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Flood risk under future climate in data sparse regions: Linking extreme value models and flood generating processes

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SUMMARY

For many areas in the world, there is a need for future projections of flood risk in order to improve the possible mitigation actions. However, such an exercise is often made difficult in data-sparse regions, where the limited access to hydrometric data does not allow calibrating hydrological models in a robust way under non-stationary conditions. In this study we present an approach to estimate possible changes in flood risks, which incorporates flood generating processes into statistical models for extreme values. This approach is illustrated for a West African catchment, the Mono River (12,900 km^2), with discharge, precipitation and temperature data available between 1988 and 2010 and where the dominant flood generating process is soil saturation. A soil moisture accounting (SMA) model, calibrated against a merged surface soil moisture microwave satellite dataset, is used to estimate the annual maximum soil saturation level that is related to the location parameter of a generalized extreme value model of annual maximum discharge. With such a model, it is possible to estimate the changes in flood quantiles from the changes in the annual maximum soil saturation level. An ensemble of regional climate models from the ENSEMBLES–AMMA project are then considered to estimate the potential future changes in soil saturation and subsequently the changes in flood risks for the period 2028–2050. A sensitivity analysis of the non-stationary flood quantiles has shown that with the projected changes on precipitation (−2%) and temperature (+1.22°) under the scenario A1B, the projected flood quantiles would stay in the range of the observed variability during 1988–2010. The proposed approach, relying on low data requirements, could be useful to estimate the projected changes in flood risks for other data-sparse catchments where the dominant flood-generating process is soil saturation.

1. Introduction

The vulnerability to floods has increased in Africa during the recent decades (Douglas et al., 2008; Di Baldassarre et al., 2010). Therefore, future projections of flood risks using climate models are needed in order to improve the mitigation actions. Probably the most common method to evaluate the climate change impacts on hydrology is the top-down approach: the outputs of general circulation models (GCM) are downscaled to the catchment of interest and subsequently run into a hydrological model to evaluate the climate change impacts. It is well known that there are potentially great uncertainties at the different levels of this type of approach, namely in the downscaling methods (Fowler et al., 2007; Teng et al., 2012) and the validity of hydrological models under different climatic conditions (Wilby, 2005; Peel and Blöschl, 2011). Indeed, a great problem faced when conducting climate change impact studies on flood risks in Africa is the lack of data available to calibrate hydrological models in a robust manner. The same statement applies to other data-sparse regions of the world. Physical-based models could be useful tools to estimate the climate change impacts on hydrological processes (Dankers and Feyen, 2009; Cornelissen et al., 2013) but they require a great amount of hydrometric and physiographic characteristics data that is often not available in the target catchments. On the other side, conceptual hydrological models require less input data but several studies have warned about their use under non-stationary conditions (Vaze et al., 2010; Amoussou et al., 2014). Indeed the calibrated parameters of conceptual models may be dependent of climatic conditions (Merz et al., 2011).

Beside top-down modeling chains and their potential limitations, a growing number of studies have considered bottom-up

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approaches to model flood risk and vulnerability to changing climatic conditions (Cunderlik and Simonovic, 2007; Prudhomme et al., 2010; Wilby and Dessai, 2010; Peel and Blöschl, 2011; Kay et al., 2013). These approaches relies on first understanding the processes linked with hydrological hazards and then performing a sensitivity analysis to assess the possible changes on flood risk given a possible range of climatic variability. Milly et al. (2008) argued that the concept of stationarity, i.e. the idea that natural systems are fluctuating within an unchanging envelope of variability, should be abandoned and only non-stationary models should be used in water resource planning. Statistical models in the framework of extreme value theory (Coles, 2001) are useful tools for that purpose and they can be adapted to non-stationary conditions by relating their parameters to covariates (Katz et al., 2002; El Adlouni et al., 2007; Tramblay et al., 2012a, 2013). If the covariates are representing hydrological processes – and not time –, such models can be used to make future scenarios.

Merz and Blöschl (2008a,b) emphasized the need for a better understanding of the local flood producing factors to improve the flood frequency estimation methods. Indeed, the purpose of the new 2013–2022 decade of International Association of Hydrological Sciences "Panta Rhei" (Montanari et al., 2013) is to improve the prediction of water resources dynamics in a changing environment. With precipitation, the role of antecedent moisture conditions plays a major role in modulating floods (Brocca et al., 2008; Tramblay et al., 2010; Pathiraja et al., 2012). Some recent studies have considered extreme value models for floods with explanatory covariates other than soil moisture. Examples could be found in Delgado et al. (2013), who modeled non-stationary flood probabilities as a function of monsoon intensity in the Mekong River, or López and Francés (2013) who considered climatic and reservoir regulation indices as covariates in extreme value models for 20 continental Spanish rivers. One key issue is to merge statistical and deterministic methods in order to provide better flood risk estimates in a changing climate. The first step would be to identify the relevant flood generating processes that can also explain the observed trends (Ishak et al., 2013). Only a few studies have considered yet the joint use of extreme value models with hydrological model outputs, which can provide relevant information about flood-generating processes that cannot be observed straightforward. Seidou et al. (2012a,b) used such a framework in a Canadian basin by linking the parameters of an extreme value model for floods with the SWAT model monthly outputs. They related the location parameter of a GEV distribution of annual maximum discharge to the maximum 9-day average flow computed with a SWAT model. However the proper calibration of such a model in a data sparse catchment can be difficult since it requires a great amount of hydro-meteorological, land cover and soil data. To adapt this approach in catchments with limited access to data, there is need to consider parsimonious models able to reproduce the main flood generating factors.

In this study a similar approach, taking into account the scarcity of the data, is developed to evaluate the change in flood risks in a medium-scale catchment in West Africa, the Mono River upstream of the Nanbgéto dam (12,900 km^2). In this catchment, only a few rain gauges and meteorological stations are available, which makes difficult the implementation of distributed physical-based models. Previous work on the same catchment (Amoussou et al., 2014) has shown that a lumped conceptual hydrological model did not perform well in validation when the calibrated parameters were transferred to different time periods. Since the dominant flood driver in this catchment is soil saturation in the present study we tested a simple soil moisture accounting (SMA) model to evaluate if the soil saturation level can be related to the magnitude of flood events. In addition, an ensemble of regional climate model simulations is used to estimate the future projected changes in soil moisture dynamics. The study area and datasets are described in Section 2, in Section 3 is detailed the modeling approach and in Section 4 the results.

2. Study area and data

2.1. The Mono River and the Nangbéto dam

The Mono River is located across the countries of Togo and Bénin, its portion upstream of the Nangbéto dam is under a tropical climate influenced by the West African monsoon. A good correlation exist between the annual maximum discharge and soil saturation in the catchment, several processes studies in that area (Giertz et al., 2006; Le Lay et al., 2008; Séguis et al., 2011; Cornelissen et al., 2013) have shown the important contribution of the top few meters of soils to runoff and the little interaction with deep groundwater.

Daily discharge between 1988 and 2010 at the dam intake and precipitation at 14 different stations are available (Fig. 1). The catchment area upstream the Nangbéto dam is 12,900 km^2, rainfall is interpolated through ordinary block kriging, using a climatological variogram fitted with a spherical model. Potential evapotranspiration (PET) is computed with the Oudin et al. (2005) formula using the daily temperature records at the dam. A preliminary study has shown the absence of trends in the hydro-meteorological records, with the notable exception of a steady temperature increase since the 1970s (Amoussou et al., 2014). In addition, daily surface soil moisture data were obtained between 1988 and 2010 from the ECV merged surface soil moisture microwave satellite dataset (Dorigo et al., 2010; Liu et al., 2011; Loew et al., 2013) distributed in the framework of the climate change initiative for soil moisture (http://www.esa-soilmoisture-cci.org/) The ECV data set shows good correspondence with ground-based measurements over the nearby AMMA network (Dorigo et al., in preparation). The soil moisture (SM) data is retrieved for the pixels at a 25 km resolution over the Mono catchment and averaged to produce a single time series of SM for the catchment.

2.2. Regional climate model simulations from ENSEMBLE–AMMA

In order to provide a future climate change signal, an ensemble of 4 regional climate model (RCM) simulations driven by 2 general circulation models (ECHAM and HADCM) at a spatial resolution of 50 km are extracted over the catchment (Table 1). These simulations are provided from the EU projects AMMA and ENSEMBLES (Paeth et al., 2011). This ensemble allow the reduction of the uncertainties related either to the choice of the RCM or the GCM by comparison to individual simulations. Indeed as shown on Fig. 2, the multi-model ensemble provides a better reproduction of the seasonal patterns of precipitation or temperature in the catchment than individual model simulation during the reference period 1988–2010. The projected changes are assessed by analyzing the raw or bias-corrected precipitation and temperature outputs of the models during the projection period 2028–2050, under the emission scenario A1B.

Since time series of precipitation and temperature simulated by climate models can be affected by a bias that precludes their direct use in an impact model (Piani et al., 2010; Paeth et al., 2011), a monthly quantile-mapping bias correction method (Déqué 2007; Themeßl et al., 2012) is applied in the present study. The quantile-mapping method is a non-parametric approach that allows correcting each quantiles of the simulated cumulative distribution functions by comparison with the observed ones. In addition, a new threshold is defined for daily RCM precipitation in order to match the observed frequency of wet days. The same corrections