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Uncertainty in climate change impacts on low flows

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Abstract It is crucial for low flow management that information about the impacts of climate change on low flows and the uncertainties therein becomes available. This has been achieved by using information from different Regional Climate Models for different emission scenarios to assess the uncertainty in climate change for the River Meuse in Northwestern Europe. A hydrological model has been used to simulate low flows for current and changed climate conditions. The uncertainty in the hydrological model is represented by the uncertainty in its parameters. Climate change results in an increase of the average annual discharge deficit (a low flow measure) of about 2.6 10^8 m^3 or 35%. This impact is considerable, resulting in an increase of water shortages in the Meuse basin during low flow periods. The uncertainty in this impact is about 10% as a result of uncertainties in climate change and HBV parameters, and does not disguise the climate change signal.

Key words climate change; discharge deficit; fuzzy objective function; HBV model; low flows; Meuse basin; Monte Carlo analysis; Regional Climate Model; uncertainty

INTRODUCTION

Water management in Western Europe often focuses on water levels and discharges during floods. The reason is obvious, since floods determine maximum water levels and therefore chances of inundation. The focus on floods is partly forced by the fact that, in future, higher and more frequent floods are expected as a result of climate changes (e.g. Arnell, 1999; Middelkoop *et al.*, 2001; Booij, 2005). However, climate changes are also expected to lead to drier summers in Western Europe (e.g. Schär *et al.*, 2004). Consequently, low flows in rivers may become more frequent in future, although Hisdal *et al.* (2001) have shown that drought conditions in Europe in general have not become more severe or frequent in the last century. They based their findings on daily stream-flow records of more than 600 stations in Europe. Low flows, occurring during dry periods, may result in several types of problems to society, e.g. lack of water for drinking water supply, irrigation, industrial use and power production, hindrance to navigation and deterioration of water quality. Facing these problems, it is crucial for low flow management that information about the impacts of climate change on low flows and the uncertainties therein becomes available.

Smakhtin (2001) states that despite the obvious importance of the issue of climate change impacts on low flows, the literature specifically investigating such effects is relatively scarce at present. An example of a paper using historical flow records is Arnell (1989). However, Arnell concluded that the approach of using flow records from the past as a reasonable model for the future is unrealistic. A combination of climate change scenarios and hydrological models seems to be more promising, such as Wilby *et al.* (1994) and Querner *et al.* (1997). This enables the assess-ment of impacts of changing spatial and temporal climate patterns on low flows, where usually impacts of changes in mean temperature and precipitation on hydrological behaviour are determined. Middelkoop *et al.* (2001) found a decrease of summer low flows for the Rhine basin of 5–15% for 2050 using a monthly water balance model and results from two Global Climate Models (GCMs). Other studies, using the conceptual hydrological model HBV (Bergström, 1995) and (downscaled) GCM results, found decreases in summer discharges in Europe as well. For the Mulde basin in Germany, this is caused by an increased simulated evapotranspiration (Menzel & Bürger, 2002) and for six Swedish basins, this is due to both an increased evapotranspiration and a shift of snowmelt from spring to winter (Andréasson *et al.*, 2004). Assessments of climate change impacts on low flows using results from Regional Climate Models (RCMs) are even more scarce than those using GCM results. An example is the climate impact study of Payne *et al.* (2004) on water resources of the Columbia River basin in the USA and Canada.

A cascade of uncertainty sources is present in this climate impact assessment ranging from uncertainties about future greenhouse gas emissions and responses of the global climate models to uncertainties in regional climatic effects, physical catchment characteristics and hydrological models.

The uncertainty sources in emissions and climate models can be aggregated and represented by scenarios for future radiative forcing for different global climate models (Carter *et al*., 1999). The uncertainty sources in the hydrological model can be grouped into model input uncertainty (including uncertainties from emissions and climate models), model parameter uncertainty and model structure uncertainty. Numerous studies have assessed these different uncertainties, for emissions and climate models (e.g. Visser *et al*., 2000), as well as for hydrological models (e.g. Uhlenbrook *et al*., 1999). However, only a few attempts have been made to evaluate the whole uncertainty cascade associated with the impact of climate change on low flows, a notable one being Wilby (2005) for the River Thames in the UK.

Therefore, the objective of this study is to assess the uncertainty in impacts of climate change on low flows in the River Meuse in Northwestern Europe. This objective is achieved by first assessing climate change and its uncertainty for the study area. Next, an existing hydrological model is calibrated and validated and uncertainty sources in the hydrological model quantified. The different uncertainty sources are propagated through the hydrological model using Monte Carlo simulation. Finally, results are discussed and conclusions are drawn.

METHODOLOGY AND DATA

Climate change and uncertainty

Changes in climate variables relevant for low flow, in particular precipitation and temperature, are assessed using observed station data and results from Regional Climate Models (RCMs) for different greenhouse gas emission scenarios. The RCM results have been obtained from the EU-project PRUDENCE (Christensen *et al.*, 2002) in which 10 different RCMs for two different IPCC emission scenarios (A2 and B2), different driving GCMs and different samples have been compared. The uncertainty in the climate change projections of climate variables (input uncertainty of hydrological model) is therefore assumed to be mainly the result of different emission scenarios, sampling errors, different boundary forcing by GCMs and different RCMs. The uncertainty in future emissions is underestimated by using results of only the two scenarios A2 (Medium–High emissions) and B2 (Medium–Low emissions), i.e. the difference in the global mean temperature in 2100 as a result of scenarios A2 and B2 is about 1.1°C compared to 2.6°C for the two most extreme scenarios (IPCC, 2001). The uncertainty in changed climate variables (temperature and precipitation) is captured in Gaussian probability distributions for relevant statistics of these variables based on Déqué (2004) and Christensen (2004). In the uncertainty analysis, statistics are randomly drawn from these probability distributions and used to transform current and changed climate series using the change factor (CF) method. The CF method calculates climate series by adding (temperature) or multiplying (precipitation) climate information from the RCMs to observed time series (see e.g. Middelkoop *et al*., 2001).

Hydrological modelling and uncertainty

The conceptual hydrological model HBV (Bergström, 1995), lumped for each of the 15 sub-basins in the Meuse basin upstream of Borgharen with a daily time step, is used to simulate hydrological behaviour in general and low flows in particular for current and changed climate conditions. This model (HBV-15) has originally been applied to high flow simulation in the Meuse basin by Booij (2005). To improve low flow simulation as well, HBV-15 has been re-calibrated for current climate conditions using a fuzzy measure as an objective function (as in e.g. Seibert, 1997). This fuzzy measure combines several objective functions for low flow simulation (e.g. modelling error in discharge deficit) and simulation of the discharge regime (e.g. Nash-Sutcliffe coefficient). Fuzzy logic allows the handling of the concept of a partial truth value between completely truth and completely false. Validation of the model is done for a different period (1985–1996) to the calibration period (1970–1984).

The uncertainty in the hydrological model is represented by the uncertainty in its parameters. Through consideration of this parametric uncertainty, model structure related uncertainties are not explicitly taken into account. However, these are assumed to be at least partly covered by the parametric uncertainty. In the same manner as for the climate variables, in the uncertainty analysis,

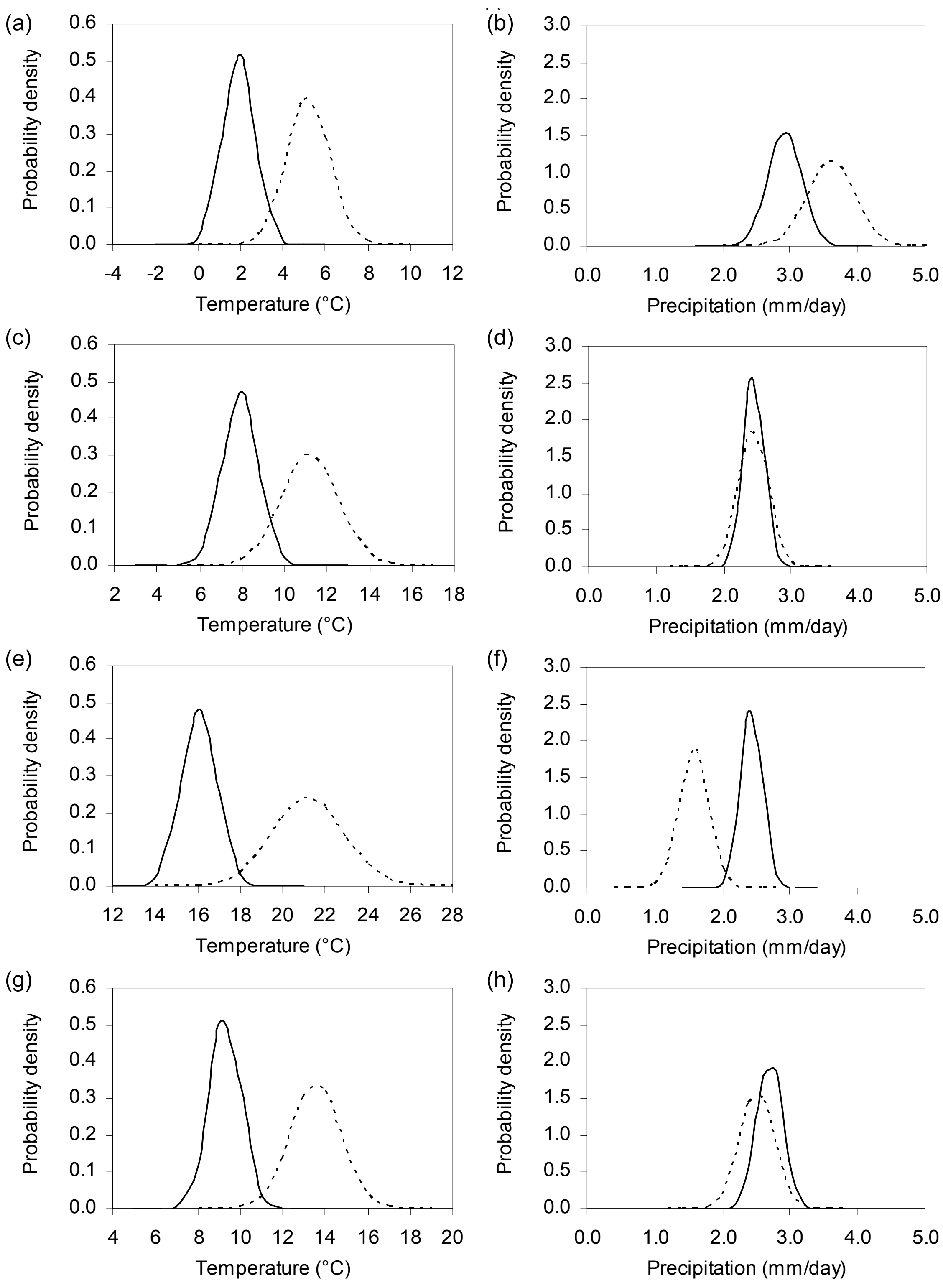

Fig. 1 Probability density functions as a result of different uncertainty sources for current climate (solid) and changed climate (dotted) for DJF (a), MAM (c), JJA (e) and SON (g) temperature (°C), and DJF (b), MAM (d), JJA (f) and SON (h) precipitation (mm day^{-1}).

values for HBV parameters are randomly drawn from uniform probability distributions of these parameters. The HBV parameters are assumed to have the same relative uncertainty range (expressed relative to their means) of 25% (mean value ±12.5%).

Uncertainty analysis

The different uncertainty sources (input uncertainties, HBV parameters) are propagated through the HBV model using Monte Carlo analysis. This finally results in a probability distribution of low flows for current and changed climate conditions. This enables an assessment of the significance of changes in low flow conditions with climate change by comparing changes and uncertainties. Low flows are described by the average annual discharge deficit. The discharge deficit is the cumulative shortage of water with respect to a certain threshold important for river functions like agriculture and drinking water supply. The threshold chosen is 100 $m^3 s^{-1}$ (45% of the mean discharge at Borgharen) corresponding to the starting phase for water allocation measures in the Netherlands and Belgium.

RESULTS AND DISCUSSION

Climate change and uncertainty

Figure 1 shows the probability density functions of basin averaged temperature and precipitation as a result of different uncertainty sources for the current (1970–1996) and changed (2071–2100) climate for DJF (December–January–February), MAM (March–April–May), JJA (June–July–August) and SON (September–October–November). The results show an average increase in annual temperature of 4.0°C for climate change conditions varying between 3.3°C in DJF and 5.1°C in JJA. Precipitation decreases slightly by 2.5% on an annual basis varying between +24% in DJF and –35% in JJA. Uncertainties with climate change (expressed as standard deviation) vary between 1.0°C in DJF and 1.7°C in JJA for temperature and 8.9% in MAM and 13.4% in JJA for precipitation. Uncertainties in these climate variables for current conditions (1971–2000) are somewhat (30–50%) smaller, because emission scenario uncertainties do not apply. In general, changes in temperature seems to be significant for all seasons and changes in precipitation seem to be only significant for winter (DJF) and summer (JJA) taking into account the uncertainty in these variables as a result of different emission scenarios, different RCMs, different boundary forcing by GCMs and sampling.

Hydrological modelling

Results of the HBV model calibration show good performance for low flow as well as for average and high flow simulation using the fuzzy measure. Nash-Sutcliffe coefficients for different sub-basins of the Meuse are between 0.80 and 0.90 and over 0.90 for the complete basin showing a slight improvement with respect to Booij (2005). Differences between observed and simulated discharge deficits are less than 5%. Figure 2 gives an illustration of the calibration results using a fuzzy objective function. It shows dotty plots of values of HBV parameters *FC* (affecting both low and high flow conditions), *ALFA* (primarily affecting high flow conditions) and *PERC* (affecting low flow conditions) against the Nash-Sutcliffe coefficient and the fuzzy measure when varying all other relevant HBV parameters randomly at the same time. For all parameters together, the identifiability has increased using this fuzzy measure with considerable improvements for parameters affecting low flows (e.g. *PERC*, see Fig. 2) and slight deteriorations for parameters primarily affecting high flows (e.g. *ALFA*). Validation results are slightly better than calibration results due to the better data quality for the validation period as has been observed by Booij (2005) as well.

Impacts of climate change on low flows and uncertainty

Combining RCM and HBV results enables an assessment of climate change impacts on low flows and related uncertainties. Figure 3 shows probability density functions of the average annual discharge deficit for the current and changed climate. Climate change results in an increase of the average annual discharge deficit of about 2.6×10^8 m^3 or 35%. This increase is caused by both a decrease of precipitation, in particular in JJA and in SON, and an increase of temperature and related evapotranspiration all year round. The uncertainty in this impact (expressed as standard deviation) is about 0.9×10^8 m^3 as a result of uncertainties in climate change, 0.2×10^8 m^3 as a result of uncertainties in HBV parameters and 1.0×10^8 m^3 as a result of both. For current climate

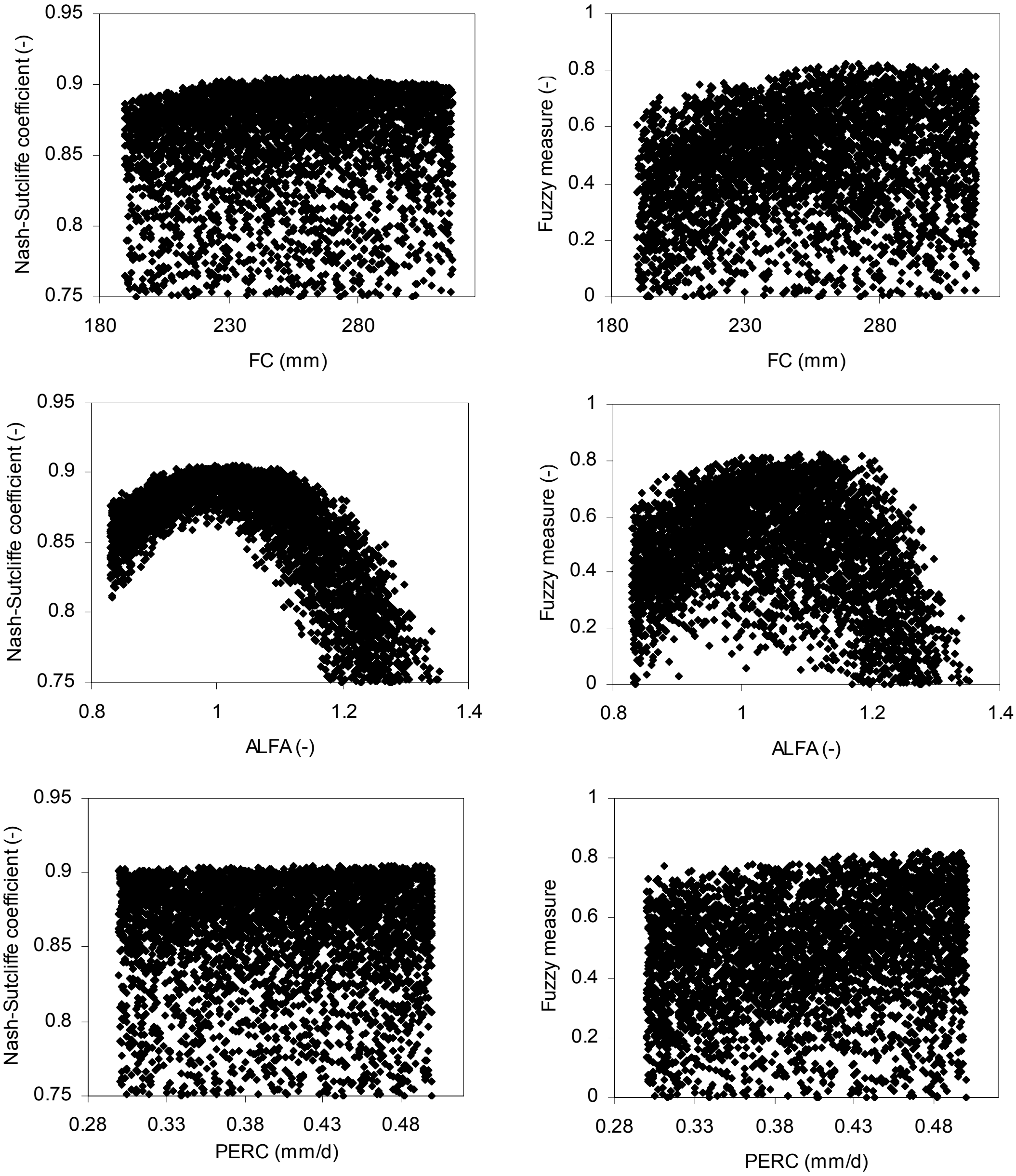

Fig. 2 Dotty plots of the Nash-Sutcliffe coefficient (left) and fuzzy measure (right) for HBV parameters FC (mm), ALFA (–) en PERC (mm).

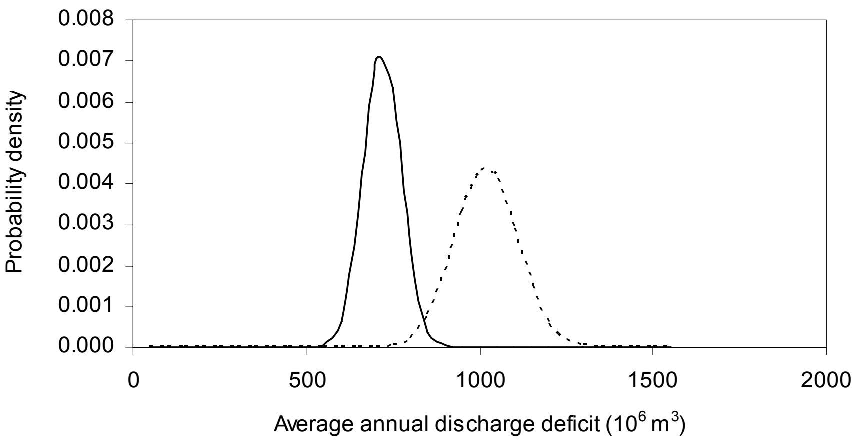

Fig. 3 Probability density functions of the average annual discharge deficit (10^6 m^3) as a result of different uncertainty sources for current climate (solid) and changed climate (dotted).

conditions, these uncertainties are about 0.5×10^8 m^3, 0.2×10^8 m^3 and 0.6×10^8 m^3 respectively. Relative uncertainties of discharge regime variables (with respect to their means) like the standard deviation of daily discharges have a similar magnitude (5–15%).

CONCLUSIONS

It thus can be concluded that the impacts of climate change on low flows are considerable resulting in an increase of water shortages in the Meuse basin during low flow periods. Uncertainties in these impacts are large, although not disguising the climate change signal. These uncertainties are mainly the result of uncertainties in climate variables and to a smaller extent due to uncertainties related to the hydrological model. It is expected that uncertainties in phenomena occurring at low frequencies with climate change will be considerably larger than the uncertainties in relatively frequent-occurring phenomena investigated here (discharge deficit, daily variability).

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