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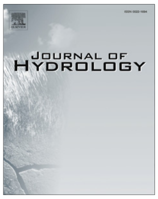

Developing tailored climate change scenarios for hydrological impact assessments

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SUMMARY

To account for the high uncertainty in climate change scenarios, it is advisable to include the maximum possible amount of climate model simulations. Since this is not always feasible, impact assessments are inevitably performed with a limited set of scenarios. The development of few synthesised scenarios is a challenge that needs more attention as the number of available climate change simulations grows. Whether these scenarios are representative enough for future climate change is a question that needs addressing. There is thus a vital need for techniques which can carefully examine the climate model simulations and extract representative climate scenarios that facilitate impact studies. This study presents a methodology of constructing tailored scenarios for assessing runoff flows including extreme conditions (peak flows) from an array of future climate change signals of rainfall and potential evapotranspiration (ETo) derived from the climate model simulations. The aim of the tailoring process is to generate few scenarios that can optimally represent the spectrum of climate scenarios. These tailored scenarios have the advantage of being few in number as well as having a clear description of the seasonal variation of the climate signals, hence allowing easy interpretation of the implications of future changes. The tailoring process begins with an analysis of the hydrological impacts of the climate change signals from all available climate model simulations in a simplified (computationally less expensive) impact model. The climate change signals are transferred to the rainfall and ETo input series of the impact model based on a quantile perturbation technique that accounts for the changes in extremes. The climate model simulations are then subdivided into high, mean and low hydrological impacts using a quantile change analysis. From this impact classification, the corresponding rainfall and ETo change factors are back-tracked on a seasonal basis to determine rainfall–ETo covariation. The established rainfall–ETo variations are used to inform the scenario construction process. Additionally, the 'back-tracking' of extreme flows from driving scenarios is a useful diagnostic of the physical responses to climate change scenarios. The method is demonstrated through the application of 28 RCM runs and a selected catchment in central Belgium.

1. Introduction

The latest generation of climate models have given impetus to research on hydrological climate change impacts. Advances in the climate science have increased the confidence in the climate models (Christensen et al., 2007; Christensen and Christensen, 2007; Knutti, 2008). Regional Climate Models (RCMs) have improved the representation of the land surface features such as the spatial variation of the topography and vegetation, which are vital in resolving the small scale processes. Additionally, the availability of climate change simulations has improved and the number of climate experiments has increased to sample a wider range of future uncertainties. To account for these uncertainties, it is desirable to apply a large ensemble of climate model simulations. However, the number of impact studies that apply such a large set of climate model simulations (say more than 20) is still rather limited. One reason for this is that next to climate change impact assessments other assessments are necessary for an integrated analysis of future impacts. Such assessments may include adaptation scenarios, land use change scenarios, socio-economic scenarios, among others. Whilst computing resources have advanced to enable few tens of simulations, calculation times remain prohibitive in such assessments. Thus impact studies implementing complex or large-scale models are faced with the challenge of synthesising climate scenarios and developing or choosing scenarios that are reasonably sufficient for analysing the future climate change impacts. Bakker et al. (2011) developed a standard year scenario that optimally represented 30-year intra-annual changes in future climate. In this way, quick assessments of several

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combinations of adaptive strategies and climate scenarios can be evaluated. The drawback for the standard year scenario is that it is too short to include many extreme events. Christierson et al. (2012) applied a latin-hypercube sampling method to reduce 10,000 scenarios to 20 scenarios. The sampling method, however, was based on monthly change factors of rainfall and temperature which was not robust for daily runoff extremes. These studies demonstrate that when it is not feasible to run several long-term scenarios, the use of few scenarios is inevitable. However, while constructing such scenarios, it is important to understand the implication of methodologies on the resulting impacts. If extreme runoff impacts are of interest the scenario generation method should be able to account for changes in extreme conditions of the driving variables such as rainfall and evapotranspiration.

Numerous studies have exhibited the development of climate change scenarios for rainfall, temperature and evaporation (Engen-Skaugen, 2007; Graham et al., 2007a; Prudhomme et al., 2002; Vidal and Wade, 2008). These studies have explored different methods for transforming observed data into plausible future scenarios. Other approaches make use of bias corrected series obtained from the climate model simulations rather than historical series (Wood et al., 2004) or make use of stochastic generators (Fowler et al., 2007). Also, new methods for assimilating the available scenarios are being availed. These include ensemble techniques, which have recently received increased attention (Knutti et al., 2010; Teutschbein and Seibert, 2010; Fowler and Ekström, 2009). Ensembles are required because of the high uncertainties involved in the parameterizations of the climate models (Collins, 2007). Also probabilistic techniques have been proposed but the use of the probabilistic data is still in its infancy and their use may misrepresent the uncertainty (Hall, 2007) and consequently raise questions and difficulties for impact modellers (New et al., 2007).

The change factor approach is a popular method applied in climate change analysis because of its simplicity (Deque et al., 2007; Diaz-Nieto and Wilby, 2005; Prudhomme et al., 2002), because it involves intrinsic bias correction and it can combine in one step statistical downscaling and bias correction (Willems et al., 2012). A main assumption of this method is that relative changes from climate models are more reliable than absolute values. Typically, a ratio of future to present climate defines a multiplicative factor that is applied to ratio measures like rainfall and evapotranspiration. What is implicit in the change factor technique is the assumption of future biases being equivalent to present model biases. However this has not been extensively investigated except for a few studies (Knutti et al., 2010; Muerth et al., 2013), which have shown that the assumption has some basis. Christensen and Christensen (2007), and Giorgi and Coppola (2010) found that irrespective of the bias in individual models, the climate change signal were more robust amongst the models. However, the traditional change factor approach is faced with caveats. For instance, the basic change factor method only changes the mean and ignores other changes in the statistical properties such as frequency, temporal sequencing and variability. It is for these reasons that variants of the change factor approach have been proposed such as quantile scaling, mapping or perturbation techniques (Harrold and Jones, 2003; Olsson et al., 2009; Chiew et al., 2009). These methods perturb rainfall intensities with percentile-based change factors, which are change factors that vary with exceedance probability. This approach is suitable in cases where there is increased variability; for instance, in cases where heavy rainfall events may increase at higher rates compared to mild events. Indeed, results from climate models often indicate that the increase in rainfall extremes is greater than the increase in mean rainfall (Kharin and Zwiers, 2005), even in regions where a decrease in mean seasonal or annual rainfall is projected (Chiew et al., 2009).

Whilst the aforementioned methods are valuable for impact analysis, they do not explicitly consider how the future covariations of different variables such as rainfall and evapotranspiration affect the climate change impacts. This is a crucial point as covariations can reveal the underlying physical properties that influence seasonal runoff mechanisms. For instance, groundwater dominated catchments experience gradual flooding while other catchments are subject to rapid flooding such as catchments with steep slopes, clay-dominated catchments, and urban catchments where sewer flooding is triggered by intense rainstorms. Thus scenarios for winter floods should be clearly distinguished from scenarios for summer floods. In this way, the interpretation of climate change impacts would be improved and this could potentially improve the uptake of climate change information (Wilby et al., 2009).

This study presents a methodology for the construction of tailored rainfall and potential evapotranspiration (ETo) scenarios for the impact assessment of runoff extremes (peak flows) in a small catchment in Belgium. The tailoring process involves an assessment of hydrological impacts of the climate change signals from all available climate model simulations using a quantile perturbation approach and a simple conceptual hydrological model. The high, mean and low impacts are identified and corresponding rainfall and ETo change factors are back-tracked on a seasonal basis to determine rainfall–ETo covariation. This covariation is a useful guide in constructing the tailored scenarios. Section 2 provides details of the climate models and simulations used in the study. Section 3 describes the non-parametric perturbation analysis for the rainfall and ETo variables. Section 4 focuses on the development of the tailored scenarios for the impact analysis. Finally, Section 5 presents an overview of the study findings and concluding remarks.

The methodology is demonstrated for the Erpe-Mere catchment, which is one of the sub-catchments of the Dender basin in Flanders, Belgium. The catchment has a total area of about 47 km^2 and is highly urbanised. This makes it an interesting case study not only for climate change but also for its high vulnerability to flooding. Fig. 1 shows the location of the study area.

2. Data and models

2.1. Climate model data

The RCM simulation data used in this study are summarised in Table 1. The RCM simulation data were provided by the PRUDENCE project (http://prudence.dmi.dk), which only considered the SRES (Special Report on Emissions Scenarios) scenarios A2 and B2. From the SRES family of scenarios (Nakicenovic and Swart, 2000), A2 and B2 are considered as ‘medium–high’ and ‘medium–low’ scenarios. Compared with B2, the A2 scenario is characterised by higher carbon dioxide emissions, higher population, greater energy consumption, more land use change, and less application of technology. The horizontal resolution of most RCMs is 50 km with a few RCMs at 25 km (RCAO and HIRHAM). The RCMs were driven with four GCMs with resolutions of 150 km (HadAM3H, HadAM3P) and 250 km (ECHAM4/OPYC, ARPEGE). The RCMs were from: (1) Swedish Meteorological and Hydrological Institute (SMHI), (2) Royal Netherlands Meteorological Institute (KNMI), (3) Norwegian Meteorological Institute (METNO), (4) Danish Meteorological Institute (DMI), (5) Swiss Institute of Technology (ETH), (6) UK Met Office Hadley Centre (HC), (7) Geesthacht Institute for Coastal Research (GKSS), (8) Max Planck Institute (MPI), (9) Centre National de Recherches Météorologiques (CNRM), and (10) Universidad Complutense de Madrid (UCM). One model, from Abdus Salam International Centre for Theoretical Physics (ICTP), was excluded in this study because it did not provide wind data for the