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Continuous simulation for flood estimation in ungauged mesoscale catchments of Switzerland – Part II: Parameter regionalisation and flood estimation results ☆

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SUMMARY

Flood estimations for ungauged mesoscale catchments are as important as they are difficult. So far, empirical and stochastic methods have mainly been used for this purpose. Experience shows, however, that these procedures entail major errors. In order to make further progress in flood estimation, a continuous precipitation–runoff-modelling approach has been developed for practical application in Switzerland using the process-oriented hydrological modelling system PREVAH (Precipitation–Runoff–EVApotranspiration-HRU related model).

The main goal of this approach is to achieve discharge hydrographs for any Swiss mesoscale catchment without measurement of discharge. Subsequently, the relevant flood estimations are to be derived from these hydrographs. On the basis of 140 calibrated catchments (Viviroli et al., 2009b), a parameter regionalisation scheme has been developed to estimate PREVAH's tuneable parameters where calibration is not possible. The scheme is based on three individual parameter estimation approaches, namely Nearest Neighbours (parameter transfer from catchments similar in attribute space), Kriging (parameter interpolation in physical space) and Regression (parameter estimation from relations to catchment attributes). The most favourable results were achieved when the simulations using these three individual regionalisations were combined by computing their median.

It will be demonstrated that the framework introduced here yields plausible flood estimations for ungauged Swiss catchments. Comparing a flood with a return period of 100 years to the reference value derived from the observed record, the median error from 49 representative catchments is only −7%, while the error for half of these catchments ranges between −30% and +8%. Additionally, our estimate lies within the statistical 90% confidence interval of the reference value in more than half of these catchments. The average quality of these flood estimations compares well with present empirical standard procedures, while the range of deviations is noticeably smaller. Additionally, the availability of complete hydrographs and the process-oriented background bear potential for analyses that go beyond the mere estimation of peak flows.

Introduction

Reliable estimates for peak flow values with various return periods are an indispensable prerequisite for planning measures which reduce or even prevent flood damage (see e.g. Pilon, 2004). Particularly on the mesoscale (drainage area of roughly 10–1000 km^2 in the present case), there is a great need for such estimates, as was e.g. shown in the aftermath of the 2005 flood events in the European Alps (Bezzola and Hegg, 2007).

For catchments with long gauge records, floods with various recurrence intervals are estimated with relatively little effort using extreme value statistics (DVWK, 1999). However, the results for rare events are noticeably influenced by the choice of theoretical extreme value distribution function and parameter estimation method (see Vogel et al., 1993; Klemeš, 2000), and different conditions and processes governing individual flood events are usually not considered. Above all, gauge records are too short or totally absent in the majority of cases.

Far more frequently, however, flood estimates are sought for ungauged catchments. This refers to the concept of regionalisation,

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i.e. 'to make predictions about hydrological quantities at sites where data are absent or inadequate, frequently for design purposes' (Beran, 1990). In flood estimation, two families of methods are most commonly applied:

Regional transfer functions are used to apply information from gauged to ungauged basins, e.g. using regionally differentiated enveloping curves or regressions; a wide variety of such methods are available today (see e.g. Dalrymple, 1960; Cunnae, 1988; Hosking and Wallis, 1993; Bobée and Rasmussen, 1995; Burn et al., 1997). Although measures related to hydrological processes or meteorological conditions may be involved, these are usually considered in an empirical rather than causal manner.

Simple concept models like the rational formula (Chow, 1964) and more sophisticated derivates of it (e.g. Kölla, 1987) involve some considerations regarding the most relevant processes, but are criticised for containing parameters which are difficult to estimate (e.g. runoff coefficient) or for being founded upon questionable assumptions (e.g. identical return period for precipitation and resulting peak flow).

These methods have been widely applied in the past and proven successful for average conditions (Weingartner, 1999). For estimation concerning an individual basin, however, the disagreement between results from different approaches may be considerable (see Weingartner et al., 2003), particularly if unusual conditions prevail (e.g. regarding soil, geology, or climatology). This means that the above-mentioned methods show a lack of robustness.

In this paper, we present a deterministic, process-oriented alternative for estimating floods in catchments without gauge records. More precisely, we employ continuous long-term simulation at hourly resolution for ungauged mesoscale catchments in Switzerland. The simulated hydrographs are subsequently analysed using extreme value statistics, which leads to estimations of flood peak values with the desired recurrence interval. Our main intent is to provide robust and independent estimates which extend and improve today's flood estimation methods. The suitability of the modelling framework is tested extensively in application, by considering a large number ($n = 140$) of study catchments. This lays the foundation for a comprehensive nation-wide flood estimation system with practical relevance.

Comprehensive 'real-world' applications of continuous simulation were only rendered possible in the past decade when the numerous data sets required became available in digital form and in sufficient quality, and when computers started to be able to process them efficiently, although the idea of continuous simulation had already been conceived in the 1970s (Eagleson, 1972; see also Beven, 2001). A comprehensive review of continuous simulation applications for design flood estimation is found in Boughton and Droop (2003); they report operational systems for Australia, Europe, South Africa, the UK, and the USA most of which are aimed at gauged (i.e. calibrated) catchments. For ungauged catchments, the only application to date which is comparable in extent to ours is found in the UK (Calver et al., 2005; see also Lamb and Kay, 2004 and references therein); in contrast to our framework, however, it is not entirely based on hourly time steps.

This paper is structured as follows: After introducing the regionalisation methods in "Modelling framework" (including the attributes necessary for describing the catchments), results are presented for standard efficiencies ("Model efficiency") and, most importantly, for flood estimation ("Flood estimation"), which is then compared to popular empirical and stochastic methods ("Comparision with standard procedures"). The characteristics of estimation errors are discussed in "Estimation errors", while important issues concerning the regionalisation approaches are highlighted in "Regionalisation approaches" and "Is the proposed regionalisation scheme effective?". Concluding remarks and an outlook follow in "Conclusions and outlook".

Modelling framework

Our approach to obtaining estimations for ungauged catchments in Switzerland has been developed on the basis of 140 calibrated mesoscale catchments (see Viviroli et al., 2009b) and tested using 49 representative catchments with long and reliable gauge records. We use the conceptual process-based hydrological modelling system PREVAH (Precipitation–Runoff–EVApotranspiration-HRU related model; for definition of HRU see below) (Viviroli et al., 2009a), which has a respectable record of successful application in topographically complex regions, particularly in Switzerland (for a compilation see Viviroli et al., 2007, 2009a). The spatial resolution of PREVAH is currently based on hydrological response units (HRUs), which we aggregated for this study on the basis of 0.5×0.5 km^2 raster cells. The temporal resolution for inputs and outputs is hourly throughout. This is of special relevance for flood estimation since large peak values are smoothed severely when a coarser temporal resolution (e.g. daily time step) is used, especially in smaller mesoscale basins (Viviroli, 2007). Data interpolated from the Swiss standard meteorological gauging network are used to operate the model from 1984 to 2003, namely precipitation, air temperature, global radiation, relative sunshine duration, wind speed and relative humidity. For interpolation, Detrended Inverse Distance Weighting (e.g. Garen and Marks, 2001) and Ordinary Kriging (e.g. Isaaks and Srivastava, 1989) are used. Details of the modelling framework are furnished in the companion paper by Viviroli et al. (2009b).

Regionalisation methods

While the tuneable model parameters of PREVAH are calibrated for catchments with gauge records (Viviroli et al., 2009b), the model's application to ungauged catchments requires a parameter regionalisation procedure. The 12 tuneable model parameters are estimated using three independent approaches (Nearest Neighbours, Kriging and Regression), which are subsequently combined by calculating the median of the three respective simulated discharge hydrographs. For glaciated catchments, two more parameters need to be regionalised. Regionalisation is based on an extensive set of model parameters from 140 catchments which were calibrated using a cost-efficient procedure; particular focus was put on the appropriate representation of peak flows (for both calibration methods and results see Viviroli et al., 2009b).

This chapter describes the methods for regionalisation of the tuneable model parameters. First of all, attributes have to be evaluated which are able to describe any catchment within the study area. Then, the three regionalisation approaches are introduced and the respective outputs finally combined into a single simulation for ungauged catchments.

Catchment attributes

Characterising catchments for regionalisation purposes requires appropriate attributes. A large variety of such catchment descriptors have been presented in the past (e.g. Pearson, 1991; Sefton and Howarth, 1998; Seibert, 1999; Peel et al., 2000; Blöschl and Merz, 2002; Lamb and Kay, 2004; Merz and Blöschl, 2004; Bárdossy et al., 2005). For Switzerland and the Alpine region in general, the collection of Breinlinger et al. (1992) is most relevant and comprehensive, while a useful collection was also prepared by Pfaundler (2001). All of these studies agree that a set of attributes must always be tailor-made for the respective goals and study area.