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Patterns of streamflow regimes along the river network: The case of the Thur river

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ABSTRACT

A modeling framework for point-wise prediction of the probability density function and flow duration curve of streamflows along complex river networks is presented. The predictions are based on catchment-scale climatic and morphological features, without calibration on observed discharge time-series. The framework was applied to a test basin in north-eastern Switzerland, and relevant flow statistics were validated at six sub-catchment outlets with satisfactory results. Spatial patterns of flow regime exhibit a strong climatic signature, mostly driven by reduced rainfall depths and increasing effective rainfall frequency in the downstream areas. The increasing non-linearity of the catchment response with contributing area is reflected by the observed increase in the recession parameters along the main river channel. This framework offers a novel approach for assessing the spatial patterns of streamflows based on limited information, which is important for evaluation of human and ecological functions in riverine systems.

1. Introduction

The natural spatial variability of flow regimes within riverine systems is a major control for both human and ecological functions in river corridors (e.g. Bertuzzo et al., 2012; Ziv et al., 2012; Jaeger et al., 2014; McCluney et al., 2014). These spatial patterns are a complex by-product of climatic and morphological features of the contributing catchment. Modeling and predicting this variability and the underlying drivers, particularly where discharge data scarcity is a limiting factor, represents an important topic of research.

The main features of the flow regime for any given point along the network can be summarized through streamflow statistics, such as the probability density function (PDF) of streamflows and the flow duration curve (FDC)(Vogel and Fennessey, 1995). Spatially explicit characterization of these flow statistics has received much attention in recent years, and diverse modeling approaches have been proposed. Spatially distributed models are complex and capable of estimating the spatiotemporal heterogeneity of main hydrological processes in a study area (Kumar et al., 2013; Murphy et al., 2013; Ryo et al., 2015). However, they often depend on a large number of unknown parameters that must be calibrated. This number can be reduced through utilization of hydrological response units (Flügel, 1995; Gurtz et al., 2005; Viviroli et al., 2009) or regionalization techniques (Götzinger and Bárdossy, 2006; Kling and Gupta, 2009; Samaniego et al., 2010; Singh et al., 2012). However, despite recent progress in parametrization across scales (Kumar et al., 2013), parameters calibrated at a particular spatial resolution are often not applicable to other scales.

Geostatistical models have proved capable of predicting a variety of hydrometric indices and one, or a series of, flow quantiles based on empirical correlations among available discharge observations (Castellarin 2014; Pugliese et al., 2014; Laaha et al., 2014). However, statistical models often do not directly account for flow generation processes, require observed streamflow time series, and are very sensitive to data quality and density (Blöschl et al., 2013; Müller and Thompson, 2016).

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Stochastic, process-based models have been demonstrated to be well suited for prediction of the complete flow duration curve (Botter et al., 2007, 2009; Muneepeerakul et al., 2007; Schaefli et al., 2014; Pumo et al., 2013; Ceola et al., 2014; Müller et al., 2014). They often use a limited number of physically meaningful parameters, with low computational burden, to mechanistically link the drivers, state and hydrologic response of the catchment (Müller and Thompson, 2015). Process-based models can also be applied in the absence of long term discharge time series, as they require minimal or no calibration (Doulatyari et al., 2015). Such attributes make this category of model a valuable alternative for predicting the spatial variability of flow regimes, especially in cases where hydrometric stations are lacking. To date, this type of models have only been applied to individual catchment outlets.

In this paper we employ the stochastic analytical model developed by Botter et al., 2007 to provide a framework capable of estimating the complete FDCs, at any arbitrary point along a complex river network. The model has four physically based parameters, which are estimated for each point along the network, without calibration to discharge time series. The estimation process accounts for the heterogeneity of the underlying climatic and geomorphic drivers by quantifying the spatial patterns of effective rainfall and recession features, as well as the interplay between these driver in all the relevant contributing areas. The framework was implemented in conjunction with a custom web GIS and geodatabase, based on mainly open source software. The original contribution of this paper is in two main areas: (*i*) for the first time a parsimonious process based formulation is framed in a spatially explicit setting to analyze the patterns of FDC along the river network; (*ii*) scaling relationships for recession parameters and discharge variability are analyzed. Furthermore, a web GIS tool is developed for the characterization of hydro-climatic patterns which may be useful to research and water managers;

The paper is organized as follows: Sections 2 and 3 presents the essential details about the study area and summarize the hydroclimatic data used. A brief description of the geo-database and Web GIS platform is also included here. Section 4 outlines the modeling approach as well as the theoretical framework used for estimating the four main model parameters. Results are presented in Section 5. These include the validation of the model at six outlets, spatial patterns of model parameters and flow regimes, and scaling of recession parameters. Advantages and limitations of the methods used are discussed in Section 6. Section 7 provides the overall conclusions and implication of this novel modeling method.

2. Study area

The modeling method was tested on the Thur basin, located in Northeast Switzerland. The Thur river, a tributary of the Rhine river, has a length of approximately 130 *km* (Fig. 1). It is highly monitored and the contributing catchments shows pronounced gradients of rainfall. Therefore it is very well suited for analyzing the relationship between climate gradients and spatial patterns of flow regimes.

There are 19 rainfall stations evenly distributed within the boundaries of the Thur catchment (Table A.2). Discharge data were available in a set of six nested discharge stations (Table A.1) spanning a wide range of contributing areas (from 16 to 1700 km^2). The annual mean discharge of the Thur river is 53 m^3/s and discharge fluctuates rapidly in the entire course of the river, especially after heavy rainfalls in the upper catchment (Cirpka et al., 2007). The are no significant lakes or reservoirs along the river. The effects of snow dynamics have been observed to be relevant in the headwaters catchment (Seneviratne et al., 2012). The discharge station Andelfingen represents the outlet for the entire basin (Fig. 1). Suitable subsets of these discharge stations that represent a sequence of mutually nested sub-catchments (e.g. Jonschwil, Halden, Andelfingen) can be identified and used to analyze the scaling of hydrological properties and flow regimes.

The Thur basin can be divided into two main morphologic regions: the upper pre-alpine section with the maximum altitude of 2500 *m.a.s.l.* (meters above sea level) at Mount Säntis; and the Swiss plateau with altitudes of approximately 350 *m.a.s.l.* in the lower catchment containing the Thur valley aquifer. The geology in the catchment consists of mainly limestone-dominated alpine headwaters, and Molasse sandstones, marls and Pleistocene unconsolidated sediments in the Swiss plateau (Hayashi et al., 2012). Precipitation ranges from 2500 *mm*/*year* in the pre-alpine region to

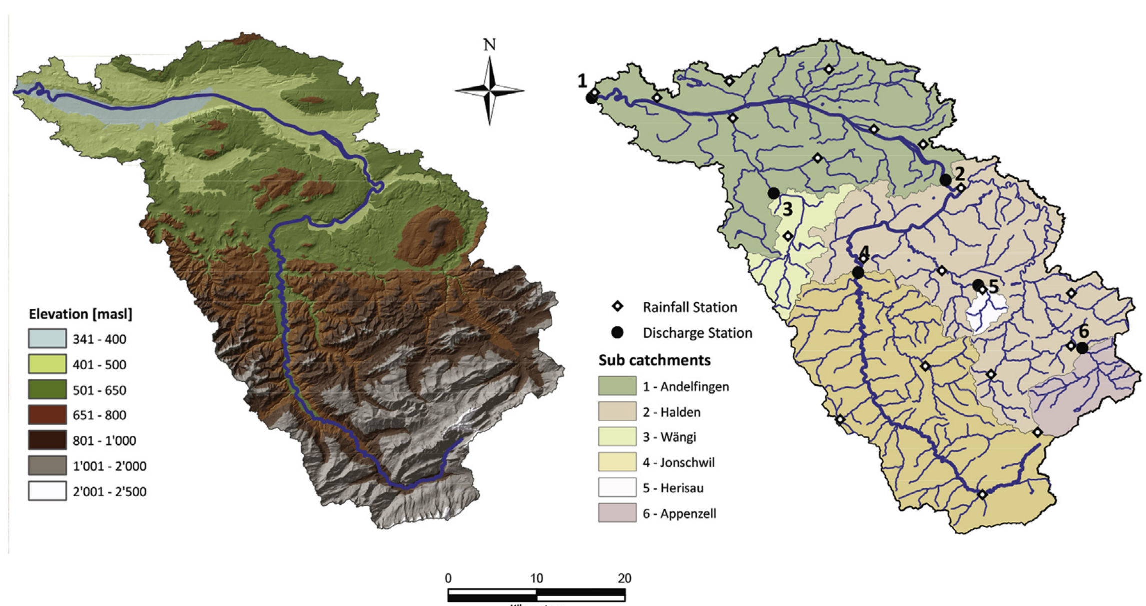

Fig. 1. (a) The digital elevation map of the Thur basin. The main morphological sections of the basin, the pre-alpine (to the south and) and the Swiss plateau (to the north), are easily distinguished. (b) The Thur basin is divided into six sub-catchments. The corresponding gauging stations as well as 19 rainfall stations are marked on the map.