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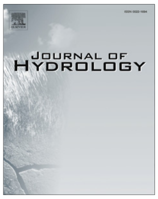

Value of different precipitation data for flood prediction in an alpine catchment: A Bayesian approach

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ABSTRACT

Flooding induced by heavy precipitation is one of the most severe natural hazards in alpine catchments. To accurately predict such events, accurate and representative precipitation data are required. Estimating catchment precipitation is, however, difficult due to its high spatial, and, in the mountains, elevation-dependent variability. These inaccuracies, together with runoff model limitations, translate into uncertainty in runoff estimates. Thus, in this study, we investigate the value of three precipitation datasets, commonly used in hydrological studies, i.e., station network precipitation (SNP), interpolated grid precipitation (IGP) and radar-based precipitation (RBP), for flood predictions in an alpine catchment. To quantify their effects on runoff simulations, we perform a Bayesian uncertainty analysis with an improved description of model systematic errors. By using periods of different lengths for model calibration, we explore the information content of these three datasets for runoff predictions. Our results from an alpine catchment showed that using SNP resulted in the largest predictive uncertainty and the lowest model performance evaluated by the Nash–Sutcliffe efficiency. This performance improved from 0.674 to 0.774 with IGP, and to 0.829 with RBP. The latter two datasets were also much more informative than SNP, as half as many calibration data points were required to obtain a good model performance. Thus, our results show that the various types of precipitation data differ in their value for flood predictions in an alpine catchment and indicate RBP as the most useful dataset.

1. Introduction

Flooding induced by heavy precipitation is one of the most severe natural hazards in Switzerland (Hilker et al., 2009; Massacand et al., 1998; Hohenegger et al., 2008; Stucki et al., 2012), and is likely to increase due to more frequent heavy precipitation events foreseen in the Alps (Beniston et al., 2011). To accurately predict this type of flood event, an accurate estimation of the causative precipitation is crucial (Masih et al., 2011; Strauch et al., 2012; Voisin et al., 2008). Yet, while runoff represents an aggregated response to the catchment's precipitation and as such can be measured at its outlet only (Vaze et al., 2011), precipitation is a spatially heterogeneous phenomenon and thus measuring its representative values at a catchment scale is not trivial (AghaKouchak et al., 2011; Krajewski et al., 2003; McMillan et al., 2012; Villarini et al., 2008).

Observations from point gauges, i.e., station network precipitation (SNP), remain the most common method for measuring catchment precipitation (AghaKouchak et al., 2010; Berne et al., 2005; Lorenz et al., 2014; Volkmann et al., 2010). The main reasons for this are: a relatively high accuracy of precipitation rates at their respective locations (Brown et al., 2001; Brussolo et al., 2008), the extended recording period suitable for analyzing long-term precipitation-runoff patterns (Xie et al., 2007), and relatively low costs of a gauge purchase and maintenance (Sikorska et al., 2012). When used as input for runoff models, such point precipitation measurements must be aggregated to a catchment wide areal precipitation (Ly et al., 2013; Rodriguez-Iturbe and Mejía, 1974) and for ungauged regions, a simple interpolation between point estimates is usually made (Girons Lopez et al., 2015). Inaccuracies in estimating a catchment's precipitation, when introduced into the runoff model, will translate into large uncertainty in model simulations (Kavetski et al., 2006; Mul et al., 2009; Oudin et al., 2006). Thus, SNP data may sometimes be insufficient to model a

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catchment's response (Bárdossy and Das, 2008; McMillan et al., 2011; Segond et al., 2007), and in some catchments might not result in a satisfying model performance (Kuczera et al., 2010).

This is especially true for poorly gauged regions (Sikorska et al., 2012), and for mountainous catchments, where due to a complex terrain, additional errors in estimating catchment precipitation need to be considered (Joss and Lee, 1995). These errors include wind and shading effects from slopes (Frei et al., 2006), biased locations of stations mostly limited to valleys while precipitation rates increase with elevation (Viviroli et al., 2011; Xie et al., 2007), and locally placed events (with or without orographic influence) induced by the natural mountainous barrier. To capture such spatial and elevation dependent precipitation fields, a finer spatial measuring resolution (and covering different elevation zones) would be required (Ly et al., 2013). Hence, it has been proposed to smooth the precipitation rates across the terrain by using a number of point measurements from an extended area (Frei et al., 2006; Vaze et al., 2011). These point measurements are interpolated and next aggregated into gridded cells of homogeneous precipitation rates, giving interpolated grid precipitation (IGP). Yet, the problem with a limited representation at high elevations remains.

As an alternative to point gauges, meteorological weather radars can immediately provide information on spatial precipitation at a large scale and also at high elevations (Andrieu et al., 1997; Berne and Krajewski, 2013; Borga, 2002; Kidd et al., 2012; Krajewski and Smith, 2002). Thus, some research has been devoted to assessing the usefulness of such radar-based precipitation (RBP) for hydrological purposes (e.g., Abon et al., 2015; AghaKouchak et al., 2010; Borga, 2002; Collier, 1986; Hazenberg et al., 2011; Hossain et al., 2004). Yet, due to the need to transform radar attenuation measurements into ground precipitation rates; disturbances in the beam attenuation and, in mountains, also beam shielding (Collier, 1989; Hossain et al., 2004; Joss and Lee, 1995; Viviroli et al., 2011); limited spatial resolution (Germann et al., 2006; Wilson and Brandes, 1979); and high costs of data purchase; their practical value for hydrological purposes in small and medium-size catchments has been questioned (Lanza et al., 2001; Tetzlaff and Uhlenbrook, 2005).

Given the above issues, it remains unclear which dataset, among the three mentioned, is the most informative for understanding hydrological response and predicting flood events in a mountainous catchment, given a limited number of observations for model calibration. While several studies have focused on designing the most optimal station network for hydrological needs (Chen et al., 2008; Jung et al., 2014; Villarini et al., 2008; Volkmann et al., 2010; Wood et al., 2000), a comparison of radar and point gauge estimates at a catchment scale has gained continual attention since the 1980s (e.g., Andrieu et al., 1997; Biggs and Atkinson, 2011; Borga et al., 2000; Collier, 1986; Hossain et al., 2004; Piman and Babel, 2013). More recently, effects of precipitation uncertainty on runoff predictions have been studied within different uncertainty frameworks for lowland and urbanized catchments (Andreassian et al., 2001; Bárdossy and Das, 2008; Biemans et al., 2009; McMillan et al., 2011; Younger et al., 2009). Yet, similar analysis of mountainous catchments are much more restricted (Masih et al., 2011) and limited to assessing the parameter uncertainty usually using a GLUE approach (Generalized Likelihood Uncertainty Estimation) (e.g., Collier, 2009; Hossain et al., 2004). However, uncertainty in precipitation data, together with structural limitations of a runoff model, result in systematic errors in runoff predictions and thus cannot be explained by the parametric uncertainty alone (Kuczera et al., 2010; Sikorska et al., 2015a). For climate related studies, these precipitation errors are dealt with by applying a bias correction to precipitation estimates (Addor and Seibert, 2014; Teutschbein and Seibert, 2012). For uncertainty analysis of runoff predictions, these errors must be described (explicitly or implicitly) adequately with respect to their properties (Brynjarsdóttir and O'Hagan, 2014; Kuczera et al., 2010; Sikorska et al., 2015b).

The objectives of this study are therefore to investigate the value of the three different precipitation datasets commonly used in hydrological studies, i.e., SNP, IGP, and RBP, for flood prediction in an alpine catchment within a Bayesian framework. Rather than focusing on designing the most optimal station network for hydrological implications, we use available precipitation products as input to a runoff model and assess their usefulness for the purpose of understanding and predicting the hydrological process. The novelty of our work lies, first, in describing the systematic model errors with an improved error model that represents both the precipitation uncertainty and the structural uncertainty of a runoff model, with an additive bias term. We demonstrate that such an error model improves the identification of the hydrological process since it provides reliable runoff predictions with all three datasets. Next, by performing a Bayesian comparative analysis, we explore the information content of each precipitation dataset and its impact on runoff predictive uncertainty. Finally, by using different period lengths for model calibration, we quantitatively evaluate how much data of each source is needed to provide a sufficient model performance for ungauged regions.

2. Material

2.1. Study site

The Plessur river, located in the Swiss Alps (Canton Graubünden), is a 33 km long tributary of the Rhine River (Fig. 1) and represents a typical alpine catchment. The catchment area is about 263 km^2 and the altitude varies from 573 m a.s.l. (outlet station in Chur) to 2867 m a.s.l. The annual mean temperature is 2.1 °C and the average precipitation in this region is 1096 mm yr^{-1}, whereof approximately 30% occurs as snowfall. The months with the most precipitation are June to August, and it is estimated from long-term analysis that approximately 30% of the annual precipitation is lost to evaporation. Consequently, precipitation and snowmelt processes account for the majority of the flooding in this catchment (Sikorska et al., 2015c). With only four point precipitation gauges situated close enough to be used (1.5 stations per 100 km^2), the Plessur catchment has an average station density for Swiss catchments, which is 1.47 stations per 100 km^2 (Viviroli et al., 2011). Out of these gauges, two are situated in valleys and two on slopes.

2.2. Precipitation datasets

To explore the value of precipitation data for the runoff prediction, we generated three different precipitation time series. For the first dataset, SNP, an areal precipitation over the entire catchment was estimated in a classical way, as a weighted sum of the precipitation rates measured at each of the four stations (Hellmann type gauges), selected from the MeteoSwiss network as being located within the catchment precipitation range. Areal daily precipitation rates were estimated using the Thiessen polygon method and related to the mean catchment elevation using a linear interpolation. The second dataset, IGP, was generated using, not just these four point stations localized within the catchment, but the entire network of ground stations in Switzerland (operated by MeteoSwiss), with a total of between 430 and 460 precipitation gauges (mostly Hellmann type gauges). The total daily precipitation sums were then computed for the whole of Switzerland from all station measurements available for a particular day to ensure maximum