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Multi-model approach to assess the impact of climate change on runoff

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SUMMARY

The assessment of climate change impacts on hydrology is subject to uncertainties related to the climate change scenarios, stochastic uncertainties of the hydrological model and structural uncertainties of the hydrological model. This paper focuses on the contribution of structural uncertainty of hydrological models to the overall uncertainty of the climate change impact assessment. To quantify the structural uncertainty of hydrological models, four physically based hydrological models (SWAT, PRMS and a semi- and fully distributed version of the WetSpa model) are set up for a catchment in Belgium. Each model is calibrated using four different objective functions. Three climate change scenarios with a high, mean and low hydrological impact are statistically perturbed from a large ensemble of climate change scenarios and are used to force the hydrological models. This methodology allows assessing and comparing the uncertainty introduced by the climate change scenarios with the uncertainty introduced by the hydrological model structure.

Results show that the hydrological model structure introduces a large uncertainty on both the average monthly discharge and the extreme peak and low flow predictions under the climate change scenarios. For the low impact climate change scenario, the uncertainty range of the mean monthly runoff is comparable to the range of these runoff values in the reference period. However, for the mean and high impact scenarios, this range is significantly larger. The uncertainty introduced by the climate change scenarios is larger than the uncertainty due to the hydrological model structure for the low and mean hydrological impact scenarios, but the reverse is true for the high impact climate change scenario. The mean and high impact scenarios project increasing peak discharges, while the low impact scenario projects increasing peak discharges only for peak events with return periods larger than 1.6 years. All models suggest for all scenarios a decrease of the lowest flows, except for the SWAT model with the mean hydrological impact climate change scenario.

The results of this study indicate that besides the uncertainty introduced by the climate change scenarios also the hydrological model structure uncertainty should be taken into account in the assessment of climate change impacts on hydrology. To make it more straightforward and transparent to include model structural uncertainty in hydrological impact studies, there is a need for hydrological modelling tools that allow flexible structures and methods to validate model structures in their ability to assess impacts under unobserved future climatic conditions.

1. Introduction

Assessing the impact of climate change on the hydrological cycle is currently one of the major challenges in hydrological research (IPCC, 2013; Peel and Blöschl, 2011). Given the large uncertainty of climate predictions, due to unknown future greenhouse gas emissions, simplifications in General Circulation Models (IPCC, 2013) and downscaling methods (Stoll et al., 2011), it has become common practice to apply an ensemble of climate change scenarios. The range in the hydrological predictions following from such an ensemble of climate change scenarios is often considered as the uncertainty range of the hydrological impact (e.g. Minville

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et al., 2008). Nevertheless, also hydrological modelling is due to stochastic and structural model uncertainty an inherently probabilistic exercise (Praskievicz and Chang, 2009; Walker et al., 2003). Stochastic model uncertainty originates from uncertainty on physically based parameters, model equifinality and model input and output measurements errors (Beven and Binley, 1992). Recent research has resulted in more efficient numerical techniques such as the Shuffled complex evolution Metropolis algorithm and other Markov Chain Monte Carlo based methods to obtain optimal parameter values and assess the impact of parameter uncertainty (e.g. Vrugt et al., 2003). Structural model uncertainty, introduced by the simplification of the hydrological processes, has however received less attention (Refsgaard et al., 2006; Rojas et al., 2010). Nevertheless, when hydrological models are applied for extrapolations towards unobservable futures such as land-use and climate changes, the model structure is likely to be the main source of uncertainty (Refsgaard et al., 2006; Usunoff et al., 1992). Applying an ensemble of hydrological models under identical boundary conditions is a first step to assess the importance of structural model uncertainty (Refsgaard et al., 2006; Breuer et al., 2009; Rojas et al., 2010; Vansteenkiste et al., 2014a,b). Additionally, by comparing the output of the models in the ensemble with the observations, the compatibility of the hypotheses of the hydrological processes represented in the models can be tested (Clark et al., 2008, 2011; Buytaert and Beven, 2010; Van Hoey et al., 2014). Although commonly applied in for example meteorology and climatology, studies applying multimodel ensembles are relatively scarce in hydrology (Breuer et al., 2009; Refsgaard et al., 2014). Model intercomparison studies (e.g. Refsgaard and Knudsen, 1996; Pitman and Henderson-Sellers, 1998; Smith et al., 2004, 2012; Duan et al., 2006; Safari et al., 2012; Vansteenkiste et al., 2014a,b) have shown that a variety of hydrological models, applying a wide range of algorithms to describe hydrological processes, exist and allow to simulate river discharge with a similar accuracy.

Ensembles of hydrological models have been applied in previous studies to assess the impact of climate change. Initially, these studies merely focused on the contribution of the hydrological model choice on the river discharge or groundwater recharge prediction using only one climate change scenario (Jiang et al., 2007; Ludwig et al., 2009; Gosling et al., 2011). Recently some studies have estimated the contribution of hydrological model uncertainty to the total uncertainty of climate change impact studies. Bae et al. (2011) applied three semi-distributed hydrological models and seven Potential Evapotranspiration (PET) computational methods to assess the hydrologic response to climate change. They concluded that the different hydrological models and PET methods can induce major differences in runoff change under the same climate change scenarios. Najafi et al. (2011) used three lumped and one distributed model with different complexity to simulate the effect of 16 statistically downscaled climate change scenarios for a basin in Oregon, USA. Bastola et al. (2011) studied six climate change scenarios using four conceptual hydrological models within the Generalised Likelihood Uncertainty Estimation (GLUE) and Bayesian Model Averaging (BMA) methods. It was shown that for the four studied Irish catchments the role of hydrological model uncertainty is remarkably high. Velázquez et al. (2013) applied several climate change scenarios and four hydrological models (HSAMI, HYDROTEL, WASIM-ETH and PROMET) on a basin in Canada and Germany. The results show a strong influence of the selected hydrological model on the simulated flow under the climate change scenarios, especially for the predicted low flows. Vansteenkiste et al. (2014a) used an ensemble of conceptual lumped to physically based distributed hydrological models to simulate the impact of climate change to the Grote Nete (Belgium). Especially for low flows, large differences in model predictions were found. Bosshard et al. (2013) propose an analysis of variance (ANOVA) based method to quantify the different uncertainty sources contributing to the total ensemble uncertainty in the runoff projections for climate change scenarios.

Above mentioned research papers have contributed to the understanding of the uncertainty introduced by the hydrological model structure in the projection of climate change scenarios. The large contribution of the hydrological model structure has initiated the development of methods to evaluate models on their suitability for prediction of ungauged changes (PUC) (Van Steenbergen and Willems, 2012; Vansteenkiste et al., 2014b; Refsgaard et al., 2014) and to reconsider the "steady state" based view on hydrology generally considered (Wagener et al., 2010; Schaefli et al., 2011; Ehret et al., 2014).

The goal of this paper is to elaborate on the current understanding of the uncertainty introduced by the hydrological model structure. Sixteen hydrological model configurations, based on four different semi-distributed and fully distributed models and four objective functions, are used in this paper to assess the impact of climate change scenario on river flow. This research introduces two important novelties. The first novelty relates to hydrological extremes. Above discussed papers primarily focus on average monthly or seasonal flow projections. Given the importance of extreme events, with regard to droughts and floods, this paper additionally evaluates the impact on the peak flows and extreme low flows. Both for peak and extreme low flows the current return periods and expected return periods due to the climate change are compared. The second novelty of this research is the application of a statistical perturbation method to summarise climate change scenarios according to their hydrological impact. Currently a large ensemble of climate change products has become available. Classical approaches therefore require a huge amount of model runs to compare the climate change and hydrological model uncertainty range. To limit the required number of model runs this paper proposes the use of statistical perturbation tool that summarises the range of climate change scenarios. Additionally, the use of climate change scenarios classified according to their hydrological impact allows comparing the hydrological model uncertainty in combination with the predicted change in climate.

2. Methods

2.1. Study area

The Kleine Nete catchment, situated in the north of Belgium (Fig. 1), is used as a study area. The Kleine Nete is a subcatchment of the Scheldt basin and has an area of 581 km^2. The catchment is characterised by a moderate rolling landscape cut by the rivers. Interfluves are only slightly elevated and valleys are broad and swamp. The average slope of the basin is 0.36%. The dominant soil texture in the basin is fine sand, in the river valleys also loamy sand occurs. The loamy sand has normally no soil profile, most sandy soils have a podzol soil horizon with clear iron and/or organic matter accumulation. The basin is dominated by an agricultural land-use with about 38% arable land and 19% grassland, forest covers about 27% of the basin, around 12% is urban built-up, 2% is open water and 1% is heather. The climate in the region is temperate and characterised by warm summer and cool to cold winters with little snowfall. The average winter and summer temperatures are 5 and 14 °C respectively. The annual precipitation (1951–2005) ranged from 600 to 1100 mm/year with an average of 828 mm/year. There is no significant difference between the precipitation volume for winter and summer. A small north-west (average precipitation of about 840 mm/year) to south-east (average precipitation of about 820 mm/year) gradient of about