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The Hydrological response to climate change of the Lesse and the Vesdre catchments (Wallonia, Belgium)

A. Bauwens, C. Sohier, and A. Degré

Univ. Liège – Gembloux Agro-Bio Tech, Hydrology and Hydraulic Eng, Passage des Déportés, 2, 5030 Gembloux, Belgium

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Correspondence to: A. Bauwens (alexandra.bauwens@ulg.ac.be)

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Abstract

The Meuse is an important rain-fed river in North-Western Europe. Nine millions of people live in its catchment splited over five countries. Projected changes in precipitation and temperature characteristics due to climate change would have significant impact on the Meuse River and its tributaries. In this study, we focus on two tributaries of the Meuse in Belgium the Lesse and the Vesdre catchments. The physically based, distributed model EPICGrid, a model which reflects water-soil-plant continuum, is driven by four sets of meteorological information. Two time slices (2020–2050 and 2070–2100) and two scenarios (wet and dry) were studied. The meteorological scenarios are produced by the CCI-HYDR Perturbation Tool, a tool specially designed for the Belgian climate and taking into account a broad range of models. Water balance, high-flows and low-flows are calculated. It highlights that towards the end of the century, plants may suffer from water shortage and excess. This may lead to a decrease in evapotranspiration and clear changes in water balances. The seasoning contrast in river discharge may be strongly accentuated.

1 Introduction

The Meuse and its catchment are very important for North-West Europe. With its river of 950 km long, the Meuse catchment covers an area of approximately 36 000 km^2 in a region densely inhabited of Europe. Almost nine millions of people live in the Meuse catchment and six millions 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 no less than five countries: France, Belgium, Grand-Duchy of Luxembourg, Germany and The Netherlands. The Meuse is a rain-fed river. It is thus strongly dependent on meteorological conditions. When flow rates are too important, large damages could occur, like during the floods of 1993 and 1995. During low-flows, consequences for the water quantity and quality could occur with impacts on water supply, shipping, agriculture and economy (Driessen et al., 2009).

It is now recognized that the rise in temperature observed these last years will continue this century with an impact on rainfall characteristics (IPCC, 2007). Nowadays, the future rainfall evolution is largely more uncertain than the temperature evolution (Marbaix and van Ypersele, 2004; Willems et al., 2008; Goderniaux et al., 2008, ...). However, more precipitations are expected to fall in the form of extreme events. Despite the large uncertainties on the future climatic context, climate models become more and more accurate. Hydrological modelling of these scenarios allows us to understand the range of the possible future behavior of rivers.

Most of the research on climate change impacts on the hydrology of the Meuse used the HBV semi-distributed rainfall-runoff model for time slice 2070–2100 (Van Pelt et al., 2009; Leander et al., 2008; Booij et al., 2005; De Wit et al., 2007; Driessen et al., 2009). The impacts of climate change on river discharges results from the use of gridded patterns of change in temperature and precipitation issued from GCM or RCM.

The authors forced the HBV model with perturbed meteorological data coming from different combination of GCM/RCM under different SRES scenarios. Leander et al. (2008) simulate future precipitation in the Meuse River Basin with a combination of three RCM-GCMs under SRES scenarios A2. Booij et al. (2005) used three GCMs (CGCM1, HadCM3, CSIR09) with two RCMs (HadRM2, HIRHAM4) and choose one emission scenario. De Wit et al. (2007) derived the regional climate simulations from the PRUDENCE project. Driessen et al. (2010) used one combination of GCM/RCM under three emission scenarios A1B, A2 and B1 while Van Pelt et al. (2009) used one combination of GCM/RCM under the SRES scenario A1B with two bias correction methods. Many of these studies applied a limited number of RCMs although they studied hydrological impacts. The study of Teutschbein and Siebert (2010) indicates that multi-model approaches are more useful for climate change impact assessments than single RCM.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Results of these studies indicate that high-flows could strongly increase, between 10% and 55%. Only Leander et al. (2008) present a little decrease in high-flows for intermediate return periods. Low-flows are few studied, indeed the HBV model is trained for flood events. The number of drought decreases whereas their length and intensity both increase (De Wit et al., 2007). None of them studied sub-catchments individually in order to manage the impacts from upstream, only Driessen et al. (2010) focused on the Ourthe, a tributary of the Meuse.

Our approach is quite different in three points.

First, we used a physically based model while most of the study used a conceptual model. Conceptual models are not calibrated to take into account modifications due to climate change on the physiological development of plants, like growth and temporary asphyxia of their roots. Physically based models permit to take into account the whole complexity of phenomenons in the soil-plant-atmosphere continuum. The EPICGrid model works at catchment scale whereas lots of physically based models studying the soil-plant-atmosphere continuum work at field or plant scale (Hernandez-Santana et al., 2003; Eitzinger et al., 2003; Mera et al., 2006; Holden and Brereton, 2006). While the CERES-Wheat model predicts a diminution of ETP and canopy transpiration for wheat in Austria under ECHAM4/OPYC3, HADCM2 and NCAR DOE-PCM scenarios, ETP increases for oaks in Spain and for soybean and maize in Africa (Hernandez-Santana et al., 2003; Eitzinger et al., 2003; Mera et al., 2006; Holden and Brereton, 2006).

Second, we have used a perturbation tool CCI-HYDR, specially designed for Belgium, in order to study the impacts of climate change on hydrology. This tool reflects the whole range of GCM and RCM used in the PRUDENCE database and the IPCC AR4 database and the different SRES scenarios. Other studies generally use one or few GCM/RCM. The use of the CCI-HYDR perturbation tool gives a broader range of possibilities when estimating future changes of the underlying hydrometeorological variables. In literature, the application of several RCMs are relatively rare although it avoids biased modelling results and includes inter-model variability while the climate and weather models do not perform consistently all variables and periods of time; for these reasons the use of a multi-model ensemble improves the performance of probabilistic and deterministic predictions (Baguis et al., 2010; Teutschbein and Seibert, 2010).

Third, we study two sub-catchments of the Meuse in order to understand the impact of climate change and to manage them from upstream while most of the studies focused on the Meuse behaviour downstream.

In this paper, we studied the effects of climate change on the Vesdre and the Lesse catchments in Belgium, using the hydrologic model EPICGrid (Sect. 2.2) (Sohier et al., 2009). The CCI-HYDR tool (Sect. 2.4) allows us to perturb meteorological data (temperature and rainfall) from 1967 to 2000 for the two time slices 2020–2050 and 2070–2100 and two scenarios: high (wet) and low (dry).

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 natural park of the Hautes-Fagnes near the German border. Rural areas are mainly located in the South-East (Fagnes, Jalhay), when urbanized areas are mainly seen on the west side of the catchment (Verviers, Chaudfontaine, Liège).

The Lesse catchment is located in the middle of Wallonia. The Lesse River flows into the Meuse at Anseremme near Dinant and has its origin near Ochamps.

The main characteristics of these two catchments are presented in Tables 1–3. The Vesdre catchment has a drainage area of 683 km^2 and the gauging station is located at Chaudfontaine. Extreme flows rates recorded are 0.21 m^3/s for low-flows and 274.46 m^3/s for high-flows. The Vesdre presents several dams along its river. The Lesse catchment has a drainage area of 1284 km^2 and the gauging station is located at Gendron. No dams are present in this catchment. Extreme flows recorded are 0.62 m^3/s for low-flows and 390.80 m^3/s for high-flows.

The comparison between land-uses for the Lesse and the Vesdre catchments shows that the Lesse catchment is less urbanized than the Vesdre one (8% vs. 16%) and has less moor zones (3% vs. 7%), letting these areas for deciduous forests (20% vs. 3%) and grasslands (11% vs. 2%) (see Table 2).

The main soil classes for both catchments are the loamy-stony soils, with 59% and 42%, respectively for the Lesse and the Vesdre catchments. The main difference is the presence of peaty soils for the Vesdre catchment (8%), more areas with steep slopes and loamy soils (see Table 3).

This study is only based upon the Vesdre catchment upstream of Chaudfontaine and the Lesse catchment upstream of Gendron.

2.2 EPICGrid hydrological model

The EPICGrid hydrological model (Fig. 2) has been developed at the ULG, Gx-ABT. The EPICGrid model was developed on the basis of the EPIC model (Williams et al., 1984). The EPIC 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. It has been extended to work at catchment scale and in depth beyond the root zone, up to the water table. It has been adapted to take into account belgian agricultural specificities. EPICGrid is a physically based distributed model. It affords to realize daily simulations at catchment scale. This model is built upon a "major components" approach and 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, . . . (Sohier et al., 2009).

Simulations are realized at daily time step (or hourly time step for some applications), they can be based upon water fluxes and solute towards surface water and groundwater.

2.3 Datasets

Daily observations of temperature and rainfall of the weather station in St-Hubert, Nadrin, Bierset and Rochefort are available from 1967 to 2000 (Fig. 1).

The hydrological model EPICGrid uses the land-use map in Wallonia (COSW) at 1/10 000, the digital elevation model at 1/10 000, the simplified soil map in Belgium at 1/50 000, the thickness of non saturated soil map, a meteorological database, a database with derivate data such as hydrodynamic and chemical properties of soils, a database with agronomic data such as cultural types, agricultural practices and land-use information (Sohier et al., 2009).

Moreover, daily observed discharges at Gendron and at Chaudfontaine from 1967 to 2000 are available.

Besides the observations, climate model outputs (temperature and rainfall) are available from the CCI-HYDR Perturbation Tool.

2.4 CCI-HYDR perturbation tool (Version January 2009)

The CCI-HYDR perturbation tool was developed by Leuven and RMI (Royal Meteorological Institute of Belgium) during the CCI-HYDR Project “Climate change impact on hydrological extremes in Belgium” for the Belgian Science Policy Office Programme “Science for a sustainable development”.

This tool is a perturbation algorithm which was developed to assess hydrological impacts of climate change. The observed series of data are perturbed in order to generate future time series. The observed series are perturbed on the basis of four SRES scenarios (A1B, A2, B1 and B2). The climate model simulations with A2 and B2 regional scenarios were extracted from the PRUDENCES database. The A1B and B1 scenarios were extracted from the IPCC AR4 database.

The perturbation factors were calculated based upon the differences or quotients between the scenarios and control values. The outliers are eliminated based upon standard statistical techniques. For each month a certain number of perturbations remained. The lower, upper and inter-quartile range (respectively Q1, Q2 and IQ) are calculated. The datasets extremes outliers are those values that lie outside the interval (Q1–3.IQ, Q2+3.IQ). The low, mean and high scenarios are calulated as the lowest, mean and highest perturbation values inside the interval. For further information please refers to Baguis et al., 2009.

These scenarios are based upon the expected hydrological impacts. The high scenario represents the most extreme scenario (highest flow impact) which corresponds to the most severe case for flood risk analysis. The mean scenario represents the expected average scenario (mean flow impact).The low scenario represents the opposite of the high scenario in terms of flow impact, so it corresponds to the most severe low-flows situation. The high scenario will be further called the wet scenario, while the low scenario is referred to the dry one.

The CCI-HYDR program perturbs or changes the input series of rainfall data (mm), ET0 (mm), temperature (°C) and wind speed (m/s). It uses time series of 10 min, hourly and daily time steps. The scenarios were mainly developed for catchments up to 1000 km^2.

The CCI-HYDR perturbation tool perturbs periods of data with a preference for a 30-year long period. A 30-year period corresponds to an average climate "oscillation" cycle (Ntegeka et al., 2008).

The output series represent the perturbed input series for a given time horizon in the future. The target years of 2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090 and 2100 can be selected. Each target year is the centre of a 30-year block if 30 years of data were inputed.

This tool is developed upon 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. For the other target years, the interpolation and extrapolation of the changes leads to less accurate future perturbations.

3 Methodology

Getting hydrological responses of a catchment to climate change could be realized in two main steps:

First, it is necessary to generate the climate change scenarios. In this study, two scenarios were developed using the CCI-HYDR perturbation tool for two time slices: the 2020–2050 dry scenario, the 2020–2050 wet scenario, the 2070–2100 dry scenario and the 2070–2100 wet scenario for temperature and rainfall. Analyze of these scenarios in comparison with the reference period 1967–2000 is lead in Sect. 4.1.

Second, the hydrological modeling of the catchments under these scenarios is realized with the water-soil-plant model EPICGrid. Analyze of the modeling results is presented in Sect. 4.2 for water balance, in Sect. 4.3 for monthly mean flow rates, in Sect. 4.4 for high-flow discharges and in Sect. 4.5 for low-flow discharges.

3.1 Calculation method applied to the hydrological impact variables in Wallonia

3.1.1 Estimation of maximum high-flow discharge values

The method of yearly maximums is the classical method used to evaluate exceptional high-flow discharge values. It consists in adjusting a statistical law to the set of yearly maximum flow rates observed or simulated. The work was done on the basis of hydrological years, from 1 October to 30 September of the following year.

The HYFRAN software, developed by the University of Québec, allows us to test no less than 15 classical statistical laws, among them Gumbel law, gamma, Weibull, exponential, Pareto, lognormal, Pearson III and GEV. The HYFRAN software allows us to classify the laws tested on the basis of the posterior probability, this one takes into account the statistical quality of the adjustment and the parsimony principle, giving priority to the 2 parameters laws. The 5 best classed are retained and the χ^2 test is applied in order to control the adequacy of laws to the sample of observed values. The choice of the best law is then visually performed by graphical analysis of the 5 best adjustments (Dautrebande et al., 2006).

3.1.2 Estimation of low-flow discharge values

The method of the "mean annual 7-days minimum flow" (MAM7) has been used here. The HYFRAN software has also been used in order to adjust a statistical law to the observed and simulated MAM7 set by hydrological year. The methodology is the same as the one used for maximum high flow discharge values.

4 Results

4.1 Climate projections for Wallonia with the CCI-HYDR perturbation tool

Four measured stations provided hourly rainfalls from 1967 to 2000 and daily temperatures for 1967 to 2000: Bierset, Nadrin, Rochefort and Saint-Hubert. Only the results from St-Hubert are presented in this paper. Our results are very similar between stations.

The maximum rainfall rises during the time slice 2020–2050, appearing in February with 40% (high scenario) and in April, with 15% (low scenario). During the time slice 2070–2100, they appear in February with 80% (high scenario), and in March with 20% (low scenario). During time slice 2020–2050, the maximum rainfall decline appears in August with 40% for both scenarios. During the time slice 2070–2100, it appears during the same month with 70% for both scenarios (Fig. 3). As for the temperature, the high scenario gives a more important rise in temperature than the low scenario and that for all months. No decline in temperature is predicted. The maximum temperature rises during the time slice 2020–2050 appearing in July with +3.5 °C (high scenario) and in August, with +1.5 °C (low scenario). During the time slice 2070–2100, they appear in July with +8 °C (high scenario) and +2.5 °C (low scenario). The minimum temperature rises during the time slice 2020–2050 appearing in March with +1 °C (high scenario) and in January with +0.5 °C (low scenario). During the time slice 2070–2100, they appear in February with +2 °C (high scenario) and in January with +1 °C (low scenario) (Fig. 3). Temperature and rainfall trends obtained with the CCI-HYDR tool were summarized in Table 4.

Our results indicate 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 now with the high scenario and dryer with the low scenario.

4.2 Water balance for the Vesdre and the Lesse catchments

The average water balance for the two sub-catchments are investigated for the reference period and for the four scenarios.

Figure 4 gives us an indication of the behavior of the Vesdre and the Lesse catchments during the reference period. Direct runoff and percolation are more important for the Vesdre than the Lesse catchment, when slow interflows are more important for the Lesse than the Vesdre catchment.

As we could see in Table 5, rainfall decreases in case of dry scenarios when it increases in wet ones. Direct runoff, slow interflows and percolation follow these trends too. Only the actual evapotranspiration decreases for all scenarios due to the water deficit during the growing period. It increases during the whole year in regards to the reference period, except in summer and at the beginning of autumn. The maximum of evapotranspiration is translated from August to May for future time slices and strongly declines after that moment with a slight increase in September leading to a decrease of the actual evapotranspiration for each scenario, due to a water deficit during the growing period. A 10% decrease in potential evapotranspiration is observed for the 2070–2100 wet scenario and a 17% decrease for the dry one.

Our results show direct runoff, interflows and percolation decreases during summer and autumn (except runoff which increase during September) while they increase during spring. During winter, they follow winter rainfall trends.Towards the end of the century, plants may suffer from water shortage and excess. This may lead to a decrease in evapotranspiration and clear changes in water balances.

4.3 Monthly mean flow rate for the Vesdre and the Lesse catchments

Figure 5 shows the monthly flow rates for the two sub-catchments and the different scenarios. For the wet scenarios, a strong increase in flow rates is predicted from December to May (+69% in February for 2070–2100), whereas a strong decrease is predicted from June to November (−41% in July for 2070–2100). For the dry scenarios, a decrease in flow rates is observed almost every month, except in late spring. This decrease is strongest in the summer months. At the end of the 21st century, all the scenario curves have involved in a more pronounced way but always show a low-flow season (more accentuated whatever the scenario chosen) and a high-flow season (more accentuated in the wet scenarios and less pronounced in the dry ones). PRUDENCE scenarios predict for the Meuse at Borgharen a decrease in flow rates from May to November and an increase the other months (De Wit et al., 2007). Our results show monthly mean discharge varying between −55% (July, dry scenario for 2071–2100, using EPIC-Grid) and +68% (February, wet scenario for 2071–2100, using EPIC-Grid).

4.4 Daily discharges for the Vesdre and the Lesse catchments

The analysis of maximum peak discharges is of importance for water management purposes. In this section, we briefly described the statistical laws used and the results for two catchments.

Figure 6 presents extreme discharges of the different scenarios for the two time slices and the reference period as a function of the return period.

For the Vesdre daily peak discharges, the best adjustment law is the Weibull one, whereas for the Lesse, it is the lognormal one.

In the beginning of the 21st century, the difference between the reference period and the dry scenario for the Vesdre is not important. For the wet scenarios, peak discharges are higher with respect to the reference, whereas for the dry scenarios, peak discharges are generally lower. This difference is accentuated for the end of the 21st century.

Peak discharges with a 100-year return period is included between −30% and +54% for the Lesse catchment and between −3% and +27% for the Vesdre catchment.

The CCI-HYDR project calculated changes in hourly high-flows extremes included between −29% and −21% for the low scenario and +8% and +52% for the high scenario for the time slices 2070–2100 in Flanders (Willems et al., 2009).

The original distribution shows a shift up or down depending on the applied scenario. This shift is small for low return periods but tends to be bigger for high return periods.

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

In this study, low-flow discharges are calculated as the mean annual 7-days minimum flows (MAM7).

The results are presented in Table 6. In the dry scenarios, the MAM7 values decrease for all return periods for the Lesse and the Vesdre catchments whereas it increases for the wet scenarios. These trends are more pronounced at the end of the 21st century than in the middle of the 21st century. For the dry scenarios, a decrease in the MAM7 values around 20% and 35% is predicted, respectively for the Lesse and the Vesdre at the end of the 21st century. For the wet scenarios, an increase around 20% and 15% is predicted in each case. Concerning the Vesdre, for the reference data (observed and simulated) and the scenario 2070–2100 dry scenario, the best adjustment law is the Weibull one, whereas for the other scenarios, it is the gamma one. Concerning the Lesse, the best adjustment law is the Weibull one.

5 Discussion

During the CCI-HYDR project, a comparison between the GCM of AR4 database and the RCM of PRUDENCE database has been conducted. It appears that if we look at the low, mean and high scenarios through the perturbation factors, low and mean scenarios clearly show a decrease in precipitation from January to August and then to December (perhaps with a slight decrease in precipitation even during winter for the low scenario), in the high scenario the RCM simulations show a substantially increase of precipitation in winter and marginal changes in summer, whereas the GCM simulations show a similar increase in winter but an increase of precipitation in summer too. This is partly due to the fact that the RCM simulations in PRUDENCE are driven by four different GCM, from which three provide data for only four out of nineteen RCM experiments (Ntegeka et al., 2008b). The mean of several RCM would give a better resolution of future conditions (Teutschbein and Seibert, 2010). Thus, the CCI-HYDR Perturbation Tool offers a broader range of possible future climate scenarios than just the PRUDENCE RCM one.

The hydrological modeling of the Vesdre and the Lesse sub-catchments under climate change using a physically based model that includes water-soil-plant continuum is very interesting. Indeed, the EPICGrid model developed by Gx-ABT permits to highlight the effects of climate change on plant growth and water uptake and modification of the hydrological balance of these two catchments along the year, while a non-physically based model predicts only modification in flow rates.

Modifications in the hydrological balance of a catchment are of great interest in order to study climate change impacts and to propose adaptation strategies to prevent them.

Seasoning constrat in river discharge could be strongly accentuated representing well the braod range of climate change scenarios. This variability is well reflected by the broadth of peak discharge values calculated.

Few studies have been conducted regarding the evolution of low-flow discharge under climate change for the Meuse basin. The few studies which have been carried out used the HBV model that has difficulties to represent extreme low-flows (De Wit et al., 2007). But low-flows are more pronounced when a dry winter is followed by a dry summer, like in the dry scenarios. Our results indicate that low-flows could be more or less severe depending on the scenarios studied.

6 Conclusions

The hydrological modeling of the Vesdre and the Lesse sub-catchments under climate change using a physically based model that includes water-soil-plant continuum is of major importance. Such a model permits to highlight effects of climate change on plant growth and water uptake.

It appears that climate change produced by the CCI-HYDR Perturbation Tool reflects well the broad range of climate change models. There is no difference in rainfall changes between the high and the low scenarios for spring, summer and autumn; the only season which differs is winter which is dryer for the low scenario and wetter for the high scenario. Regarding the temperature, a general increase is simulated for every scenario. But this increase is more important for the wet scenarios than for the dry ones.

Concerning the hydrological response to the Vesdre and the Lesse catchments, it appears that the actual evapotranspiration decreases in each simulation, due to water deficit during the growing period. A 10% decrease of the actual evapotranspiration is observed for 2070–2100 wet scenario and a 17% decrease for the dry one. Our study shows the importance of the use of a physically based model able to simulate water-soil-plant continuum in order to study the impact of climate change. Extreme daily flow rates could increase between 27% and 54% for the 2070–2100 wet scenarios in the Vesdre and Lesse sub-catchments. Low-flows (MAM7) could decrease between 21% and 37% following the dry scenario. It appears that the seasoning contrast could be strongly accentuated. Important impacts on hydrology have been predicted and adequate measures have to be taken to prevent damages, the use of a physically based model like EPICGrid permits to take into account the major role of the crops in the modifications of the water balance due to climate change.

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Table 1. Main characteristics of the Vesdre and the Lesse catchments.

	Station	Drainage area (km^2)	Highest gauging discharge value in high flows	Lowest gauging discharge value in low flows	Anthropogenic influence on natural flow
Vesdre	Chaudfontaine	683	274.46 m^3/s	0.21 m^3/s	dams
Lesse	Gendron	1284	390.80 m^3/s	0.62 m^3/s	

Table 2. Land-use distribution (%) for the Lesse and the Vesdre catchments.

Land-use	Lesse	Vesdre
Grassland	10.66	2.27
Cultures	27.90	33.10
Greenspaces	0.51	0.65
Moors	2.82	7.01
Forests	19.86	20.80
Deciduous forests	19.65	3.04
Coniferous forests	10.31	16.73
Mixt forests	0.01	0.01
Water	0.19	0.31
Christmas trees	0.18	0.04
Urban	7.88	15.70
No data	0.04	0.34

Table 3. Distribution of soil classes (%) for the Lesse and the Vesdre catchments, based upon the Belgian simplify pedological map at 1/50 000.

Soil classes	Lesse	Vesdre
No data	0.00	1.66
Loamy soils with textural B horizon (association moderately dry)	0.74	0.40
Loamy soils with textural B horizon (association moderately wet)	0.00	2.05
Loamy soils with textural B horizon (association wet)	0.00	3.08
Sandy-loam or silt substrate undifferentiated on the 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, with shale and sandstone load	0.00	1.23
Loamy stony soils with textural or structural B horizon, with psammite load	0.36	0.22
Loamy stony soils with textural or structural B horizon, with calcareous load	5.47	6.15
Loamy stony soils with textural or structural B horizon, with chalk load	16.83	6.41
Loamy stony soils with textural or structural B horizon, with chalk and calcareous load	4.92	1.47
Loam stony soils with textural or structural B horizon, with chalk and psammite load	3.95	6.73
Silty clay soils, shale load	5.15	0.00
Loamy soils stony with structural B horizon, with schist and phyllite load	9.67	6.19
Loamy stony soils with structural B horizon, with schist and sandstone load	11.54	12.72
Loamy soils with fewstones and structural B horizon (dry)	19.76	0.14
Loamy soils with fewstones and structural B horizon (wet)	9.18	25.05
Peat soils	0.29	8.46
Clayey soils with structural B horizon	0.00	1.82
Alluvial soils without profile development (dry)	0.74	0.46
Alluvial soils without profile development (wet)	0.35	0.00
Area with steep slopes	10.49	15.49

Table 4. % Change in rainfall and change in temperature [°C] for the different scenarios.

		% Change in rainfall for the different scenarios				
Scenarios		Annual	Winter	Spring	Summer	Autumn
2020–2050	High	2.7	28.2	−0.8	−23.6	10.7
	Low	−9.0	−5.1	−0.8	−23.6	−0.7
2070–2100	High	2.6	55.3	−11.2	−47.2	19.7
	Low	−19.2	−7.1	−11.2	−47.2	−8.1
		Change in temperature [°C] for the different scenarios				
Scenarios		Annual	Winter	Spring	Summer	Autumn
2020–2050	High	1.9	1.3	2.1	2.6	1.7
	Low	0.8	0.5	0.8	1.2	0.7
2070–2100	High	4.0	2.6	4.4	5.3	3.6
	Low	1.6	1.0	1.6	2.4	1.5

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀▮ ▶▮
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 5. Evolution of water balance for the Vesdre catchment (up) and the Lesse catchment (down) under the different climate change scenarios.

	Vesdre				
	Qsim (mm/year)	2020–2050 Wet	2020–2050 Dry	2070–2100 Wet	2070–2100 Dry
Rainfall	1110	3%	−12%	4%	−19%
Direct runoff	1145	14%	−14%	19%	−23%
Interflows	195	18%	−12%	25%	−21%
Percolation	109	11%	−10%	13%	−19%
Actual evapotranspiration	573	−8%	−11%	−11%	−17%
	Lesse				
	Qsim (mm/year)	2020–2050 Wet	2020–2050 Dry	2070–2100 Wet	2070–2100 Dry
Rainfall	1016	4%	−11%	5%	−19%
Direct runoff	1036	16%	−12%	24%	−20%
Interflows	248	18%	−14%	25%	−23%
Percolation	62	3%	−11%	4%	−17%
Actual evapotranspiration	539	−7%	−9%	−10%	−16%

Table 6. MAM7 values for the Vesdre at Chaudfontaine (left) and the Lesse at Gendron (right).

	Vesdre at Chaudfontaine					Lesse at Gendron				
T	Q_{obs}	2020–2050 Wet	2020–2050 Dry	2070–2100 Wet	2070–2100 Dry	Q_{obs}	2020–2050 Wet	2020–2050 Dry	2070–2100 Wet	2070–2100 Dry
50	1.31	7%	−25%	16%	−37%	1.4	22%	−11%	28%	−21%
25	1.54	8%	−23%	13%	−35%	1.58	18%	−12%	23%	−21%
10	1.89	7%	−20%	11%	−32%	1.84	0%	−11%	17%	−20%
5	2.23	7%	−18%	10%	−29%	2.09	10%	−11%	12%	−19%
2	2.87	6%	−14%	6%	−25%	2.52	5%	−11%	6%	−18%

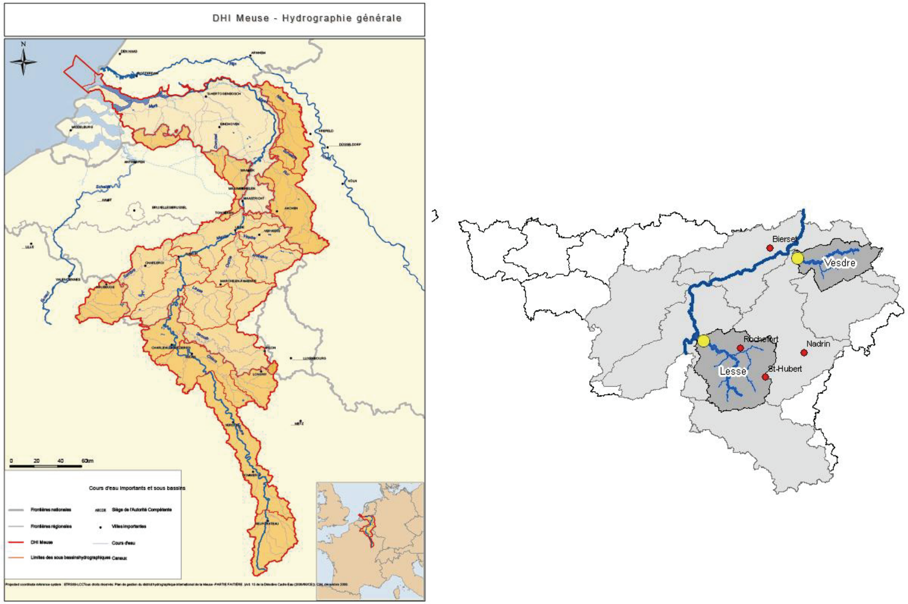

Fig. 1. The Meuse catchment (light grey) in Wallonia (Belgium) and the Vesdre and the Lesse catchments (dark grey).

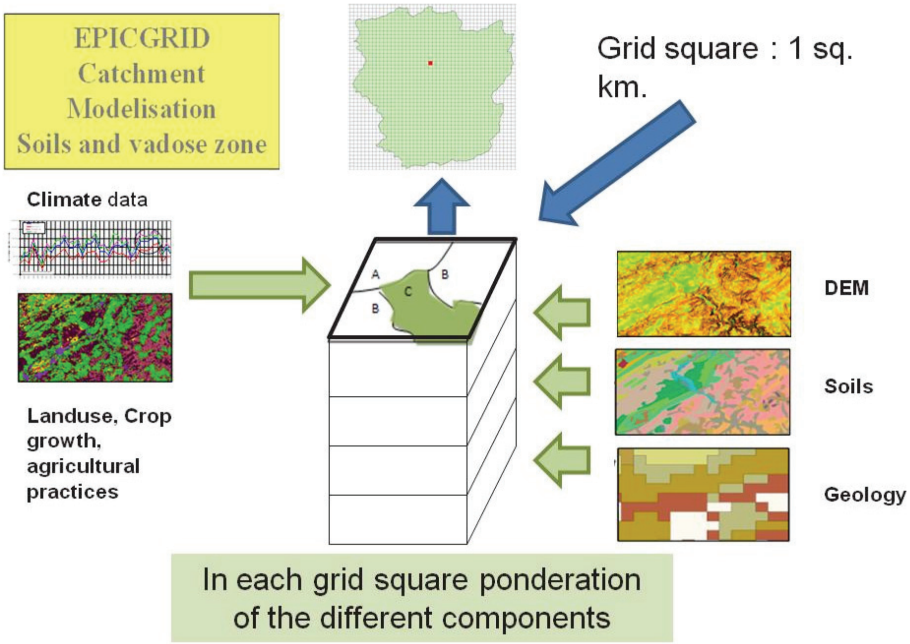

Fig. 2. Simulation structure of the EPICGrid model inside an elementary element.

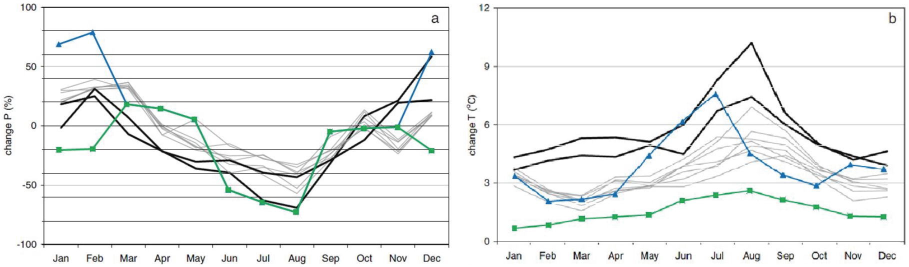

Fig. 3. CCI-HYDR wet (blue) and dry (green) scenarios vs. PRUDENCE RCM simulation (black and grey curves) – 2071–2100 (De Wit et al., 2007).

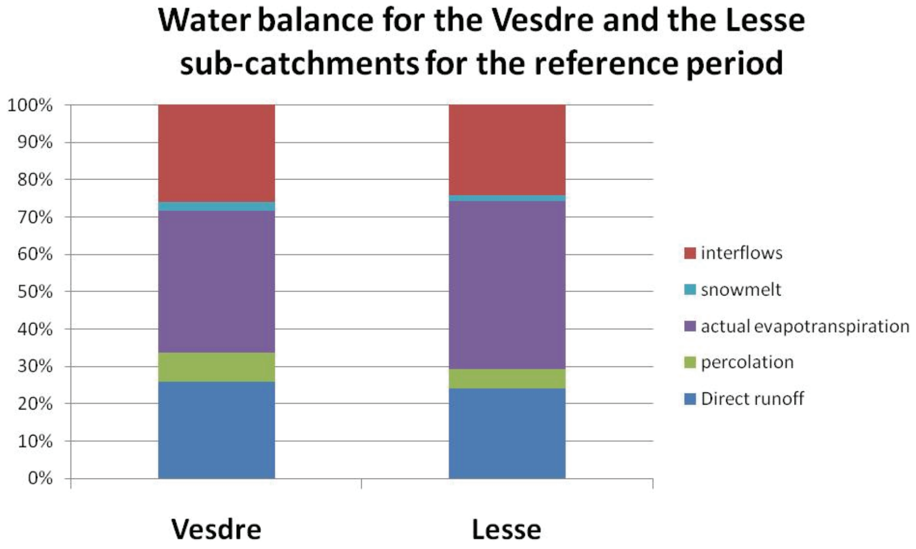

Fig. 4. Water balance for the Vesdre and the Lesse sub-catchments for the reference period.

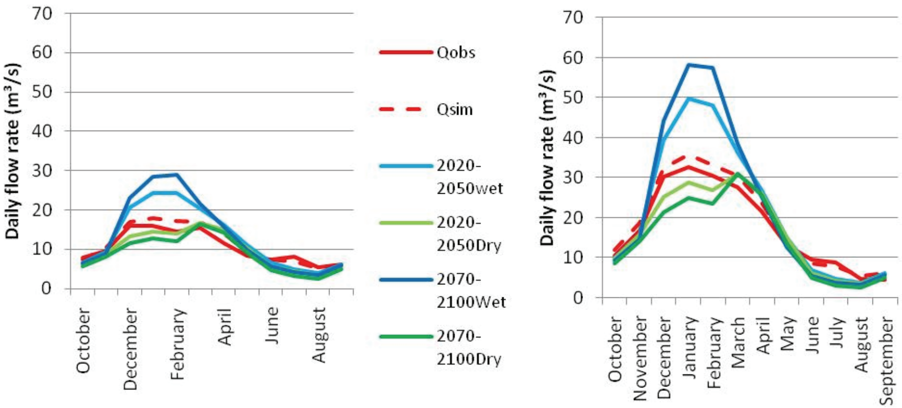

Fig. 5. Evolution of daily flow during a year for the Vesdre at Chaudfontaine (left) and the Lesse at Gendron (right).

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◄
►
◄
►
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

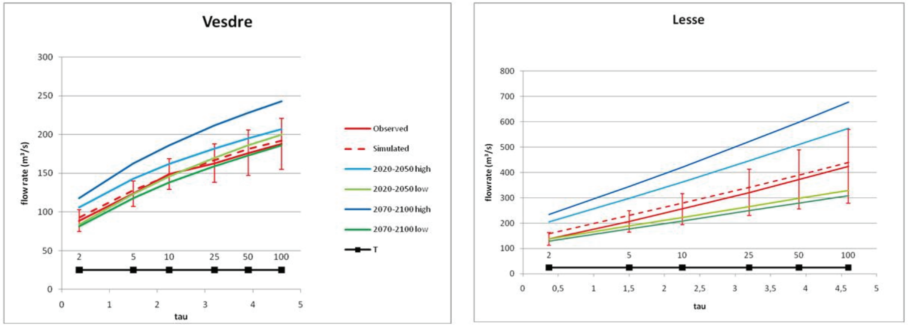

Fig. 6. Daily flood discharges for the Vesdre at Chaudfontaine (left) and the Lesse at Gendron (right). The 95% confidence interval of the reference period is plotted as red brackets.