Journal of Hydrology 524 (2015) 182–193

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Spatially coherent flood risk assessment based on long-term continuous simulation with a coupled model chain

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ARTICLE INFO

Article history:
Received 30 September 2014
Received in revised form 31 January 2015
Accepted 7 February 2015
Available online 16 February 2015
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Michael Brian Butts, Associate Editor

Keywords:
Flood risk analysis
Risk model chain
Floodplain inundation
Continuous simulation

SUMMARY

A novel approach for assessing flood risk in river catchments in a spatially consistent way is presented. The approach is based on a set of coupled models representing the complete flood risk chain, including a multisite, multivariate weather generator, a hydrological model, a coupled 1D–2D hydrodynamic model and a flood loss model. The approach is exemplarily developed for the meso-scale Mulde catchment in Germany. 10,000 years of meteorological fields at daily resolution are generated and used as input to the subsequent models, yielding 10,000 years of spatially consistent river discharge series, inundation patterns and damage values. This allows estimating flood risk directly from the simulated damage. The benefits of the presented approach are: (1) in contrast to traditional flood risk assessments, where homogenous return periods are assumed for the entire catchment, the approach delivers spatially heterogeneous patterns of precipitation, discharge, inundation and damage patterns which respect the spatial correlations of the different processes and their spatial interactions. (2) Catchment and floodplain processes are represented in a holistic way, since the complete chain of flood processes is represented by the coupled models. For instance, the effects of spatially varying antecedent catchment conditions on flood hydrographs are implicitly taken into account. (3) Flood risk is directly derived from damage yielding a more realistic representation of flood risk. Traditionally, the probability of discharge is used as proxy for the probability of damage. However, non-linearities and threshold behaviour along the flood risk chain contribute to substantial variability between damage probabilities and corresponding discharge probabilities.

1. Introduction

River flooding is increasingly seen from the risk perspective which considers not only the flood hazard, e.g. discharge and inundation extent, but also the vulnerability and adaptive capacity of the flood-prone regions (Merz et al., 2010). This shift in perspective is visible, for instance, by the development of flood risk maps demanded by the European Flood Directive on the Assessment and Management of Flood Risks (European Commission, 2007). These maps are now widely available throughout Europe and are important for risk communication and integrated flood risk management. Alfieri et al. (2014) argued, however, that these maps are generated with inconsistent methods on different spatial scales, using different data bases, and are therefore not comparable on the European scale. Even within European member states, methods might not be consistent, as it is the case for Germany where different federal states adopted different approaches for deriving and presenting flood maps (see e.g. BfG (2014) for an overview). To enable comparisons, Alfieri et al. (2014) proposed the development of a pan-European flood hazard map with a spatial consistent methodology based on the assessment of uniform 100-year flood flows for all river stretches and piece-wise hydraulic modelling of corresponding flood areas.

This proposal alleviates the problem of method and data inconsistency, but it does not overcome the problem of assuming spatially uniform return periods for flood scenarios. This traditional approach in flood risk assessment derives scenarios with a constant T-year return period (e.g. $T = 100$) for flood peaks within the entire catchment. The assumption of spatially uniform return periods is valuable for local hazard and risk assessments, however, it is of limited use for large-scale assessments, for example, for

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http://dx.doi.org/10.1016/j.jhydrol.2015.02.021
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national risk policy developments, for large-scale disaster management planning, and in the (re-)insurance industry. The assumption of a *T*-year flood peak for the entire river network gives an unrealistic large-scale picture. It is not realistic that a single flood reaches a 100-year return period in the entire large-scale river network. Flood risk would be overestimated, as the probability of a single flood reaching a 100-year return period throughout the catchment is much smaller than the probability of a 100-year flood at a single site. The overestimation of flood risk, derived with the traditional approach, was recently shown by Thieken et al. (in press) for the river Rhine in Germany.

There are different possibilities for generating flood events that respect the spatial variability of occurrence probability at the catchment scale. One approach that has recently gained attention is the application of multivariate distribution functions to represent the joint probability of flood peaks at multiple sites (e.g. Lamb et al., 2010; Ghizzoni et al., 2012; Keef et al., 2013). A multivariate distribution function, considering the spatial dependence between gauging stations, is fitted to observed flood peaks at multiple gauges and can be used to generate spatial fields of flood peaks. A disadvantage of this method is that only flood peaks are provided. It is not obvious how such an event set could be used as input into unsteady inundation models, because hydraulic models require the entire hydrographs conserving flood volume in order to simulate the temporal evolution of flood waves within the river system. This problem can be bypassed when the event generation starts with the precipitation event. Rodda (2001) developed a stochastic model generating rainfall events for the UK. These events were used as input into a hydrological model to simulate the spatial distribution of the *T*-year discharge. A disadvantage of the event based simulation approach is the assumption that the return period of flood discharge equals the return period of rainfall. This is usually not given, since storm characteristics, such as the rainfall time pattern, or the initial catchment state influence the relationship between rainfall probability and flood probability (Haberlandt and Radtke, 2014).

This simplifying assumption can be avoided by continuous hydrological simulation (e.g. Boughton and Droop, 2003; Viviroli et al., 2009; Grimaldi et al., 2013; Haberlandt and Radtke, 2014). This increasingly popular concept consists of generating long synthetic meteorological time series and using them as input into a continuous hydrological model. Flood probabilities can then be derived from the simulated synthetic discharge time series. This 'derived flood *frequency* approach based on continuous simulation' has the advantage that the complete flood event, including antecedent processes, are modelled throughout the entire catchment in a consistent way. The importance of initial catchment conditions for the flood development was recently investigated by Nied et al. (2013) and also could be observed from the disastrous flood event in 2013 in Central Europe, where the interplay of event precipitation and very wet initial catchments played a dominant role for the exceptional event severity (Schröter et al., 2015). Grimaldi et al. (2013) demonstrated the effect of a continuous hydrologic-hydraulic simulation on floodplain inundation patterns compared to an event-based approach for a small-scale basin.

In this paper we extend the 'derived flood *frequency* approach based on continuous simulation' and propose a novel concept for assessing flood risks: the 'derived flood *risk* approach based on continuous simulation' Thereby we use the synthetic discharge time series as input into flood impact models and derive flood risk directly from the resulting synthetic damage time series. In this way, the processes, and their space–time interactions, underlying the flood risk in a catchment are represented in a consistent way. For instance, the hydrodynamic simulation of floodplain processes, such as storage effects or channel-floodplain interactions, allows considering the effects of floodplain processes on flood damage patterns.

A further advantage is that flood risk can be directly derived from the synthetic damage time series. The return period of damages is thus based on the empirical distribution constructed from long-term simulation. Ideally, risk is estimated as (probability × damage), whereas probability is the probability of damage. Thieken et al. (in press) used this approach by generating a stochastic flood event set from discharge station data, combining it with a flood impact model and fitting an extreme value distribution directly to the synthetic damage data. This attempt to derive flood risk directly from the probability of damage is a rare exception in the flood risk literature. The usual way is to use the probability of discharge or the probability of precipitation as proxy for the probability of damage. However, the probability for the different phenomena (precipitation–discharge–inundation–damage) may change along the flood risk chain. For example, two events with the same flood peak discharge may lead to very different inundation and damage patterns.

In this paper, we explore the idea 'derived flood *risk* approach based on continuous simulation'. The Mulde catchment, a meso-scale catchment in East Germany, is selected as example. A multisite, multivariate weather generator is linked to the Regional Flood Model (RFM). RFM is a coupled model chain, consisting of a continuous hydrological model, 1D/2D hydrodynamic models and a flood loss model. It has been recently developed for risk assessments in large-scale river catchments and took part in a proof-of-concept study, driven by observed meteorological time series for a period of 14 years (Falter et al., in press). For the first time, RFM is driven by synthetic meteorological data, generated by a multisite, multivariate weather generator, providing 100 realisations of 100 years of data. This virtual period of 10,000 years is simulated continuously, providing a sample of more than 2000 flood events with detailed information on inundation depth, extent and damage on a resolution of 100 m. On basis of this unique data set, we present a flood risk analysis directly on damage values. Additionally, this allows us to examine the assumption that probability of peak discharge is a suitable proxy for probability of damage. Derived damage probabilities are compared to corresponding flood peak probabilities to discuss problems that may arise from transformations of flood peak probabilities to damage probabilities.

2. Methods

2.1. Weather generator

The meteorological input data for the model chain is provided by a multisite, multivariate weather generator (Hundecha and Merz, 2012), further advanced from Hundecha et al. (2009). It provides spatially consistent realisations of meteorological fields for large-scale basins. The model generates synthetic daily meteorological forcing in two stages. In the first stage, precipitation series are generated at multiple sites by respecting the spatial and temporal correlations of the observed daily precipitation amounts on monthly basis. At each station, daily precipitation is sampled from a parametric distribution, which is estimated from the observed daily precipitation series as a mixture of Gamma and Generalized Pareto distributions. The mixing weight varies dynamically with respect to the precipitation intensity. The second stage of the model simulates daily maximum, minimum and average temperatures and solar radiation by keeping the correlations between the variables as well as their inter-site correlation and the autocorrelation of each variable. Temperature values are sampled from Gaussian distributions fitted to the corresponding observations, whilst for solar radiation a square root transformation was used prior to fitting a Gaussian distribution. Both temperature and solar radiation