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Intercomparison of five lumped and distributed models for catchment runoff and extreme flow simulation

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SUMMARY

Five hydrological models with different spatial resolutions and process descriptions were applied to a medium sized catchment in Belgium in order to assess the accuracy and differences of simulated hydrological variables, including peak and low flow extremes and quick and slow runoff subflows. The models varied from the lumped conceptual NAM, PDM and VHM models over the intermediate detailed and distributed WetSpa model to the highly detailed and 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. A consistent protocol to model calibration was applied to all models. This protocol uses information on the response behavior of the catchment extracted from the river flow and input time series and explicitly focuses on reproducing the quick and slow runoff subflows, and the extreme high and low flows next to testing the conventional model performance statistics. Also the model predictive capacity under high rainfall intensities, which might become more extreme under future climate change was explicitly verified for the models. The tail behavior of the extreme flow distributions was graphically evaluated as well as the changes in runoff coefficients in relation to the changing rainfall intensities.

After such calibration, all tested models succeed to produce high performance for the total runoff and quick and slow runoff subflow dynamics and volumes, peak and low flow extremes and their frequency distributions. Calibration of the lumped parameter models is much less time consuming and produced higher overall model performance in comparison to the more complex distributed models.

1. Introduction

Hydrological models are widely applied in water engineering for design and scenario impact investigations. Depending on the type of application, the catchment characteristics and the data availability, different spatial and temporal scales, different model conceptualizations and parameterizations are considered. In some cases, the most appropriate model is selected based on these criteria. However, in many applications the model selection seems subject to the common practice of the modeller. Rarely an objective model selection seems conducted (Najafi et al., 2011). Moreover, hydrological studies are often based on one particular hydrological model. The selected model structure might, however, strongly affect the study results, as was shown before by Breuer et al. (2009), Viney et al. (2009), Huisman et al. (2009), Ludwig et al. (2009), Maurer et al. (2010), Bae et al. (2011), Gosling et al. (2011), Smith et al. (2012), Van Steenbergen and Willems (2012) and Velázquez et al. (2012), among others. However, these studies did not draw much attention to the performance of the models under extreme conditions. The calibration was based on statistics evaluating the overall runoff performance, whereas it is known that this does not necessarily lead to good model performance for high and low flow extremes (Westerberg et al., 2011). It is more appropriate to consider multiple objectives that focus on the different aspects of the fit between simulated and observed discharges. Freer et al. (1996) used several performance measures in their Generalised Likelihood Uncertainty Estimation (GLUE) framework. Boyle et al. (2000), Madsen (2000), Yu and Yang (2000), Wagener et al. (2001, 2003), Ferket et al. (2010) and Zhang et al. (2011) applied performance measures on the subflow components of the

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runoff discharges or on periods covering different catchment response modes, e.g. wet periods, draining periods, dry periods; or high and low flows above or below a threshold. Westerberg et al. (2011) developed a calibration method including flow-duration curves. Model calibration based on multiple objectives is qualitatively more balanced but does not necessarily statistically perform the best (Westerberg et al., 2011; Willems, 2014). This might raise concern that uncertainty in the impact predictions is additionally induced by the calibration of the models.

Within this paper the influence of the model structure on the model performance for catchment runoff, including high and low flow conditions, is investigated by an ensemble of five hydrological models with different spatial resolutions and process descriptions. In order to obtain consistent and reliable models for use in water engineering (design) applications or scenario-based impact assessment, all models are consistently calibrated by a given systematic but time demanding calibration protocol. The protocol relies on information of runoff subflows and various types of runoff responses derived from the observed river flow, rainfall and potential evapotranspiration (ETo) time series. Explicit focus is given to the high and low flow extremes. It is analyzed whether the models produce reliable estimates of the flow regimes under the current climate and how well they simulate the changes in quick runoff coefficient under changing rainfall intensities. To cover a wide set of model complexities, the selected models in this study vary from the 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 simulates next to the catchment runoff also internal discharges and groundwater heads.

The Grote Nete catchment in Belgium is taken as case study. It is recognized that next to testing different model structures also different catchments with different meteorological and hydrological characteristics should be studied. Practical barriers, however, prevented us from repeating the approach on other catchments. High quality data and good knowledge on the case study processes and particularities are indeed required to make exhaustive studies on model structures behavior.

2. Study area and models

2.1. Study area

The Grote Nete catchment is located in the northeast of Belgium, with an area of 385 km^2 at the outlet limnigraphic station of Geel-Zammel (Fig. 1). The long term mean annual precipitation in the catchment ranges from about 600 to 1100 mm with an areal average of 828 mm based on the years 2002–2008. The precipitation is almost equally distributed during the winter and summer periods. The long term average annual ETo is about 670 mm. The topography is flat, ranging from 12 m in the west to 69 m in the east with an average value of 22 m. It has a shallow phreatic surface. Catchment slopes are in the range of 0–5%, with an average value of 0.3%. The soils are predominantly composed of sand, sandy loam in the southern and valley areas, and silt. The Grote Nete

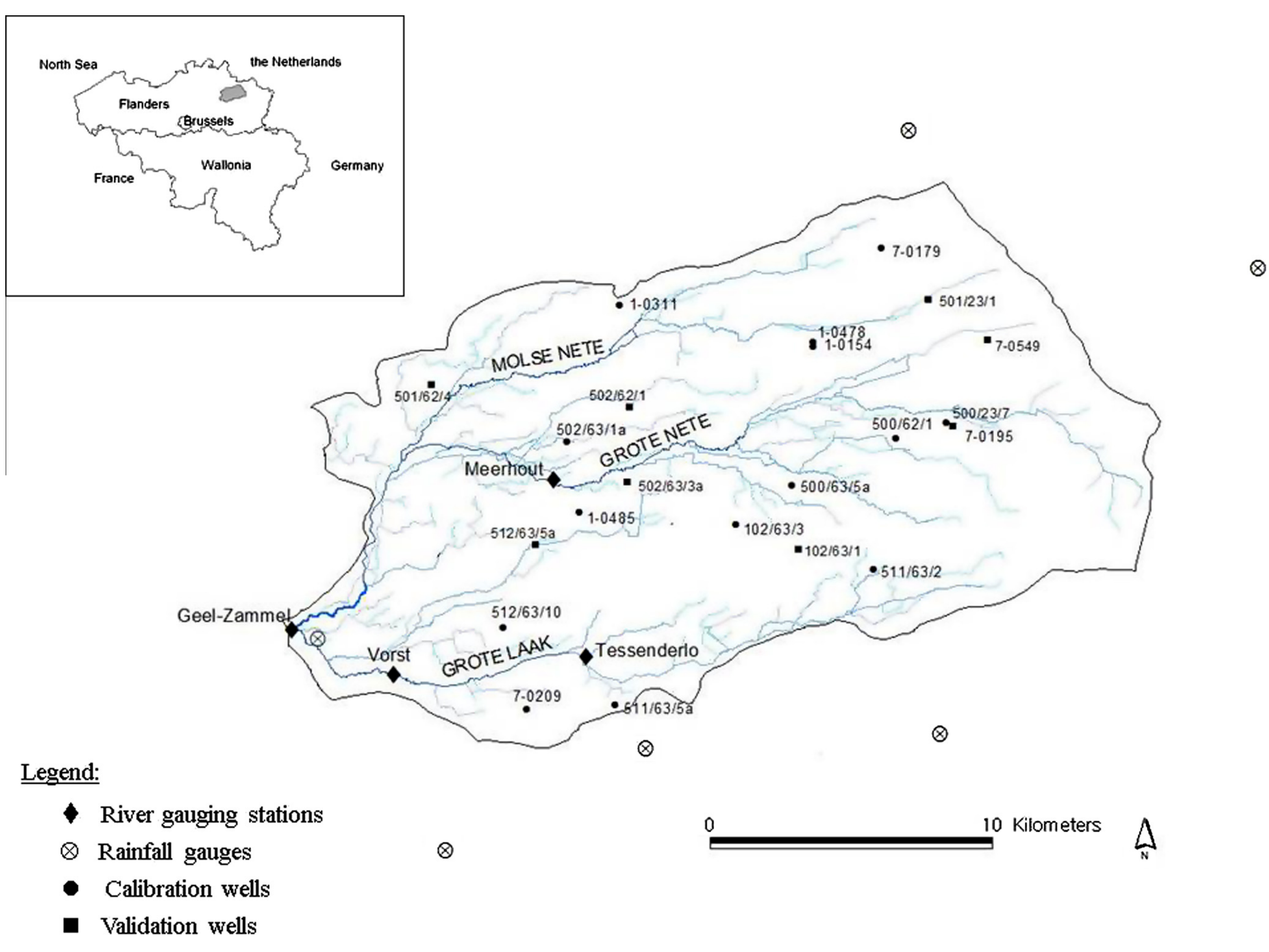

Fig. 1. Location of the Grote Nete catchment in Belgium, and position of the rain gauges, flow gauging station and groundwater wells.