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Appropriate Hydrological Modelling of Climate Change Impacts on River Flooding

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Abstract: How good should a river basin model be to assess the impact of climate change on river flooding for a specific geographical area? The determination of such an appropriate model should reveal which physical processes should be incorporated and which data and mathematical process descriptions should be used at which spatial and temporal scales. A procedure for determining an appropriate model has been developed and applied to the above mentioned specific problem for the Meuse river in France, Belgium and the Netherlands. The model appropriateness procedure consists of three steps. First, the dominant processes and associated key variables are identified. Second, statistical analyses with respect to the key variables are performed, which result in appropriate spatial and temporal scales for each key variable and relationships between key variable scales and the output variable. These latter relationships are used to combine the appropriate scales to one appropriate model scale. In the third step, mathematical process descriptions consistent with these model scales are selected. The resulting appropriate components have been implemented in an existing modelling framework to obtain the appropriate model. Two additional models were constructed to assess the sensitivity of the results to model complexity. The appropriate spatial model scale turned out to be around 10 km with a daily time step. The model results became somewhat better with increasing model complexity. The general trend with climate change (doubling of the CO_2 concentration) is a small decrease (5 %) of the average discharge and a small increase (5-10 %) of discharge variability and extreme discharges. It was found that the uncertainties in extreme discharges with climate change are large and that those due to precipitation and extrapolation errors are the most important ones.

Keywords: Appropriate; Climate change; River flooding; Spatial scales; Modelling

1 INTRODUCTION

Global climate change induced by increases in greenhouse gas concentrations is likely to increase temperatures, change precipitation patterns and probably raise the frequency of extreme events [IPCC, 2001]. This may have serious impacts on society, e.g. through an increased occurrence of flooding events. A broad palette of models is available to assess these impacts. In general, models should be sufficiently detailed to capture the dominant processes and natural variability, but not unnecessarily refined that computation time is wasted. Therefore, the question is what is an appropriate river basin model to assess the impact of climate change on river flooding for a specific geographical area?

Different approaches with respect to model appropriateness have been suggested in literature. They can be classified according to the specific part of the model which is evaluated, such as the output, processes, formulations and scales. An example of a scale-related approach is the Representative Elementary Area (REA) concept in catchment hydrology [Wood et al., 1988]. A REA can be considered as an appropriate scale at which a simple description of the rainfall-runoff process could be obtained. However, this and many other approaches employ a specific model in their procedure. Moreover, they only consider a specific part of the appropriateness problem. Preferably, the components of an appropriate model are determined in an integrated way before model construction and application. The determination should be dependent on the research objective and area considered.

This paper describes a procedure for the determination of appropriate model components dependent on research area and objective. The procedure is applied to the specific problem of climate change impacts on flooding in the river Meuse basin. The appropriate model components are implemented into an existing modelling framework to obtain the appropriate model. Two additional models are constructed to assess the sensitivity of the results to model complexity.

2 MODEL APPROPRIATENESS METHOD

2.1 Introduction

The model appropriateness procedure consists of three steps. First, the dominant processes and associated key variables are identified. Second, the appropriate spatial and temporal scales for each key variable are determined. Furthermore, relationships between key variable scales and the output variable are used to combine the appropriate variable scales to one appropriate model scale. In the third step, mathematical process descriptions consistent with these model scales are selected. The second step is described in more detail below.

2.2 Appropriate scales and their integration

The appropriate scale of a variable is assumed to be equal to a fraction of the correlation length of that variable. The fraction is determined on the basis of relationships between statistics and scale accepting an error in the estimation of the statistic of 10 %. Important statistics in this study are the standard deviation and the extreme return value, i.e. the value that has a probability to occur once in a specified time period. Relationships between these statistics and scales were adapted from Osborn and Hulme [1997] and Sivapalan and Blöschl [1998] respectively. Figure 1 shows the areally averaged return value (scaled to the point return value) as a function of spatial scale and an example of the determination of the appropriate scale. The resulting fractions of the correlation length are 0.25 for the standard deviation and 0.21 for the return value.

The integration of the appropriate variables scales to an appropriate model scale is done by multiplying the appropriate variable scales with associated weights. The weights are based on SCS curve number relationships between the peak discharge (the output of interest) and some specific parameters, such as the slope and the curve number [see Kent, 1972]. The values of these parameters are dependent on the scale of each variable. In this way, relations between the peak discharge and the variable scale are developed. Finally, the weights are determined and multiplied with the appropriate variable scale to obtain the appropriate model scale. More information about this model appropriateness procedure can be found in Booij [2002a].

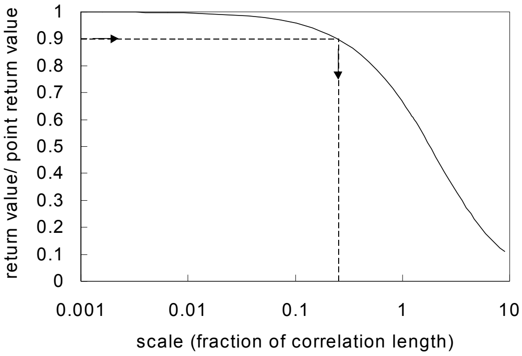

Figure 1. Determination of the appropriate scale for return values accepting a 10 % bias.

3 MEUSE RIVER BASIN

The Meuse basin is situated in France, Belgium and the Netherlands. Its surface area upstream of Borgharen is about 20 000 km^2. The average annual precipitation is 950 mm and the elevation ranges between 43 m and 676 m. The Meuse has a relatively fast response to precipitation and is therefore sensitive to floods and droughts and changes in these properties due to climate change.

Daily climatological data from a station network (39 stations), two data assimilations, three global climate models (GCMs) and two regional climate models (RCMs) are used in this analysis. Furthermore, elevation data from a global digital elevation model and a continental digital elevation model, soil data from the European Soil Bureau (ESB) and land use data from the European Environmental Agency (EEA) database are employed. The spatial resolutions are about 200 km for the data assimilations, 300 km for the global climate models, 50 km for the regional climate models, 1km and 30 m for the global and continental digital elevation models respectively, 2.5 km for ESB and 250 m for EEA. In most climate models, the time period for current and changed climate conditions is 1970-1999 and 2070-2099 (doubling of the CO$_2$ concentration). Further information about the Meuse area and the data resources can be found in Booij [2002a].

4 APPROPRIATE MODEL COMPONENTS AND MODELS

4.1 Dominant processes and variables

Dominant processes and related variables have been derived from literature on a qualitative basis. Dominant processes in flood generation can be divided in primary and secondary flood generating processes. Primary processes are, besides precipitation, infiltration excess overland flow, saturation excess overland flow and subsurface storm flow. Secondary processes are processes important for the initial conditions preceding a flooding event and are evapotranspiration and subsurface flow in the soil matrix. The key variables related to these dominant processes consist of climate and river basin variables. Dominant climate variables are precipitation, temperature and evapotranspiration and dominant river basin variables are elevation, soil type (texture, parent material) and land use type.

4.2 Variable scales and model scale

Application of the scale methodology to the dominant climate variables resulted in appropriate scales for daily precipitation, temperature and evapotranspiration of 20 km, 1000 km and 200 km respectively. The latter two scales are larger than the scale of the river basin (about 150 km), and therefore, one time series for these variables should be sufficient in a river basin model. The appropriate scale for precipitation applies to extreme daily precipitation, due to its importance for river flooding [see Booij, 2002b].

The application to the river basin variables revealed appropriate spatial scales for elevation, soil type and land use of respectively 0.1, 5.3 and 3.3 km. Figure 2 gives the dimensionless peak discharge q_p (with respect to smallest spatial scale) as a function of key variable spatial scale. The peak discharge increases slightly with scale for soils in contrast to the other key variables, which may be due to the spatial distribution of soil types. The weights associated with an appropriate variable scale are assessed by comparing the slopes of the different relationships. The larger the slope, the larger the weight which should be attributed to a specific appropriate variable scale. The sum of the four weights (precipitation, elevation, soil type and land use) is obviously equal to unity. The slope has been determined for at least the range between the appropriate variable scale and the appropriate model scale (checked a posteriori). The appropriate model scale has been determined at about 10 km.

4.3 Process formulations

Appropriate formulations related to these appropriate scales were derived from literature and some rough estimations. The formulations of importance are those related to evapotranspiration, surface flow and subsurface (storm) flow. Relatively simple formulations were found to be sufficient for this model objective and appropriate spatial scale.

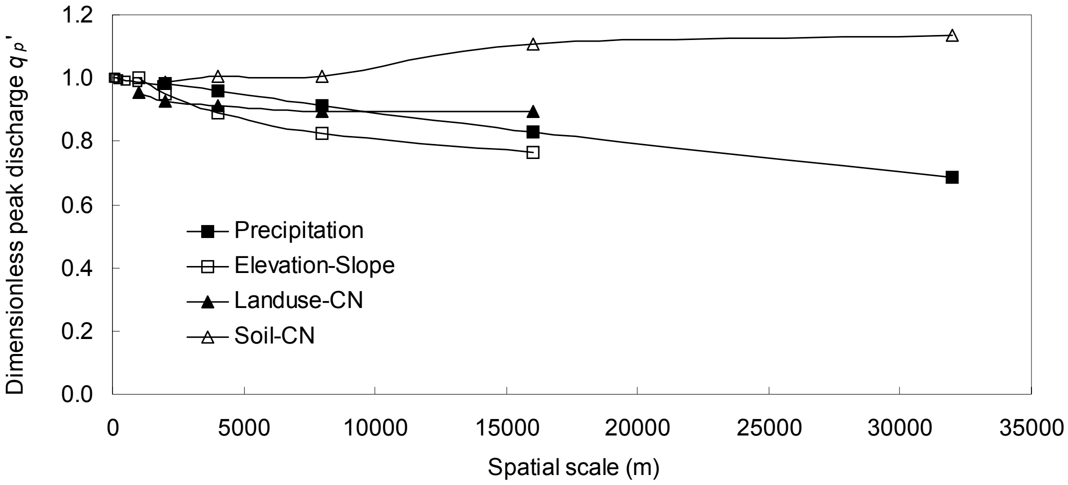

Figure 2. Dimensionless peak discharge q_p' as a function of key variable spatial scale.

4.4 Precipitation model

Precipitation time series instead of precipitation statistics are needed to assess the impact of climate change on river flooding. Besides for climate change conditions, these time series should be generated for current climate conditions in order to verify their correctness. The precipitation time series should be variable in space, because the appropriate spatial scale for precipitation (20 km) is much smaller than the river basin scale (150 km). Therefore, a space-time random cascade precipitation model has been employed to model daily precipitation for the current and changed climate.

The random cascade model [Jothityangkoon et al., 2000] consists of a temporal precipitation model for the complete region considered and a spatial model for the disaggregation of this precipitation to the appropriate scale. The temporal model consists of a discrete first-order four-state Markov chain determining precipitation occurrence and a truncated two-parameter gamma distribution describing precipitation amount. The spatial disaggregation of the temporal precipitation series is done using a discrete random cascade approach with generators determined from a beta-lognormal distribution. The parameters of these models were determined from observed and GCM- and RCM-modelled precipitation. Daily precipitation has been modelled at a 20 km scale for 76 cells for a period of 30 years in multiple realisations.

4.5 Implementation into hydrological model

An appropriate river basin model for the Meuse basin has been constructed by implementing the appropriate model components derived before into the existing modelling framework HBV. Additionally, two river basin models of differing complexities have been set up to evaluate the sensitivity of the model results to model complexity and to allow for a verification of the model appropriateness procedure. The supposedly appropriate model has 118 sub-basins (HBV-118) and the additional models have 1 and 15 sub-basin(s) (HBV-1 and HBV-15).

The HBV model [Bergström and Forsman, 1973] is a conceptual hydrological model. The model consists of a precipitation routine representing rainfall and snow, a soil moisture routine determining actual evapotranspiration, overland flow and subsurface flow, a fast flow routine representing storm flow, a slow flow routine representing subsurface flow, a transformation routine for flow delay and attenuation and a routing routine for river flow.

The parameter estimation consisted of three steps. First, the key parameters for the calibration are determined. Six key parameters were identified on the basis of previous research and are related to the soil moisture and fast flow routine. Second, a sensitivity analysis with the key parameters is done to obtain an optimal parameter set for HBV-1 and some sub-basins of HBV-15 (the parameters can not directly be determined from observed data). Three statistical quality measures (explained variance, relative error in water volume and relative error in return value) and visual inspection were used for this purpose. Third, the key parameters are regionalised to derive parameters for each sub-basin in HBV-15 and HBV-118 employing two different regionalisation techniques [see Booij, 2002a].

The impact of climate change on river flooding is assessed with HBV-1, HBV-15 and HBV-118 in four steps. These are the calibration described above, the validation, the simulation under current climate conditions with the random cascade precipitation model and the simulation under changed climate conditions with the random cascade model. The calibration and validation periods are 15 and 12 years respectively. Five realisations of 30 years for current climate conditions and ten realisations of 30 years for changed climate conditions have been generated with the precipitation model. Five discharge series of 30 years were available for calibration and verification.

5 CLIMATE CHANGE IMPACTS ON RIVER FLOODING

5.1 Current and changed climate

All relevant precipitation statistics for current and changed climate except wet day frequency were well simulated by the random cascade model. The underestimation of the wet day frequency by the model originates from the spatial disaggregation. Namely, the wet day frequency of the temporal areally averaged precipitation time series is well simulated by the random cascade model, but during the disaggregation the model gradually simulates too many dry days. This may be an artefact of the model and can be investigated in future, also because the reduction of the variability and return values is quite well simulated by the random cascade model. Temperature and evapotranspiration series were constructed from station data and GCM data.

5.2 Impact assessment with different hydrological model complexities

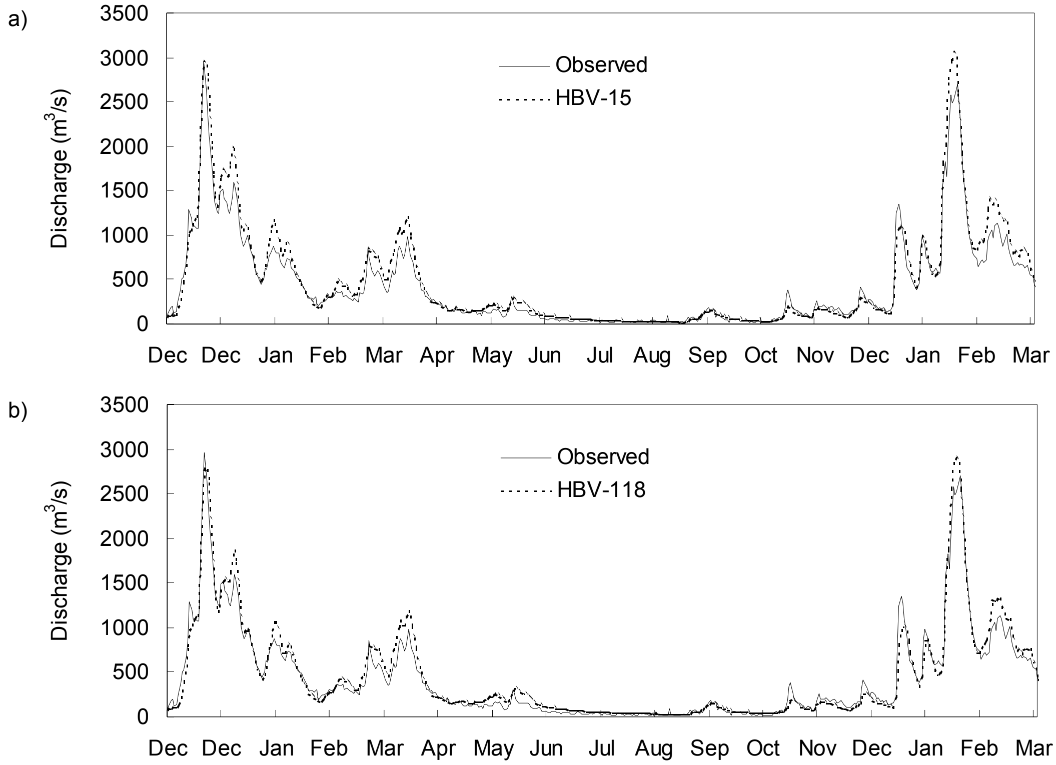

Figure 3. Observed and simulated discharge at Borgharen for December 1993-March 1995 in validation period for a) HBV-15 and b) HBV-118.

The average and extreme discharge behaviour at the basin outlet (Borgharen) is well reproduced by the three models in the calibration and validation. This is illustrated by Figure 3, which shows the observed and HBV-15 and HBV-118 simulated discharge for a 15 month period with two floods in the validation. Overall, the results become somewhat better with increasing model complexity.

The model results with synthetic precipitation under current climate conditions show a small overestimation of average discharge behaviour and a considerable underestimation of extreme discharge behaviour. The underestimation of extreme discharges can not be explained by the statistics of the synthetic precipitation input, but is caused by the observed precipitation input at the sub-basin scale. In most cases, this precipitation is not an really averaged quantity, but rather a point quantity resulting in an overestimation of observed precipitation variability and extreme behaviour at the sub-basin scale compared to the generated precipitation. This seems to be a very frequently occurring problem, which can be dealt with by increasing the density of precipitation stations in a river basin in an efficient manner.

The general trend with climate change is a small decrease of the average discharge (5 %) and a small increase of discharge variability and extreme discharges (5-10 %). The variability in extreme discharges for climate change conditions has slightly increased with respect to the simulations for current climate conditions (see Figure 4) and results from the stochasticity of the precipitation process. The differences between the climate models introduced a comparable variability in extreme discharges (from five realisations, not shown here). Other uncertainties include those related to the river basin model structure, the parameter values and the extrapolation to large return periods. Overall, it was found that the uncertainties in extreme discharges due to precipitation errors and extrapolation errors are more important than uncertainties due to hydrological model errors and parameter estimation errors.

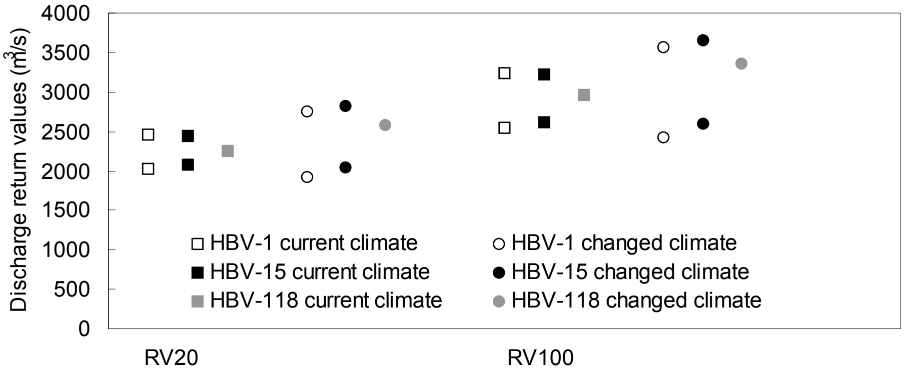

Figure 4. Discharge 20-year (RV20) and 100-year (RV100) return values from a 30 year period as simulated with five precipitation realisations for HBV-1 and HBV-15 (only minimum and maximum are shown) and one precipitation realisation for HBV-118 under current and changed climate conditions.

6 CONCLUSIONS

A model appropriateness procedure has been introduced and applied to the issue of climate change impacts on river flooding. The resulting appropriate components were implemented into an hydrological model. This model and generated precipitation series for current and changed climate conditions were used to simulate discharge series. The same process was repeated with two models with differing complexities. The reproduction of the discharge behaviour by the three models is generally good and becomes somewhat better with increasing model complexity. The appropriate model is complex enough in this study, although the differences with the less complex models are small. This is partly due to the small number of discharge series available and the small differences in model scales. Overall, the appropriateness procedure provides an useful framework for model construction and data needs.

7 ACKNOWLEDGEMENTS

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