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Hydrological response to climate change in the Lesse and the Vesdre catchments: contribution of a physically based model (Wallonia, Belgium)

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Abstract. The Meuse is an important rain-fed river in North-Western Europe. Nine million people live in its catchment, split over five countries. Projected changes in precipitation and temperature characteristics due to climate change would have a significant impact on the Meuse River and its tributaries. In this study, we focused on the impacts of climate change on the hydrology of two sub-catchments of the Meuse in Belgium, the Lesse and the Vesdre, placing the emphasis on the water-soil-plant continuum in order to highlight the effects of climate change on plant growth, and water uptake on the hydrology of two sub-catchments. These effects were studied using two climate scenarios and a physically based distributed model, which reflects the water-soil-plant continuum. Our results show that the vegetation will evapotranspirate between 10 and 17 % less at the end of the century because of water scarcity in summer, even if the root development is better under climate change conditions. In the low scenario, the mean minimal 7 days discharge value could decrease between 19 and 24 % for a two year return period, and between 20 and 35 % for a fifty year return period. It will lead to rare but severe drought in rivers, with potentially huge consequences on water quality.

1 Introduction

The Meuse and its catchment are very important for North-West Europe. With its 950 km long river, the Meuse catchment covers an area of approximately 36 000 km^2 in a densely inhabited region of Europe. Almost nine million people live in the Meuse catchment and six million of them depend on the Meuse for their water supply. The Meuse originates in Champagne-Ardenne in France and flows through France, Belgium and the Netherlands to reach the Haringvliet sea stretch. Its transnational catchment covers five countries: France, Belgium, the Grand-Duchy of Luxembourg, Germany and the Netherlands. The Meuse is characterized by a rainfall-evaporation regime with high runoff in winter and low in summer. Its future behavior will thus be strongly dependent on the perturbation of meteorological conditions. During floods, huge damages occur, such as during the floods of 1993 and 1995. During low flows, consequences for water supply and water quality occur with impacts on drinking water supply, shipping, agriculture and economy (Driessen et al., 2010).

Despite the great uncertainties regarding the future climatic context, a lot of studies have focused on hydrological modeling of climate-change effects in numerous catchments. In Belgium, Gellens and Roulin (1998) assessed how different IPCC scenarios could affect the number of flood and low-flow days in several catchments. Using a conceptual hydrological model, they showed that climate scenarios but also soil infiltrability and water storage were of major concern in order to describe catchment behavior under climate change. Similarly, in the Rhine catchment, Middelkoop et al. (2001) assessed the hydrological behavior of several small watersheds by existing conceptual hydrological models. They showed how the representation of hydrological processes in the models can affect modeling results, even if the main conclusion (increase of flood days due to climate change) was given by most of them.

More recently a series of paper have deeply discussed the impacts of climate change scenarios on the hydrology of the Meuse using the HBV semi-distributed rainfall-runoff model (Booij, 2005; de Wit et al., 2007; Leander et al.,

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2008; van Pelt et al., 2009; Driessen et al., 2010). Authors have used perturbed meteorological data from different GCM/RCM combinations under different SRES scenarios. These studies mainly focused on high flows and indicated that high flows could strongly increase, by between 10 % and 55 % during the 2070–2100 period.

It is now recognized that water shortage and low-flows have to be considered in water resources planning. Indeed, management of environmental flows, licensing of surface water and groundwater extraction and management of discharges into streams will also be affected by climate evolution (Smakhtin, 2001). There is a need to provide monitoring and analysis of low-flows to support integrative basin management (World Meteorological Organisation, 2008).

In their review of recent modeling strategies, Teutschbein and Seibert (2010) emphasized how hydrological modeling has focused on future climate uncertainty. They showed that multi-GCM/RCM approaches are more useful for climate change impact assessments than a single RCM. But they also point out that the hydrological models themselves deserve further work. The broad palette of available hydrological models was previously highlighted by Booij (2005). This author clearly stated that an optimal model needs to be found that takes into account specific modeling objectives and data availability. No study has been found using a distributed physically based model to assess climate change impacts on the Meuse catchment.

In the present study, we placed the emphasis on using a model which reflects the water-soil-plant continuum. The physically based model we used addresses the complexity of the phenomenon and the influence of climate change on this continuum. Our aim is to assess how vegetation will play its role in the response of the catchment to climate change. This is particularly important in local, more detailed modeling where an empirical model failed to predict detailed aspects of the phenomena involved (Bittelli et al., 2010; Grizzetti et al., 2005).

Indeed, many adaptation and mitigation measures recommend the renaturation of some areas aiming at increasing natural water retention. A correct modeling of the relationships between water, soil and plants is thus very important in order to simulate the behavior of the catchment before and after such adaptation measures have been employed. However, many physically based models studying the soil-plant-atmosphere continuum work at field or plant scale (Hernandez-Santana et al., 2009; Eitzinger et al., 2003; Holden and Brereton, 2006). In this study, we used a physically based model that works at watershed scale. This way, we try to build a bridge between hydrology and crop science in order to progress towards a better understanding of catchments' future behavior and to help decision on no-regret adaptation options.

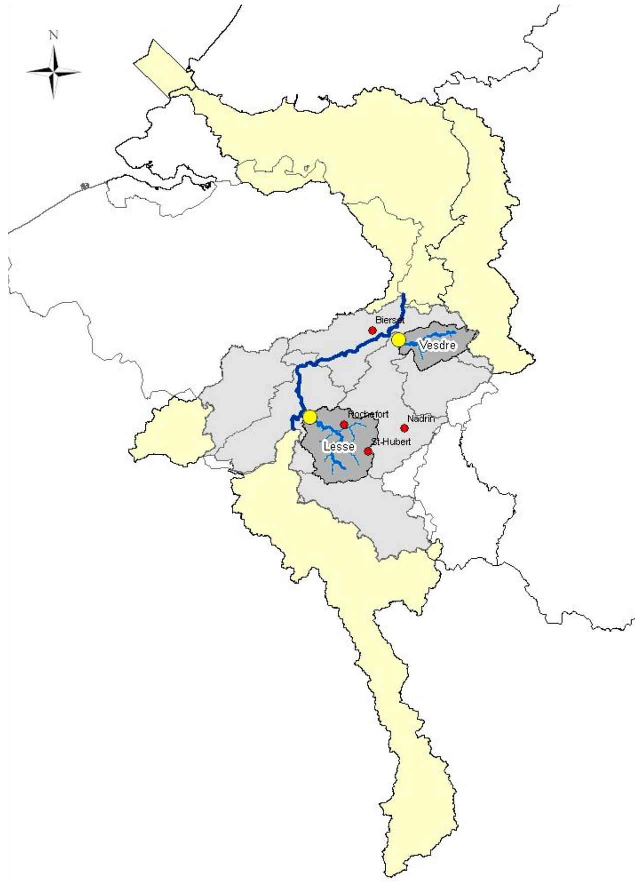

Fig. 1. The Meuse catchment (light grey) in Wallonia (Belgium) and the Vesdre and the Lesse catchments (dark grey).

2 Material and methods

2.1 Study area

The Vesdre catchment (Fig. 1) is located in the North-East of Wallonia (Belgium). The Vesdre River flows into the Ourthe in Chênée (near Liège) and has its origin in the Hautes-Fagnes nature park near the German border. Rural areas are mainly located in the South-East (Fagnes, Jalhay), while urbanized areas are mainly seen on the west side of the catchment (Verviers, Chaudfontaine, Liège). The drainage area of the Vesdre catchment is 683 km^2. Dams present on the catchment influence natural flow of the Vesdre.

The Lesse catchment is located in the middle of Wallonia and has a drainage area of 1284 km^2. The Lesse River flows into the Meuse at Anseremme near Dinant and has its origin near Ochamps.

A comparison between land uses for the Lesse and for the Vesdre catchments shows that the Lesse catchment is less urbanized than the Vesdre (8 % vs. 16 %) and has fe % vs. 3 %) and grasslands (11 % vs. 2 %).

Table 1. Distribution of soil classes (%) for the Lesse and the Vesdre catchments, based upon the Belgian simplified pedological map at 1/50 000.

Soil classes	Lesse	Vesdre
No data	0.00	1.66
Loamy soils with textural B horizon	0.74	5.53
Sandy-loam or silt substrate undifferentiated on clay-sandy complex	0.00	1.08
Loamy stony soils with textural or structural B horizon, with gravel load	1.29	0.16
Loamy stony soils with textural or structural B horizon, with chalk or chert load	0.00	1.08
Loamy stony soils with textural or structural B horizon	31.53	22.21
Silty clay soils, shale load	5.15	0.00
Loamy stony soils with structural B horizon	21.21	18.91
Loamy soils with few stones and structural B horizon	28.94	25.19
Peat soils	0.29	8.46
Clayey soils with structural B horizon	0.00	1.82
Alluvial soils without profile development	1.09	0.46
Area with steep slopes	10.49	15.49

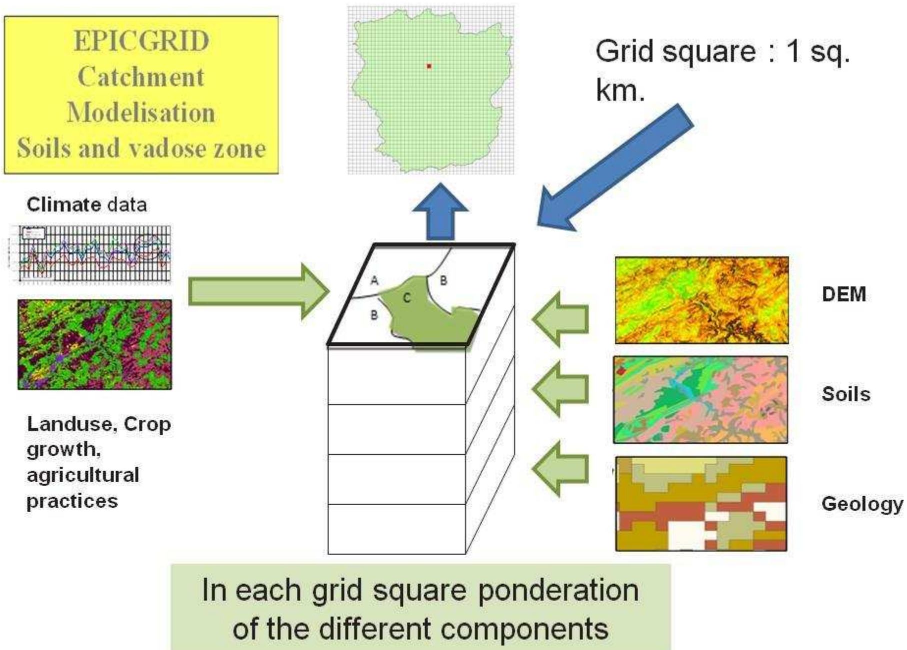

Fig. 2. Simulation structure of the EPICGrid model inside an elementary element.

The main soil classes for both catchments are loamy-stony soils, with 59 % and 42 % respectively constituting the Lesse and the Vesdre catchments. The main difference is the presence of peaty soils for the Vesdre catchment (8 %), and more areas with steep slopes and loamy soils (see Table 1).

2.2 EPICgrid hydrological model

The EPICgrid hydrological model (Fig. 2) was developed on the basis of the EPIC model (Williams et al., 1984). The EPIC model is a field scale model made up of several sub-routines dealing respectively with climate, hydrology, crop growth, tillage, erosion, nutrients cycles, pesticide movement, soil temperature, crop management and economical aspects. The EPICgrid model has been described by Sohier et al. (2009). Two main modifications have been introduced.

Firstly, field experimentations allowed one to adapt the soil description, the crop and root growth and the water uptake sub-routines to the regional context (Masereel and Dautrebande, 1995). In order to take into account the descriptions of local pedology and geology the reservoir depths in the root zone were adapted to fit the pedological horizon thickness and new reservoirs were added below the root zone down to the groundwater table in order to take the geology into account. Crop growth routine and water uptake routine were calibrated and validated by Moeremans and Dautrebande (1998) and then Cocu et al. (1999) using local measurements (crop height, soil moisture profile, root depth, crop yield) and radar imagery (surface soil moisture). The model allows us to follow the evolution of a broad range of agronomic parameters through time. Among them, the leaf area index (LAI), root depth (RD) and actual evapotranspiration (ET) are presented below. The crop growth and water uptake submodels take into account water availability into the soils and stress that affects the plant's development like drought stress (due to water deficit) or aeration stress (due to excessive water in the root zone).

Secondly, the field scale model was linked to a GIS in order to permit fully distributed hydrological modelling. A regular grid of 1 km^2 is applied to the whole Walloon Region (nearly 17 000 km^2). Each 1 km^2 cell is divided into hydrological response units (HRUs) based upon the soil description, the slope, land use and meteorological data. Each HRU is simulated separately and the outputs of a 1 km^2 grid cell are the weighted average of the HRUs'outputs, depending of their relative surface within the cell. Description and validation of the model is available in Dautrebande and Sohier (2006); Sohier et al. (2009) and Sohier and Degré (2010).

Simulations are made at a daily time step. The runoff and interflow production functions are not further calibrated. Transfer functions are based on unit hydrographs. They are calibrated on observed discharge series at the watershed outlet. There are no actual evapotranspiration (ET) measurements available. The hydrological partition between rainfall, runoff, water uptake and deep infiltration is based only on soil descriptors extracted from the Belgian soil database, taking into account daily crops' uptake and previous work cited above.

These developments made the model data intensive and more difficult to calibrate and validate, in comparison with conceptual models, like those used in previous studies (Makropoulos et al., 2008). But this model produces both classical information about daily discharge at the outlet and new information about vegetation behavior within the catchment. Indeed, actual evapotranspiration is calculated daily, on the basis of potential evapotranspiration, crop development stage and water storage in the soil.

The Nash sutcliffe criteria amount to respectively 0.75 and 0.83 for the Lesse and the Vesdre catchments (validation on a 30 year period). This difference might be explained by a karstic geology in the Lesse catchment. The 1 km^2 resolution of the geology is insufficient in these areas to correctly represent the phenomenon inherent to karstic geology. A finer scale would be necessary to correctly represent these areas.

2.3 Datasets

Daily observations of temperature and rainfall of the weather stations in St-Hubert, Nadrin, Bierset and Rochefort (Fig. 1) are available from 1967 to 2000 and daily observed discharges at Gendron and at Chaudfontaine are available for the same period. Observed weather data were spatially interpolated using the Thiessen polygons technique from the existing stations in these catchments.

The hydrological model EPICgrid uses the following inputs: a land-use map of Wallonia (COSW) at 1/10 000 scale, a digital elevation model of Wallonia at 1/10 000 scale, a simplified soil map of Belgium at 1/50 000 scale, a thickness of non saturated soil map, a database with derived data such as hydrodynamic properties of soils, and a database containing agronomic data such as cultural types and agricultural practices (from yearly national surveys) (Sohier et al., 2009).

2.4 CCI-HYDR Perturbation Tool (Version January 2009)

In addition to the observations, climate model outputs (temperature and rainfall) are available from the CCI-HYDR Perturbation Tool. The CCI-HYDR perturbation tool was developed by K. U. Leuven and RMI (Royal Meteorological Institute of Belgium) as part of the CCI-HYDR Project "Climate change impact on hydrological extremes in Belgium" for the Belgian Science Policy Office Program "Science for a sustainable development". This perturbation algorithm is especially dedicated to Belgium, and thus to the region we studied. It was developed to assess the hydrological impacts of climate change. The observed series of data are perturbed based on four SRES scenarios issued from climate model simulations extracted from the PRUDENCE and AR4 databases. The models were tested for their performance at both the local and regional scales. And the combination of regional and point performance measures led to a selection of climate models suitable for the Belgian climate. These selected models were used to investigate the climate change seasonal characteristics at both the local and the regional scale. The local scale primarily focused on observed data from the reliable Uccle station while regional analysis was based on various stations covering Belgium (Ntegeka et al., 2008). Three sets of perturbation factors (high, mean, low) are determined based upon the differences between scenarios and the reference period. The impact scenarios delivered by the CCI-HYDR perturbation tool are constructed based upon sets of perturbation factors as shown in Table 2 (Baguis et al., 2009, 2010; Ntegeka and Willems, 2008a,b). For rainfall, the changes in number of wet days and intensities are considered. The changes are quantile based to account for the fact that the changes might depend on magnitude or return period of the event. Temperature is transformed in a relative easier way by applying seasonal average changes because high

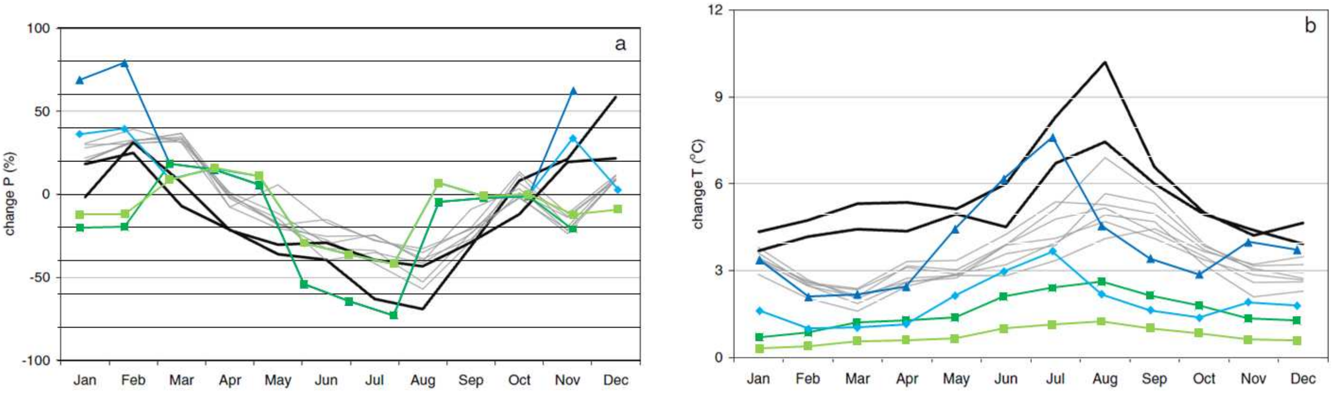

Fig. 3. CCI-HYDR high (blue) and low (green) scenarios for 2020–2050 (light colors) and 2070–2100 (dark colors) vs. PRUDENCE RCM simulation for 2071–2100 (black and grey curves) (de Wit et al., 2007). **(a)** Precipitation changes in %, **(b)** temperature changes in °C.

Table 2. CCI-HYDR impact scenarios and related changes in precipitation, temperature, ET_0 and wind (Baguis et al., 2009).

Season	ET_0/ Temperature	Precipitation/ Wind	Scenario
Winter	High	High	High/Wet
Spring	Mean	Mean	
Summer	High	Low	
Autumn	Mean	Mean	
Winter	Low	Low	Low/Dry
Spring	Low	Mean	
Summer	Low	Low	
Autumn	Low	Mean	

quantiles tend to have similar percentage changes to lower quantiles (Baguis et al., 2009).

The high scenario represents the most extreme scenario (highest hydrological impact), which corresponds to the most severe case for flood risk analysis. The low scenario represents the most severe low-flow situation. We used the low and high scenarios. One should look at the high scenario results concerning flood events and to the low scenario results concerning low-flows. The mean scenario represents mean conditions but it is not necessarily the best scenario for predicting the future (Ntegeka and Willems, 2008a).

The CCI-HYDR perturbation tool perturbs periods of data with a preference for a 30-year long period which corresponds to an average climate "oscillation" cycle (Ntegeka et al., 2008). The output series represent the perturbed input series for a target year in the future, selected between 2020 and 2100. Each target year is the center of a 30-year block if 30 years of data has been inputted. This tool was developed using data from 1961 to 1990 in order to predict climate changes from 2071 to 2100. It is thus more reliable if input data cover the periods from 1961–1990 and if the target years are within the blocks 2070, 2080 and 2090. According to Baguis et al. (2009), the linear interpolation algorithm and extrapolation of the changes could be less accurate for other target years and other reference periods.

2.5 Climate projections for Wallonia with the CCI-HYDR Perturbation Tool

As represented in Fig. 3, the largest increases in monthly rainfall during the time slice 2020–2050, appear in February and in April, respectively for the high and the low scenarios. During the time slice 2070–2100, these appear the same month as for 2020–2050, except for the low scenario when it appears one month earlier. During time slice 2020–2050 and 2070–2100, the largest decline in rainfall appears in August for both scenarios (low and high scenarios have the same related changes during the summer). For temperature, the high scenario gives a more significant rise in temperature than the low scenario and does so for all months. No decline in temperature is predicted. The largest temperature rises for both time slices appears in summer. The smallest temperature rises during both time slices appears in winter.

The CCI-HYDR Perturbation Tool was built by Baguis et al. (2009) assuming that no difference in rainfall changes between the high and low scenarios during spring, summer and autumn. The only season that differs between the scenarios is winter, which is wetter than at present with the high scenario and dryer with the low scenario.

2.6 Modeling results analysis

The hydrological response of catchments to climate change was studied following two axes. Firstly, we applied a classical statistical analysis of discharge values. The yearly maximum method is the most used to characterize exceptional high-flow. This analysis was carried out on the basis of hydrological years, from October 1st to September 30th following the method proposed by Dautrebande et al. (2006).

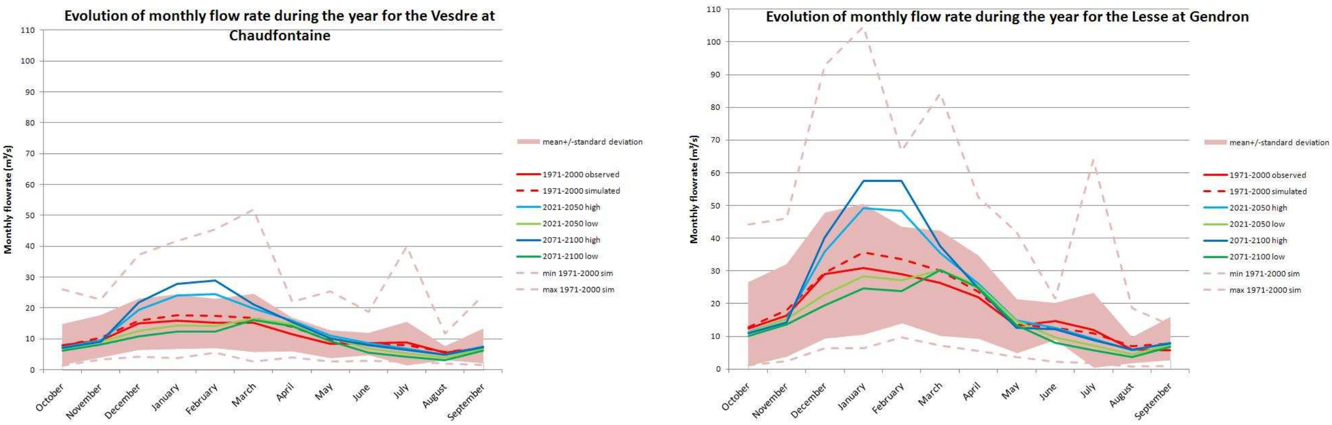

Fig. 4. Evolution of monthly flow during a year for the Vesdre at Chaudfontaine (upper panel) and the Lesse at Gendron (lower panel). The shaded areas represent the standard deviation for the reference period. Minimun and maximum represent the minimum and maximum values simulated during the reference period.

Lots of low-flows indices exist and were described by Smakhtin (2001). In this study; we used the "mean annual 7-day minimum flow" (MAM7). The methodology used was the same as the one used for maximum high flow discharge values. The evolution of discharge statistics due to climate change allows us to compare our results with those coming from conceptual models.

Secondly, we propose a study of water balance modifications. It will highlight major behavioral changes occurring in the catchments. In this study, we will focus on actual evapotranspiration, one of the major water fluxes of the two catchments. The variability of the hydrological variables and the main modifications of the behavior of vegetation due to climate change will be presented.

Booij (2005) showed that model uncertainty was low in comparison with climate scenario uncertainty and mainly scale related (using HBV). In the following, we will present our results in the frame of a thirty years calculation in order to show the temporal variability of the hydrological fluxes. Note that a complete uncertainty analysis should include a full range of climate scenario. This is beyond the scope of this paper.

3 Results

3.1 Monthly mean flow rates for the Vesdre and the Lesse catchments

Figure 4 shows the monthly flow rates for the two subcatchments and the different scenarios. For the high scenario, a strong increase in flow rates is predicted from December to May (+69 % in February for 2070–2100). For the low scenario, a decrease in flow rates is observed almost every month, except in late spring. This decrease is strongest in the summer months.

3.2 Extreme daily discharges for the Vesdre and the Lesse catchments

3.2.1 High-flow discharges for the Vesdre and the Lesse catchments

Figure 5 shows the extreme discharges in the different scenarios for the two time slices using the high scenario and the reference period in relation to the return period. For the Vesdre daily peak discharges, the Weibull law is used, whereas for the Lesse, the lognormal law is used which is in accordance with the study of Dautrebande et al. (2006). It is noticeable that observed and simulated extreme discharges correspond to each other during the reference period. The confidence interval relates to the observed data.

At the middle of the 21st century, the difference between the reference period and the high scenario stays limited. For the Vesdre catchment, it stays within the confidence interval of the reference period. The difference is accentuated for the end of the 21st century. Peak discharges with a 100-year return period reach +54 % for the Lesse catchment and +27 % for the Vesdre catchment.

3.2.2 Low-flow discharges for the Vesdre and the Lesse catchments

In this study, low-flow discharges are calculated as the mean annual 7-day minimum flows (MAM7). For this low-flow statistical analysis, the Weibull law is the best choice for both catchments (Verstraete et al., 2011). The observed and simulated low-flow discharges during the reference period are presented in Table 3. They show a very good accuracy for the Vesdre catchment. The model is less efficient in the Lesse catchment, due to the particular geology, which of course affect specially the low flow values.

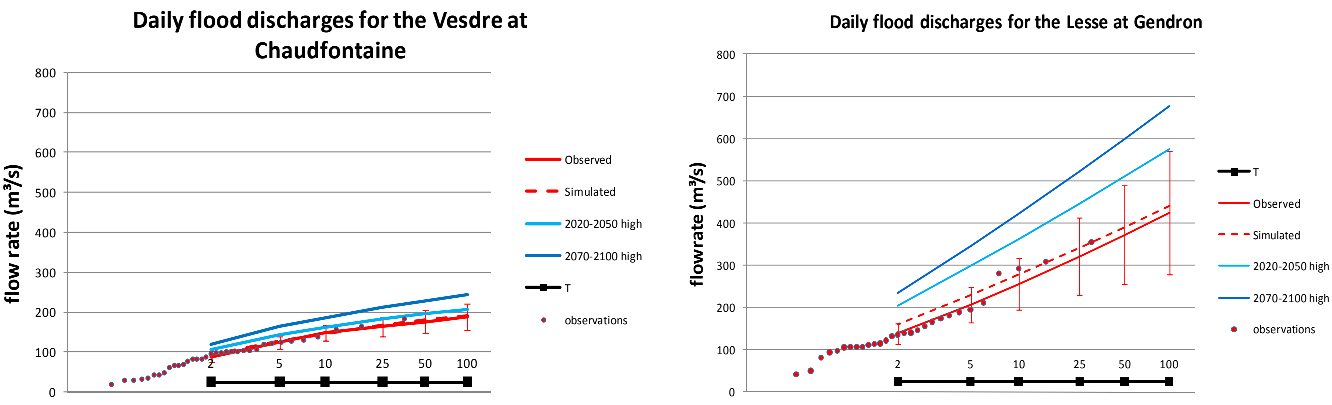

Fig. 5. Daily flood discharges for the Vesdre at Chaudfontaine (upper panel) and the Lesse at Gendron (lower panel) for different return period (T). The 95 % confidence interval of the reference period is plotted as red brackets. Dots represent maximum observed daily discharges, the red line represents the fitted distribution of the observed values.

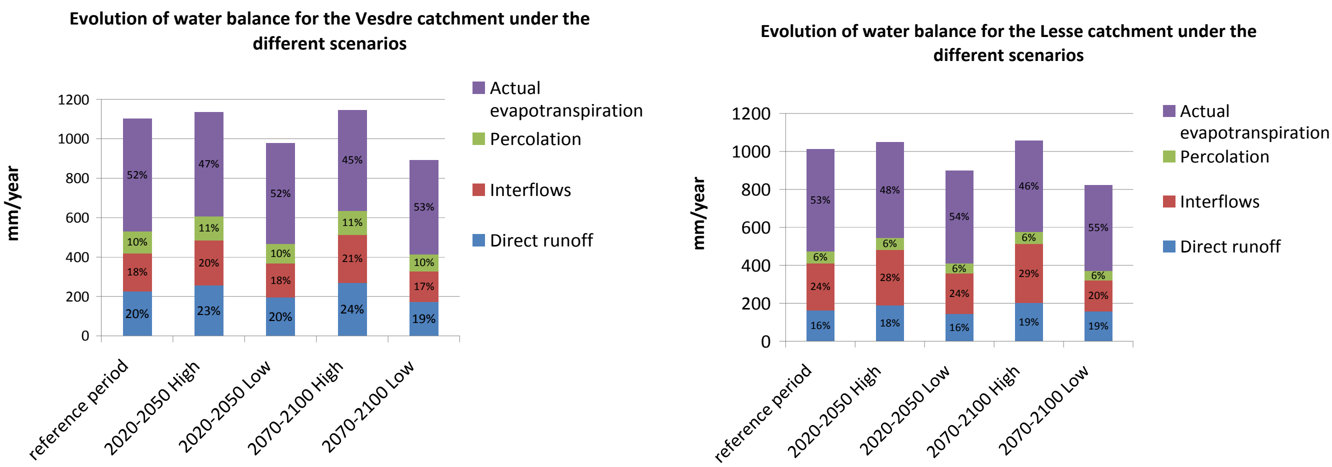

Fig. 6. Water balance for the Vesdre and the Lesse sub-catchments for the different scenarios and time slices.

The changes in MAM7 values are presented in Table 3. In the low scenario, the MAM7 values decrease for all return periods for the Lesse and the Vesdre catchments. These trends are more pronounced at the end than at the middle of the 21st century, and the decrease is more pronounced for high return periods. A decrease in the MAM7 values of around 20 % and 35 % is predicted for a 50 years return period, respectively for the Lesse and the Vesdre at the end of the 21st century.

3.3 Water balance for the Vesdre and the Lesse catchments

The average water balances for the two sub-catchments were studied for the reference period and for both time slices using high and low scenarios. Figure 6 gives an indication of the intrinsic behavior of the Vesdre and the Lesse catchments for the different scenarios. Direct runoff and percolation are more important for the Vesdre than for the Lesse catchment, while slow interflows are more important for the Lesse. Regarding water balance, we can see that approximately half of the water input into the catchments is exported by evapotranspiration. This is a non negligible quantity of water transported by plants and it deserves more attention.

Rainfall decreases in the case of dry scenarios, while it increases in wet scenarios. Direct runoff, slow interflows and percolation follow these trends, depending on the scenario. Only actual evapotranspiration decreases for every scenario. Yet, potential evapotranspiration increases.

3.4 Crop growth and water uptake

In Fig. 7, we plotted crop development index (LAI), root depth (RD) and actual evapotranspiration (ET) against time. It relates to a three year crop rotation (maize, wheat and then barley) at plot scale and aims at showing the vegetation response to our climate change scenarios. It shows that the crops start to grow earlier at the end of the century than

Table 3. Comparison between observed and simulated MAM7 during reference period and changes in MAM7 values for the Vesdre at Chaudfontaine (left) and the Lesse at Gendron (right) for different return periods (T).

	Vesdre at Chaudfontaine				Lesse at Gendron			
T	Q_{obs} (ref period)	Q_{sim} (ref period)	2020–2050 low	2070–2100 low	Q_{obs} (ref period)	Q_{sim} (ref period)	2020–2050 low	2070–2100 low
50	1.23	1.14	−22 %	−35 %	0.426	1.03	−11 %	−20 %
25	1.45	1.34	−20 %	−32 %	0.562	1.22	−10 %	−20 %
10	1.81	1.69	−18 %	−30 %	0.817	1.52	−11 %	−20 %
5	2.16	2.02	−16 %	−28 %	1.1	1.81	−11 %	−19 %
2	2.80	2.64	−13 %	−24 %	1.72	2.36	−11 %	−19 %

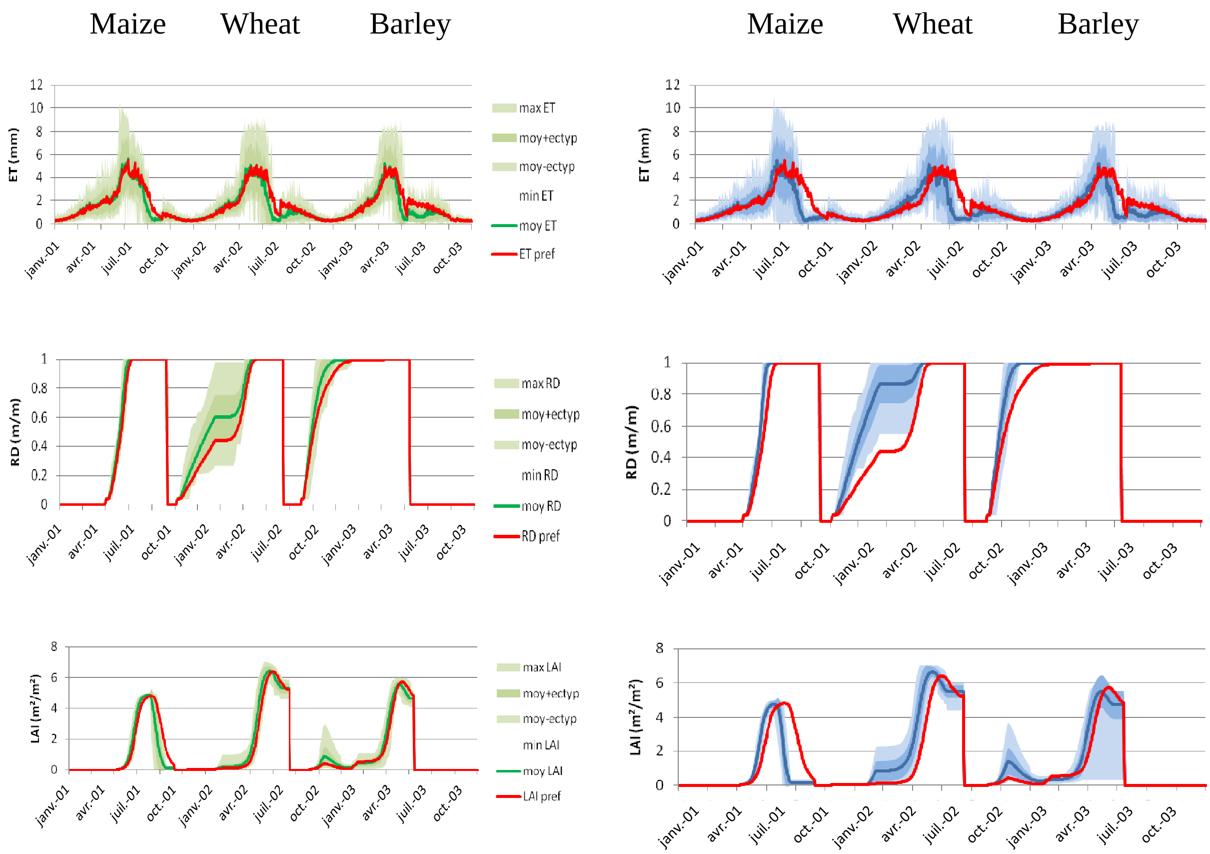

Fig. 7. Evolution of actual evapotranspiration (ET), root depth index (RD) and leaf area index (LAI) for 3 crops (maize, wheat, barley) for the end of the 21st century under the climate change scenario generated by CCI-HYDR low (left panel) and CCI-HYDR high (right panel). (Respectively actual evapotranspiration, root depth index and leaf area index on y-axis, time on x-axis).

during the reference period, the shift is more pronounced for the High scenario than the Low one. It means a higher need for water earlier in the growing season. At the same time, this early growth induces a deeper rooting system, particularly for wheat, and more pronounced for the High scenario.

Actual evapotranspiration (ET) combines the climatic increasing demand for water evaporation with the crop development stage and soil water content. Actual evapotranspiration reaches its higher level earlier and diminishes drastically at the end of the summer.

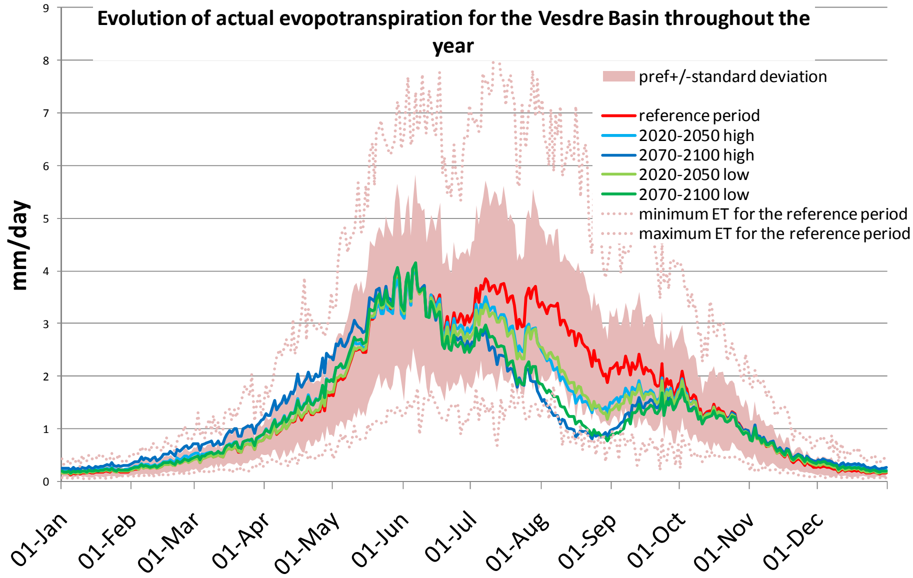

Fig. 8. Evolution of actual evapotranspiration for the Vesdre reference scenarios (red) and the four future scenarios. The shaded area represents the standard deviation for the reference period. Minimum and maximum represents the minimum and maximum values simulated during the reference period.

At the catchment scale, we combine the results from arable lands but also grasslands, forests, and other land uses. Figure 8 shows actual evapotranspiration modeled at a daily time step during the reference period and for the four future scenarios. We can see how actual evapotranspiration is affected by climate change through the year. It appears clearly that changes are not linear. For the reference period, the evolution of actual evapotranspiration is unimodal, except for a slight decrease around 10th June. For the future scenarios, a bimodal evolution of actual evapotranspiration is observed. Around 10 June a decrease is more pronounced and evapotranspiration increases again after August20th.

Vegetation begins to evapotranspirate earlier, at the very beginning of the year. Actual evapotranspiration reaches its maximum value at approximately the same time as during the reference period but it is then severely reduced due to water scarcity in summer. During autumn, actual evapotranspiration restarts and reaches the same value than during the reference period. The comparison between the low and the high scenarios shows that the vegetation evapotranspirates less water in spring in the low scenario. Water scarcity is also noticeable in summer but to a slightly lesser extent than in the high scenario. It can be surmised that the maturity (and need for water) of crops under the high scenario reaches a higher level when water availability decreases in the summer. Actual ET is also higher due to an increase in temperature.

Actual evapotranspiration presents a high variability from year to year but the climate change signal clearly impacts its value throughout the year. Actual evapotranspiration is reduced by 11 % between the reference period and the 2071–2100 high scenario. The reduction is 17 % in the low scenario.

Our results show direct runoff, interflows and percolation decreases during summer and autumn (although runoff increases during September), while these elements increase during spring. During winter, these components of water balance follow winter rainfall trends. This may lead to obvious changes in the water balance.

4 Discussion

Seasonal contrasts in river discharge could be strongly accentuated due to climate change in the Vesdre and Lesse catchments. At the end of the 21st century, all the scenario curves have evolved in a more pronounced way but they always show a low-flow season (which is more accentuated whatever scenario is chosen) and a high-flow season (obviously more accentuated in the high scenario and less pronounced in the low one). These results are consistent with those of de Wit et al. (2007). The variability observed in the evolution of hydrological impact variables is a logical consequence of the available climate change scenarios.

Results of the previous studies on the Meuse (using HBV model) indicate that high flows could strongly increase, by between 10 % and 55 % which is in accordance with our results. Only Leander et al. (2008) present a small decrease in high flows for intermediate return periods.

In surrounding catchments, the same order of magnitude is proposed. Indeed, Willems et al. (2009) calculated changes in hourly high-flow extremes including between +8 % and +52 % for the high scenario for time slice 2070–2100 for the Dender in Flanders with the MIKE-SHE model. The RheinBlick 2050 project has delivered results for the Rhine catchment. It used the semi-distributed HBV model, 7 lumped models and 37 climate model simulations. Concerning high flows, overall increasing tendencies are projected for the distant future for the upper part of the Rhine basin, at between 0 and +35 %. No conclusions have been drawn for the downstream part, since there is limited confidence in the extreme discharge projections, due to a problem with the applied bias-correction in this part of the catchment (Görgen et al., 2010).

Low flows have been rarely studied in the Meuse catchment; indeed the HBV model is designed for flood events. Moreover, de Wit et al. (2007) discussed the evolution of discharge deficit in Borgharen and showed that the number of periods of drought decreases, although their length and intensity both increase. Driessen et al. (2010) focused on the Ourthe, a tributary of the Meuse. In the beginning of the 21st century, they forecast that the number of drought events decreases while for the end of the 21st century, the averaged number of events decreases, but the average duration of an event and the intensity show a large increase. A comparison with our results is not obvious since the low flows indices differ but again, they seem consistent.

The RheinBlick 2050 project used the MAM 7 indices. It predicted for the distant future that the lowest 7-day mean discharges will decrease between 30 % and 10 %. These values are consistent with our results. Furthermore, we noticed that low flow decrease is more pronounced for a higher return period (50 years). This suggests rare but huge water management challenges that deserve more attention.

Modifications in the hydrological balance of a catchment are of great interest in the study of climate-change impacts and in identifying adaptation strategies to prevent them. A non physically based model often conceptualizes a catchment by a number of interconnected stores representing different water stores in a catchment and fluxes in between. The hydrological modeling of the Vesdre and the Lesse subcatchments under climate change using a physically based model, highlights the effects of climate change on plant growth and water uptake and modification of the hydrological balance of these two catchments throughout the year. The evolution of actual evapotranspiration due to climate change is non linear and depends on vegetation behaviour. For the future scenarios, vegetation begins to evapotranspirate earlier in spring due to the increase in temperature and reaches its maximum value at the same time as in the reference period. Afterwards, a severe decrease can be observed due to summer water scarcity. Rainfall during autumn allows the vegetation to restart evapotranspirating and to reach the same value at the end of the year as in the reference period. These results are in agreement with specific studies like those made with the CERES Wheat model (Eitzinger et al., 2003; Mera et al., 2006). The CERES-wheat model was designed to simulate the effect of crop management on crop growth, development and yield. It is intended to be useful at farm level for yield forecasting and for various policy questions (Ritchie and Otter, 1985). The development of plant root systems is closely impacted by the evolution of soil temperature. So it appears that global warming could result in an earlier root growth in spring (Pregitzer et al., 2000; Zhou and Shangguan, 2006) which is in accordance with our results.

Adaptation measures need to consider the importance of the water-soil-plant relationship in order to correctly take into account the evolution of the catchment responses to climate change. Future work should also take into account a full range of climate scenario since the uncertainty related to those scenarios can sorely affect hydrological results.

5 Conclusions

The hydrological modeling of the Vesdre and the Lesse subcatchments under climate change using a physically based model that takes into account the water-soil-plant continuum is of major importance. Such a model highlights the effects of climate change on plant growth and water uptake.

Concerning the hydrological response of the Vesdre and the Lesse catchments, extreme daily flow rates could increase respectively by between 27 % and 54 % for the 2070–2100 high scenario. Low flows (MAM7) could decrease by between 20 % and 35 % according to the low scenario for a 50 year return period. It appears that the contrast between seasons could be strongly accentuated. Our model is consistent with previous studies at catchment scale and permits a deeper understanding of the catchment behavior, particularly the crops growth and water uptake. Thereby, it appears that crop development is faster in the beginning of the growing season. Nevertheless, actual evapotranspiration decreases for all scenarios, due to water deficit during the crop growing period. A 10 % decrease in actual evapotranspiration is observed for the 2070–2100 high scenario and a 17 % decrease for the low scenario.

Our study shows how a physically based model can help understanding the water-soil-plant continuum in order to study the evolution of climate change impacts throughout the year. Such modeling can be of importance for agriculture and when mitigation measures involve renaturation.

On the other hand, it is data intensive and would be more difficult to calibrate in other regions than simpler models.

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