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Intercomparison of hydrological model structures and calibration approaches in climate scenario impact projections

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SUMMARY

The objective of this paper is to investigate the effects of hydrological model structure and calibration on climate change impact results in hydrology. The uncertainty in the hydrological impact results is assessed by the relative change in runoff volumes and peak and low flow extremes from historical and future climate conditions. The effect of the hydrological model structure is examined through the use of five hydrological models with different spatial resolutions and process descriptions. These were applied to a medium sized catchment in Belgium. The models vary from the lumped conceptual NAM, PDM and VHM models over the intermediate detailed and distributed WetSpa model to the fully distributed MIKE SHE model. The latter model accounts for the 3D groundwater processes and interacts bi-directionally with a full hydrodynamic MIKE 11 river model. After careful and manual calibration of these models, accounting for the accuracy of the peak and low flow extremes and runoff subflows, and the changes in these extremes for changing rainfall conditions, the five models respond in a similar way to the climate scenarios over Belgium. Future projections on peak flows are highly uncertain with expected increases as well as decreases depending on the climate scenario. The projections on future low flows are more uniform; low flows decrease (up to 60%) for all models and for all climate scenarios. However, the uncertainties in the impact projections are high, mainly in the dry season. With respect to the model structural uncertainty, the PDM model simulates significantly higher runoff peak flows under future wet scenarios, which is explained by its specific model structure. For the low flow extremes, the MIKE SHE model projects significantly lower low flows in dry scenario conditions in comparison to the other models, probably due to its large difference in process descriptions for the groundwater component, the groundwater–river interactions. The effect of the model calibration was tested by comparing the manual calibration approach with automatic calibrations of the VHM model based on different objective functions. The calibration approach did not significantly alter the model results for peak flow, but the low flow projections were again highly influenced. Model choice as well as calibration strategy hence have a critical impact on low flows, more than on peak flows. These results highlight the high uncertainty in low flow modelling, especially in a climate change context.

1. Introduction

Observational records and climate projections provide abundant evidence that water resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems (IPCC, 2007). Water resource managers should be aware of the projections on climate change and be prepared to deal with the effects on hydrological variables. A growing number of studies look at how water resources may be impacted by the climatic changes. They apply hydrological models to translate hypothetical climate scenarios into hydrological responses. The accuracy of the impact results then obviously depends on the accuracy of these models. Because climate change scenarios often involve extrapolation beyond the range of historical conditions considered during model calibration, the accuracy of the model based impact results

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strongly depends on the model performance in making extrapolations (Milly et al., 2008; Coron et al., 2012). The latter can be partly controlled by the model calibration, but also strongly depends on the conceptual accuracy of the model structure. This is the case for all types of models, independent on whether the model structure is simple conceptual or more detailed and spatially distributed.

Some authors examined rainfall–runoff model performance for making extrapolations outside calibration conditions, e.g. in the context of climate change. Seibert (2003) did this by validating models calibrated on periods with lower peak flows, to periods with higher peak flows. This was based on the differential split sample test proposed by Klemes (1986) to verify the ability of the model to simulate flows under conditions different from the calibration period. A similar approach was applied by Coron et al. (2012) comparing the model performance for different validation period after calibration for other periods. Vaze et al. (2010) assessed the validity of the model parameters for changing rainfall conditions by looking at the rainfall characteristics (wet/dry) of the calibration period, hence defining bounds of change in rainfall for which the model can make reliable impact simulations. Also Merz et al. (2011), Seifert et al. (2012) and Brigode et al. (2013) examined the differences in model efficiency between calibration and different validation periods. They all found that conceptual models lack robustness when used in contrasted climatic conditions. However, Van Steenbergen and Willems (2012) showed that the model (structure) can be partly tested for its capacity to simulate flow changes in response to rainfall increases. Such evaluation has, however, its limitations because it is based on historical data only, and because limited or no observations are available for the model state variables (e.g. soil moisture state) and/or at the scales of the model (e.g. catchment averaged values for lumped models, grid averaged values for spatially distributed models). Another approach, which is commonly applied in climate (impact) modelling, is to acknowledge that model inadequacy is inevitable because of lack of knowledge and data. Under this paradigm, one can test different alternative model structures, inter-compare the results and acknowledge the uncertainty in the impact results because of lack of knowledge on the proper model structure. This involves implementation and calibration of a model ensemble rather than a single model. Such ensemble testing of models allows analysis and comparison of the results produced by various models in order to study the advantages and shortcomings of their structure. International initiatives such as DMIP (Smith et al., 2004; Smith and Gupta, 2012), MOPEX (Schaake et al., 2006; Chahinian et al., 2006) and HEPEX (Schaake et al., 2007; Thielen et al., 2008) were successful examples of the ensemble approach in hydrological modelling. Recently, also some studies reported on ensemble hydrological modelling in the climate change context. Ludwig et al. (2009) investigated and compared the responses within an ensemble of three hydrological models, each representing a different model complexity in terms of process description, parameter space and spatial and temporal scales. Under future climate projections by general circulation models (GCMs) and regional climate models (RCMs), the models projected high deviations in water shortages and spring flood intensities. Maurer et al. (2010) compared a lumped and a distributed model driven by 22 climate model outputs. The estimated changes in monthly stream flows and in high and low flows did not significantly differ between the two models, except during the summer season. Bae et al. (2011) applied similar impact comparison between three semi-distributed models simulating 13 GCM results with three greenhouse gas (GHG) emission scenarios. They showed that the monthly and seasonal runoff changes largely differ between the models, and this was particularly significant during the dry season. Gosling et al. (2011) developed two types of distributed hydrological models for six catchments to analyse the impact uncertainty from seven GCM runs. Both models simulated similar climate change signals, but differences were found in the mean annual runoff, the seasonality of runoff, and the magnitude of changes in extreme monthly runoff. Also Velázquez et al. (2012) demonstrated for two regions, using an ensemble of four hydrological models with a diversity of structural complexity (i.e. lumped, semi-distributed and distributed models), that the largest relative difference in hydrological model outputs after climate forcing is seen in the low flow changes. Changes in high flows were less sensitive to the choice of the hydrological model. All these studies demonstrate the importance of the model structure in impact projections. Najafi et al. (2011) demonstrated that the model calibration, next to the different model structures, might also have high influence on the climate change impact results, particularly on the low flow results. This was concluded after calibrating three lumped and one semi-distributed model using three objective functions and subsequently forcing them with eight GCM simulations and two GHG emission scenarios. Also Poulin et al. (2011) investigated the effect of model structure and parameter equifinality on the uncertainty related to hydrological modelling in climate impact studies. Their study revealed that the impact of the hydrological model structure on the simulation of total streamflows is more significant than the uncertainty in the model parameters.

In this paper the influence of the hydrological models and calibration strategies on climate change impact projections, including impacts on flow extremes, is investigated. The first is done by an ensemble of hydrological models with different spatial resolutions and process descriptions, which were calibrated by Vansteenkiste et al. (2014) for the Grote Nete catchment in Belgium. The models covered a wide range of model complexities: from lumped conceptual models NAM, PDM and VHM, over the intermediate detailed and distributed model WetSpa, to the highly detailed and fully distributed model MIKE-SHE. The latter model also simulates internal discharges and groundwater heads in the catchment. Vansteenkiste et al. (2014) have shown that after their calibration, the models produced reliable estimates of the flow regimes under the current climate. They also demonstrated that the models do well in simulating changes in the runoff coefficient under changing rainfall intensities. The second – the influence of calibration strategies – is examined by comparing the multiple automatic calibration approaches by Willems et al. (2014) with a manual, step-wise model structure identification and calibration method for the VHM model. The manual method was applied by Vansteenkiste et al. (2014). It relied on information derived from the observed time series, such as runoff subflows and various types of runoff responses, and also focussed explicitly on the high and low flow extremes. The different model structures and calibration approaches were applied to quantify and intercompare the hydrological impacts of climate scenarios for Belgium. Disagreements among the model predictions are examined in terms of relative change of the flow extremes under recent past climate and future projections for the-end-of-century (2071–2100) horizon.

2. Study area

The catchment of the Grote Nete river is located in the northeast of Belgium (Fig. 1) and has an area of 385 km^2. The catchment contains numerous river tributaries, and a dense network of ditches and subsurface drains that feed into the main Grote Nete, Molse Nete, and Grote Laak rivers (Fig. 1). Next to the outlet limnigraphic station at Geel-Zammel, it has three internal stations (Fig. 1). There are several observation wells in the catchment, which consist of a nest of several piezometers, monitoring groundwater in one or more different geological units. The hydro-geology is limited to Quaternary and Tertiary formations constituting the upper, Quaternary aquifer (HCOV 0100) and the deeper, Campine aquifer system (HCOV