMICE, 2010)

<table>
<thead>
<tr>
<th>Name</th>
<th>GR4J/PRESAGES</th>
<th>AGYR</th>
<th>HBV</th>
<th>NASIM</th>
<th>GR4J</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country</td>
<td>France</td>
<td>France</td>
<td>The Netherlands</td>
<td>Germany</td>
<td>Germany</td>
</tr>
<tr>
<td>Type of RR model</td>
<td>Lumped reservoir based</td>
<td>Lumped reservoir based</td>
<td>Semi-distributed conceptual model</td>
<td>Distributed physically based/conceptual model</td>
<td>Lumped reservoir model</td>
</tr>
<tr>
<td>Number of parameters</td>
<td>4</td>
<td>4</td>
<td>5-6</td>
<td>Several</td>
<td>4</td>
</tr>
<tr>
<td>Groundwater infiltration and recharge</td>
<td>Percolation function + basin water exchange</td>
<td>Percolation function + basin water exchange</td>
<td>Percolation function</td>
<td>Percolation function + basin water exchange</td>
<td>Percolation function + basin water exchange</td>
</tr>
<tr>
<td>Runoff components</td>
<td>Overland flows, Base flows</td>
<td>Overland flows, Base flows</td>
<td>Fast and slow runoff response</td>
<td>Overland flows, Base flows</td>
<td>Overland flows, Base flows</td>
</tr>
<tr>
<td>Input of climate data</td>
<td>P, PET</td>
<td>P, PET</td>
<td>P, PET, T</td>
<td>P, PET</td>
<td>P, PET</td>
</tr>
<tr>
<td>Temporal resolution</td>
<td>Daily</td>
<td>Minutes to hour</td>
<td>Daily</td>
<td>15-30min</td>
<td>Daily</td>
</tr>
<tr>
<td>Efficiency in high flows</td>
<td>-</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Efficiency in low flows</td>
<td>-</td>
<td>-</td>
<td>Moderate</td>
<td>-</td>
<td>Good</td>
</tr>
</tbody>
</table>
For a similar climate change study on the Rhine (Middelkoop et al., 2001), the impact results by different hydrological models, applied by different countries, were combined. The hydrological models include:

- the WaSiM-ETH model, which is based on the TOPMODEL (Beven and Kirkby, 1979; Beven et al., 1984) and the IRBM model (Bultot and Dupriez, 1976) for the Rhine part in Switzerland,
- the Hydrological Simulation Program Fortran (HSPF) for the part in Germany;
- the ‘Wageningen model’ (Warmerdam et al., 1993) for the Dutch part.

In the above studies impact results are combined over the country borders to assess the impact of climate change on a larger scale. However, this does not provide information on the range of diversity obtained when different hydrological models are used for a given climate scenario. To consider the model structural uncertainty a set of models need to be considered and compared. This type of research has not been widely investigated and reported in literature. A few examples of studying the difference in hydrological impact could be found.

In the study by Ducharne et al. (2010), 5 hydrological models are used and their differences in predicting hydrological impacts of climate change scenarios are compared. The study is performed on the Seine and the Somme basins in Northern France using the following hydrological models:

- SIM (= combined SAFRAN-ISBA-MODCOU model),
- MODCOU (= the distributed hydrological model Coupled Model),
- CLSM (= the Catchment-based Land Surface Model),
- EROS/GARDENIA,
- GR4J (= Genie Rural a 4 parametres Journalier).

Similar research was done by Murphy (2010) on the Suir catchment in Ireland using

- HBV (Bergström et al., 1973);
- HYSIM (Manley, 2003).

The results and conclusion of these studies are described in the next section. Other intercomparison was done by Jiang et al. (2007) for the Dongjiang basin in South China with six monthly water balance models.

3.2 Climate change impact analysis and methodology

In the climate change impact analysis water managers and policy makers are interested in the changes of the flow profile and more specific in the extreme behavior under current as well as under future conditions including climate change. Knowledge of this extreme behavior (flood peak discharges and drought periods) and their alterations in the future is essential for water resources planning, risk management, project design, etc. The objective of this section is to present some impact studies in neighbouring countries and highlight their methodology and impact results.

From reported impact studies across Europe (a.o. Dankers and Feyen, 2008; AMICE, 2010; Ducharne et al., 2010) it follows that probability distribution families are commonly used to assess the impact on hydrological extremes. These allow us to quantify the impact of climate change by the shift in the distribution of the extremes under current climate and future scenarios.

In AMICE (2010) a transboundary climate change impact analysis is described for the Meuse. High flow analysis is based on the annual maximum discharges (hourly as well as daily). Low flow analysis uses the MAM7 or mean annual 7 - day minimum flows. This is the lowest value of the moving average of the flows reached during 7 consecutive days a year. After selecting these high and low flow extremes, different methods and distributions were used to fit these extremes. Discharges under current and future climate conditions are generated from the distribution for the return period 2 - 5 - 10 - 25 - 50 - 100 years and compared to assess the impact.

Dankers and Feyen (2008) applied an identical method to investigate the impact of climate change impact on flood hazard in Europe. Discharges with return period of 100 years were generated from the distributions and relative changes between the current and future climate assessed.
Ducharne et al. (2010), who examined the impact on the hydrological extremes for Seine and Somme rivers by 5 hydrological models, also applied this classical frequency analysis method. Annual monthly minima were applied for low flows analysis; annual daily maxima for high flows. The impact was assessed on the mean return period of 5 and 10 years for respectively low and high flows as these two variables are operationally used as alert thresholds and for infrastructure design, and are thus relevant for water management issues. Intercomparison of the different models reveals a wide range in simulated impact. The models are predicting different impacts on the high but as well on low flow quantiles.

Intercomparison of the sensitivity to climate scenarios for 2050 and 2080 of HBV and HYSIM hydrological model was examined by Murphy (2010). High and low flows were defined by the 5th and 95th percentiles of the annual flows. These are respectively the flows reached or exceeded 5% and 95% of the year. HBV-Light modelled much greater percentage changes in high flow than HYSIM for the 2050s and the 2080s climate scenario. For low flows, HYSIM consistently modelled greater absolute changes in low flows for both future time slices. It again is concluded that the hydrological impacts of climate change are quite different depending on the hydrological model, even when the same climate scenarios are used for the simulations.

These studies and results confirm the findings in the hydrological impact analysis by WetSpa and MIKE SHE (Vansteenkiste et al., 2011). However, more studies using different hydrological models on different catchments need to be carried out in order to provide more general conclusions; although at the same time it should be mentioned that impact results might differ from region to region.
4 Conclusion

4.1 Recapitalizations

This inventory attempted to provide a complete picture of the hydrological climate impact research in Belgium and to compare this with the recent and ongoing studies in neighbouring countries.

Hydrological models of Belgian catchments were developed with different characteristics and purposes. Many different hydrological models types are and have been applied to model the hydrological response of Belgian catchments. Conceptual rainfall-runoff models like NAM and PDM are commonly used due to their significant advantages regarding parameter estimation and computational time, when compared to physically based models. Physically based, distributed models require a large amount of high quality spatially-explicit input data. They are often difficult to parameterise and have extended simulation times. Only a limited number of studies with these models are known for Belgian catchments. Intermediate physical-conceptual models also exist and have some applications in Belgium (e.g. WetSpa, SWAT). Investigation of the model performance showed that all hydrological model types are able to simulate the overall hydrological regimes for Belgian catchments in an acceptable way. However, it is experienced at Flanders Hydraulics Research that the NAM model code has difficulties in accurately simulating low flows, while research on the predictive capacities for peak flow modeling indicated that PDM might overestimate peak flows in climate change impact studies. These findings have to be taken into account in the impact research.

Over the past decennia many hydrological models have been used to study the impacts of climate change on water resources for the Belgian territory. A large scale impact study (with conceptual models) at Flanders Hydraulics Research investigated the trends in the changes of high and low flow extremes over the Flanders region of Belgium. Similar trends were found for all catchments: higher as well as lower winter discharges as a result of increased winter precipitation and evapotranspiration, and lower summer discharges due to the reduced summer rainfall volumes and increased evapotranspiration. When the impact results are considered in detail, small differences between the catchments show up. These can firstly be attributed to different physical characteristics of the studied areas, but also the applied models might affect the results. Comparison of the impact results for simple (lumped, conceptual) and more detailed physically-based hydrological models showed major differences. These were found on the impact of low flow minima, while the differences in high flows changes between the models were rather limited. One reason is that precipitation is the dominant factor in peak runoff estimation, while in the dry period the model structure plays the major role. The physically-based MIKE SHE model results in a considerable smaller decrease of the low flows than other models (HBV, NAM, WetSpa). This difference might be a consequence of the flexibility of the MIKE SHE model structure, which has a mechanism that more realistically accounts for groundwater flow. Simplifying the representation of the groundwater system (conceptual models) might lead to discrepancies in the climate projections. It also can be due to the overparameterization of the MIKE SHE model. In spite of the uncertainties among the climate scenarios and applied models, the results indicate similar changes in the discharge regime by 2100. The results should therefore be interpreted in terms of overall trends rather then accurate quantitative predictions of hydrological changes. Climate impact studies in neighbouring countries also found these uncertainties related to the hydrological model. However only little research has been conducted on the uncertainty in climate change impact assessments derived from impact models, while uncertainty due to climate modelling and scenarios has been well documented.

4.2 Suggestions

Comparison of the impact results from the different modeling studies in this inventory indicated that the model structural uncertainty might be an important source of uncertainty in local climate impact assessment. More studies using different hydrological models on different catchments need to be carried out in order to provide more general conclusions. Therefore, we recommend further research in this area in order to exhaustively explore hydrological impact of climate change.
Primarily the hydrological model codes available at Flanders Hydraulics Research need to be further examined. These model codes are VHM, PDM, NAM, WetSpa and MIKE SHE and range from simple conceptual to highly complex physically based ones. Physically based models should, in principle, reflect our understanding of hydrological systems more closely and should therefore be more robust in extrapolation to other conditions. However, little information is known about the predictive power of the hydrological models under changing (climate) conditions. Research towards this predictive power of hydrological models has been initiated by Van Steenbergen et al. (2010) for peak flows. That research needs to be continued and extended with a quantitative technique for the evaluation of modelled low flows. By applying this technique to the available models, we might be able to answer the question whether the available model codes are suitable to study the hydrological cycle in a future climate, which differs from the climate the model was calibrated for. Additional research is also needed on the research question whether groundwater flows needed to be modelled in a fully physically-based way in order to obtain a reliable prediction of the impact of climate change on the base flows. If this way of physically-based modelling indeed produces more reliable results, similar model structures can be tested like the SWAT model with MODFLOW extension, GSFLOW which combines the PRMS with MODFLOW, MOHISE. Also other conceptual models which are used in neighbouring countries like NASIM, … can be tested.

The impact research moreover needs to be extended to other catchments, which are from hydrological point of view different and which represent the most relevant hydrological regions of the country. It might allow us to investigate the sensitivity of basin characteristics to climate change. It is expected that catchments in which the fast runoff components dominate over groundwater base flow, are more sensitive to climate change than others.

Additionally the contribution of external discharges from wastewater treatments plants and industry and their impact on the low flows need to be further examined.
Referenties


AMICE, 2010. Analysis of climate change, high - flows and low - flows scenarios on the Meuse basin. WP1 report - Action 3


Effect of climate change on the hydrological regime of navigable water courses: Subreport 1 - Literature review of the climate research in Belgium


Fortin, V., Turcotte, R., 2006. Le modèle hydrologique MOHYSE. Note de cours pour SCA7420, Département des sciences de la terre et de l’atmosphère, Université du Québec `a Montréal.


Effect of climate change on the hydrological regime of navigable water courses: Subreport 1 - Literature review of the climate research in Belgium


Soresma, 2002. Hydrologische modellering van de Heulebeek te Heule, in opdracht van AMINAL.


Thornthwaite, C.W., Mather, J.R., 1955. The Water Balance, Laboratory of Climatology, Publ. No. 8, Centerton NJ.


Effect of climate change on the hydrological regime of navigable water courses: Subreport 1 - Literature review of the climate research in Belgium


Willems, P., 2010. Parsimonious rainfall-runoff model construction supported by time series processing and validation of hydrological extremes. EGU General Assembly 2010, 2-7 May, Vienna


