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Technical review of large-scale hydrological models for implementation in operational flood forecasting schemes on continental level

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ABSTRACT

Uncertainty in operational hydrological forecast systems forced with numerical weather predictions is often assessed by quantifying the uncertainty from the inputs only. However, part of the uncertainty in modelled discharge stems from the hydrological model. A multi-model system can account for some of this uncertainty, but there exists a plethora of hydrological models and it is not trivial to select those that fit specific needs and collectively capture a representative spread of model uncertainty. This paper provides a technical review of 24 large-scale models to provide guidance for model selection. Suitability for the European Flood Awareness System (EFAS), as example of an operational continental flood forecasting system, is discussed based on process descriptions, flexibility in resolution, input data requirements, availability of code and more. The model choice is in the end subjective, but this review intends to objectively assist in selecting the most appropriate model for the intended purpose.

Contents

1. Introduction

According to the European Environment Agency (EEA, 2010), floods caused economic losses of over 60 billion Euros and 1126 fatalities in Europe between 1998 and 2009. The losses increased in Europe over the past decades, mainly because of an increase in

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population and per capita wealth, which has resulted in increased exposure of both assets and people in flood-prone areas (EEA, 2010). Following the devastating floods in Elbe and Danube in 2002, the European Commission launched the development of a pan-European Flood Awareness System (EFAS; Bartholmes et al., 2009; Thielen et al., 2009) to improve disaster risk management through early warning information on European scale and subsequently reduce damages in the member states.

EFAS provides information on floods in Europe through a fully operational forecasting system. Currently, the system makes use of multiple meteorological forecasts including ensemble prediction systems to produce probabilistic flood forecasts and to assess the uncertainty of the forecasts. However, uncertainty in hydrological modelling is not limited to the meteorological forcing, but stems from a number of different sources: input data (including forcing), parameters, model structure and evaluation data, e.g., discharge (Refsgaard and Storm, 1996; Thielen et al., 2010). Several hydrological modelling studies have shown that the uncertainty introduced by model parameters and structure can be significant (e.g. Butts et al., 2004; Haddeland et al., 2011; Lohmann et al., 2004). For example, Haddeland et al. (2011) showed that an ensemble of 11 global models forced with the same data exhibited significant differences in the partitioning between evaporation and runoff, with global runoff estimates ranging from 290 to 457 mm yr^{-1}. Velázquez et al. (2011) found that using a multi-model framework for probabilistic flood forecasting outperformed both using a single hydrological model driven with ensemble meteorological data and using multiple hydrological models driven by deterministic meteorological forecasts in a study of 16 lumped catchment models in 29 French catchments.

In a recent study by Wetterhall et al. (2013), operational flood forecasters ranked using multiple hydrological models as one of the top priorities for improving EFAS. A multi-model system would create a more robust forecasting system by better representing the model structural uncertainties and therefore better assess the total uncertainty. In view of these uncertainties, as well as the high cost of implementation of new model systems, it is of great importance to select the best model(s), not only in terms of performance, but also in terms of feasibility of technical implementation. Trambauer et al. (2013) review 16 large-scale models with the specific focus on suitability for drought forecasting in Africa, and Sood and Smakhtin (2015) review the emergence of global hydrological models, with a focus on 12 models, and trends in and constraints for model development. However, to our knowledge, no study has focused on the applicability of this type of models for large-scale operational flood forecasting.

The aim of this paper is to provide a comprehensive review of large-scale models in the context of suitability of pan-European operational hydrological forecasting. However, the assessment is deliberately broad, which would fit any application on the continental or large sub-basin scale. Special emphasis will be put on the model availability and adaptivity to the specific purpose, but the hydrological process descriptions of each model is also an important factor. This paper does not contain a direct hydrological model performance comparison. Instead it focuses on an assessment of the suitability of implementation in the context of an operational flood forecasting system. A review of potential large-scale routing models is also included since routing is fundamental for flood forecasting, but not always included in large-scale hydrological models.

2. Framework for model selection

2.1. EFAS

The current modelling system within EFAS is fully operational and produces a number of forecast products based on meteorological forcings from three different providers: the European Centre for Medium-Range Weather Forecasts (ECMWF), the Deutscher Wetterdienst (DWD) and the Consortium for Small-scale Modelling (COSMO). The forcings used are: 10-day forecasts from ECMWF (deterministic and ensemble with 51 members), 7-day forecasts from DWD (deterministic) and 5-day forecasts from COSMO (ensemble with 16 members). There is only one hydrological model, LISFLOOD (van der Knijff et al., 2008), which is run on a 5 km grid for the entire European domain with a 6-hourly time step for all forcings apart for the ECMWF ensemble, which is run with a daily time step.

EFAS issues flood alerts to the member states' hydrological services based on return periods determined from running the system with observed data for a 20-year period and post-processing the results with generalised extreme value fitting. This ensures that the modelling system is consistent since the same parameterisations are used in deriving the flood alert levels and in the discharge forecasts. EFAS is a complement to existing national flood-forecasting tools, since it forecasts flooding in trans-boundary catchments across Europe in one system. The main purpose of EFAS is to deliver early probabilistic warnings rather than very detailed forecasts that one would be able to get from a national forecasting system.

2.2. Criteria for a continental hydrological model

The first steps in any in any model selection process is to assess the aim, resolution and scope of the model system (Bennett et al., 2013; Jakeman et al., 2006). In the case of EFAS, the purpose of the system was clear from the start, to provide a European-wide forecasting system. The development of the system is a constant balance between the wishes from the users, the scientific progress of probabilistic forecasting and constraints due to computational costs and data availability (Wetterhall et al., 2013). This review is a qualitative rather quantitative model assessment, and as such evaluates the models from a number of selection criteria, for example identification of user community, demands on model structure, complexity, flexibility etc. (Bennett et al., 2013). The selection criteria are in the end subjective since they are a consequence of the application in question, and the list below reflects the demands for an operational continental system.

Many technical aspects need to be carefully considered in order to adapt a model to an operational continental-scale modelling system. These include for example process descriptions, availability in terms of licencing, open source code etc. and applicability to the given problem at hand. One important process of a flood-forecasting model is the ability to respond to differences in the precipitation patterns in different parts of a catchment. This can be accounted for with a fine spatial distribution (typically on the order of 1–10 km), but can also be assessed through statistical representation of flood-producing mechanisms. Other important processes that are crucial for flood forecasting on European scale are, for instance, snow accumulation and snow melt which affects the timing and magnitude of spring flows in cold regions. In addition, runoff generated within a computational unit needs to be converted to discharge and routed along a river network to produce discharge forecasts along a river course. However, since not all large-scale hydrological models include a routing component, this study also provides a short review of existing large-scale river routing models (see Appendix B online supplementary material).

In addition to the review of the process descriptions, a list of criteria were set up to guide the model selection in terms of adaptivity to continental scale forecasting. The criteria were modelled on EFAS to be used over a pan-European domain and may