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Representative sets of design hydrographs for ungauged catchments: A regional approach using probabilistic region memberships

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ABSTRACT

Traditional design flood estimation approaches have focused on peak discharges and have often neglected other hydrograph characteristics such as hydrograph volume and shape. Synthetic design hydrograph estimation procedures overcome this deficiency by jointly considering peak discharge, hydrograph volume, and shape. Such procedures have recently been extended to allow for the consideration of process variability within a catchment by a flood-type specific construction of design hydrographs. However, they depend on observed runoff time series and are not directly applicable in ungauged catchments where such series are not available. To obtain reliable flood estimates, there is a need for an approach that allows for the consideration of process variability in the construction of synthetic design hydrographs in ungauged catchments. In this study, we therefore propose an approach that combines a bivariate index flood approach with event-type specific synthetic design hydrograph construction. First, regions of similar flood reactivity are delineated and a classification rule that enables the assignment of ungauged catchments to one of these reactivity regions is established. Second, event-type specific synthetic design hydrographs are constructed using the pooled data divided by event type from the corresponding reactivity region in a bivariate index flood procedure. The approach was tested and validated on a dataset of 163 Swiss catchments. The results indicated that 1) random forest is a suitable classification model for the assignment of an ungauged catchment to one of the reactivity regions, 2) the combination of a bivariate index flood approach and event-type specific synthetic design hydrograph construction enables the consideration of event types in ungauged catchments, and 3) the use of probabilistic class memberships in regional synthetic design hydrograph construction helps to alleviate the problem of misclassification. Event-type specific synthetic design hydrograph sets enable the inclusion of process variability into design flood estimation and can be used as a compromise between single best estimate synthetic design hydrographs and continuous simulation studies.

1. Introduction

Classical design flood estimation has been focusing on the univariate analysis of peak discharges even though other event characteristics such as hydrograph volume and shape are equally important for hydraulic design tasks involving storage (Pilgrim, 1986). More recent flood estimation procedures allow the representation of both the magnitude and the shape of an event through synthetic design hydrographs (SDHs). Synthetic design hydrographs provide a more complete picture of the flood behavior of a catchment than classical approaches. SDHs include event-based approaches using event rainfall as input (Grimaldi et al., 2012; Rogger et al., 2012) and statistical approaches using observed runoff in bivariate flood frequency analyses (Brunner et al., 2017b). However, as the classical approaches, they neglect the variability of flood events within a catchment caused by different processes, which are mirrored by various flood types, such as flash floods, short-rain-, long-rain-, and rain-on-snow floods (Merz and Blöschl, 2003). To overcome this deficiency, (Brunner et al., 2017b) proposed an approach for the construction of a set of flood-type specific SDHs. The approach splits the flood sample into four subsets, one for each flood type, and uses each of these samples to construct a flood-type specific design hydrograph. The shape of the design hydrographs is modeled by a probability density function (PDF) while the magnitude of the event is modeled via a bivariate frequency analysis taking into account the dependence between peak discharges and hydrograph volumes via a copula model. This ensemble-based SDH construction

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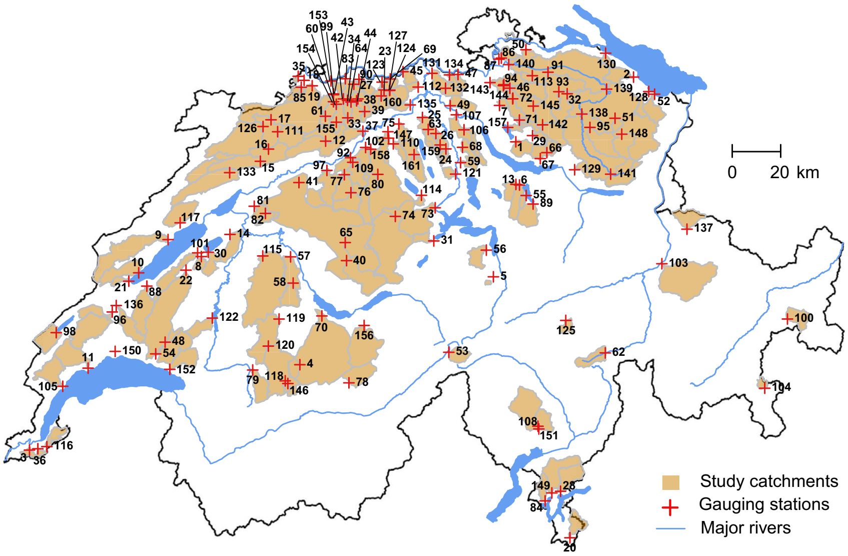

Fig. 1. 163 study catchments in Switzerland.

approach takes into account process variability but is based on observed flood events and cannot be easily transferred to ungauged catchments where no runoff information is available. There, design floods have traditionally been estimated by a regional index flood approach focusing on peak discharges.

The index flood approach consists of two main steps. In a first step, regions with a similar flood behavior are delineated. In a second step, the data within these similar regions are used for regional flood frequency analysis. Hydrologically similar regions are often delineated based on hydrological catchment characteristics or runoff signatures (Burn and Boorman, 1992) since physiographical and climatological catchment similarity do often not correspond to hydrological similarity (Ali et al., 2012; Oudin et al., 2010). Brunner et al. (2017a) suggested to use entire hydrograph shapes in the delineation of homogeneous regions with the argument that those provide more information on the flood behavior of a catchment than statistical measures of individual hydrograph characteristics. In this previous study, it was shown that flood reactivity regions can be delineated by characterizing each catchment in the dataset by a set of three representative hydrograph shapes: a fast, an intermediate, and a slow shape. Grouping catchments with similar sets of representative hydrograph shapes delineates regions which are similar in terms of their flood behavior. Such regions were shown to have a hydro-meteorological meaning and are potentially useful in regional flood frequency analysis.

Regional frequency analysis is often done using the index flood approach which was proposed by Dalrymple (1960) for annual maxima series and later extended to partial duration (peak-over-threshold) series (Madsen et al., 1997). It assumes that frequency distributions at different sites within a region are identical apart from a scale factor. It describes a local quantile estimate $Q_i(F)$ as the product of an index flood (μ_i) and a regional growth curve ($q(F)$) estimated based on the data at N sites as:

$$Q_i(F) = \mu_i q(F) \quad i = 1, \ldots, N. \tag{1}$$

The index flood can be any location measure of the at-site distribution but is often taken to be its mean. The regional growth curve is a dimensionless quantile function computed based on dimensionless regional data, which are obtained by dividing the observed flood event data by the index flood. Regional analysis using the index flood approach yields more accurate quantile estimates than at-site analysis even if a region is heterogeneous. It was thus found to be a robust and efficient estimation procedure (Lettenmaier et al., 1987; Madsen et al., 1997).

The classical index flood procedure focuses on peak discharges. Requena et al. (2016) therefore proposed an approach for a multivariate regional index approach that allows for the consideration of more than one design hydrograph characteristic, e.g. peak discharge and hydrograph volume. While such a bivariate regional approach allows the joint consideration of peak discharges and hydrograph volumes, neither hydrograph shape, nor process variability can be considered. To our knowledge, no methodology has so far been proposed for the regional construction of event-type specific sets of SDHs in ungauged catchments. The aim of this study was therefore to propose an approach that allows for the construction of SDHs in ungauged catchments which on the one hand jointly represents the magnitude and shape of an event and on the other hand allows for the consideration of process variability. We here propose an approach that delineates regions of a similar flood reactivity using the approach by Brunner et al. (2017a), applies the bivariate index flood approach proposed by Requena et al. (2016) within these flood reactivity regions, and uses the resulting design variable pairs in the SDH construction approach proposed by Brunner et al. (2017b). Instead of flood types, we use the three event types fast, intermediate, and slow in design hydrograph construction Brunner et al. (2017a). The three event-type specific SDHs together form a set of design hydrographs which considers the process variability within an ungauged catchment.

Our research more specifically addresses the following research questions:

1. How can an ungauged catchment best be assigned to one of the flood reactivity regions?
2. How can event-type specific SDH sets for ungauged catchments be constructed?
3. Can probabilistic class memberships be used in regional SDH construction to reduce the problem of misclassification?

2. Data

This analysis used runoff and catchment characteristics data from 163 Swiss catchments (Fig. 1) with a wide range of catchment characteristics and flood behaviors. The selected catchments have hourly flow series of at least 20 years in duration ranging up to 53 years. In these catchments, runoff is neither altered by regulated lakes upstream or inland canals nor by urbanized areas. The catchments are small to medium-size (6 to 1800 km^2), situated at mean elevations between 400 and 2600 m.a.s.l., and have no or only a minor glacier coverage.