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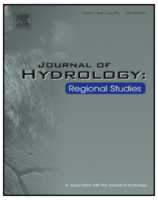

Regional flood frequency analysis and prediction in ungauged basins including estimation of major uncertainties for mid-Norway

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ABSTRACT

Study region: 26 boreal catchments (mid-Norway).
Study focus: We performed regional flood frequency analysis (RFFA) using the *L*-moments method and annual maximum series (AMS) of mean daily streamflow observations for reliable prediction of flood quantiles. We used similarity in at-site and regional parameters of distributions, high flow regime and seasonality, and runoff response from precipitation-runoff models to identify homogeneous catchments, bootstrap resampling for estimation of uncertainty and regression methods for prediction in ungauged basins (PUB).
New hydrological insights for the region: The rigorous similarity criteria are useful for identification of catchments. Similarity in runoff response has the least identification power. For the PUB, a linear regression between index-flood and catchment area ($R^2 = 0.95$) performed superior to a power-law ($R^2 = 0.80$) and a linear regression between at-site quantiles and catchment area (e.g. $R^2 = 0.88$ for a 200 year flood). There is considerable uncertainty in regional growth curves (e.g. −6.7% to −13.5% and +5.7% to +24.7% respectively for 95% lower and upper confidence limits (CL) for 2–1000 years return periods). The peaks of hourly AMS are 2–47% higher than that of the daily series. Quantile estimates from at-site flood frequency analysis (ASFFA) for some catchments are outside the 95% CL. Uncertainty estimation, sampling of flood events from instantaneous or high-resolution observations and comparative evaluation of RFFA with ASFFA are important.

1. Introduction

Flooding is a natural phenomenon. Human encroachments on natural waterways, and impacts of land use and climate change have a potential to modify runoff response of catchments that can trigger occurrences of extreme floods and hence increases vulnerability and risks. Statistical methods for flood frequency analysis by utilizing systematic streamflow observations are usually employed for estimation of flood quantiles corresponding to return periods (T) of interest. Prevalence of severe floods or increasing trends in one or more flood characteristics (e.g. flood frequency, magnitude and timing) in different parts of the world, for instance, in Europe (e.g., Yiou et al., 2006; Knight and Samuels, 2007; Pinskwar et al., 2012; Kundzewicz et al., 2013; Hall et al., 2014; Vormoor et al., 2016), in United States (e.g., Mallakpour and Villarini, 2015; Hirsch

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and Archfield, 2015), in Canada (e.g. Cunderlik and Ouarda, 2009) and in China (e.g. Zhi-Yong et al., 2013) substantiate the need for more reliable prediction of flood quantiles for design and management of water and transportation infrastructure such as spillways, culverts, bridges, sewers, etc. in order to minimize flood risks and hence economic damages. For instance, in Norway, a 200-year flood is used for flood hazard mapping for roads and railroads, and a 500-year, a 1000-year and probable maximum floods are used for dam safety analysis, depending on the safety class of the dam (Wilson et al., 2011). Kochanek et al. (2014) in their study in France noted that hazard mapping typically uses a 100-year return period, while some civil engineering structures (large dams and nuclear power plants) may require 10^3–10^4 target return periods.

At-site flood frequency analysis (ASFFA), which is based on short record length, is widely applied. However, regional flood frequency analysis (RFFA) may provide superior results compared to the ASFFA because extrapolation of the at-site short records for estimation of quantiles for longer return periods may provide unreliable results (see Hosking et al., 1985a; Lettenmaier and Potter, 1985; Lettenmaier et al., 1987). Several studies also illustrated the use of historical flood information to extend short systematic gauged records (e.g. Condie and Lee, 1982; Cohn and Stedinger, 1987; Jin and Stedinger, 1989; Francés et al., 1994; Martins and Stedinger, 2001; O'Connell et al., 2002; Frances, 2004; Ouarda et al., 2004; Reis and Stedinger, 2005; Mei et al., 2015; Engeland, 2015). Mei et al. (2015) on their study on the impacts of historical flood records on extreme flood variations detected that there is a decrease in 100-year flood quantile when introducing historical information into flood frequency analysis for the United States and noted that the magnitudes of 100-year flood events have increased over the last century. Engeland (2015) demonstrated the use of historical floods from the 18th century combined with 19th century systematic observations in western Norway. However, the author noted two challenges of using historical data: transfer of watermarks to streamflow due to changes in the river profile and non-stationarity of the extreme events related to climatic change. Therefore, regional flood frequency analysis (RFFA) could augment limited at-site systematic records by the principle of "trading space for time" for more reliable estimation of higher quantiles and for prediction in ungauged basins. The method is widely employed and involves pooling of flood data from different stations in a hydrologically homogeneous region to obtain regional flood information (e.g. Burn, 1988, 1990a, 1990b; GREHYS, 1996a, 1996b; Hosking and Wallis 1997; Castellarin et al., 2005).

Hosking and Wallis (1993) proposed combined uses of the so-called index flood method (Darlymple, 1960; Stedinger and Lu, 1995; Robson and Reed, 1999) and regional growth curves based on the method of *L*-moments (Hosking, 1990) and the method remains a most widely used procedure for regional flood frequency analysis. The regional growth curves are plots of quantiles representative for all sites of a homogeneous region, where as the at-site flood quantiles vary only in the scale factor known as index flood. The *L*-moments are linear combinations of probability weighted moments or PWMs (Greenwood et al., 1979) and can be directly interpreted as measures of scale and shape of probability distributions. Several studies have been performed on regional flood frequency analysis based on the index flood and *L*-moments methods, to mention a few, Hosking and Wallis (1988), Burn (1988), Stedinger et al. (1993), Hosking and Wallis (1997) and Saf (2009).

However, regional frequency analysis is subject to major uncertainties. Some of previous studies estimated uncertainty in quantile estimates using asymptotic approximations (e.g. Stedinger, 1983; Ashkar and Ouarda, 1998; Cohn et al., 2001), Monte Carlo simulations (e.g. Hosking and Wallis, 1997) and Bayesian approach (e.g. Reis and Stedinger, 2005; Merz and Thieken, 2005; Ouarda and El-Adlouni, 2011). There are also few studies that applied non-parametric approaches that does not involve making a distributional assumption, for instance, bootstrap resampling for regional frequency analysis (e.g. Potter and Lettenmaier, 1990 for flood quantiles; Faulkner and Jones, 1999 for rainfall regional growth curve; Reed et al., 1999 and Burn, 2003 for flood quantiles and Hailegeorgis et al., 2013 for extreme precipitation quantiles) and leave-one-out jack-knife method for flood quantiles (Rutkowska et al., 2016). The major sources of uncertainties in regional flood frequency analysis are pertinent to:

1. Data series from which the extreme events are sampled: non-stationary series or trends, serial and spatial correlations, sampling variability (data length and period, temporal resolution of data, etc.);
2. Heterogeneity of catchments that are included in the regional flood frequency analysis;
3. Selection of frequency distribution; and
4. Parameter estimation

Estimates of flood quantiles using recorded data would be biased if the hydroclimate is non-stationary (Dawdy et al., 2012). Cunderlik and Burn (2003) proposed an approach for non-stationary pooled flood frequency analysis based on a local time-dependent component, which comprise the location and scale parameters of the distribution. The authors noted that ignoring even a weakly significant non-stationarity in the data series may seriously bias the quantile estimation. Trend analysis is useful to detect non-stationarity in flood series but requires records preferably in excess of 50 years (Kundzewicz and Robson, 2000) to distinguish climate change-induced trends from climate variability.

Independence of data series is one of the main assumptions in frequency analysis. Both spatial and serial correlation may exist in data series. The effect of intersite dependence on the regional *L*-moment algorithm is to increase the variability of the regional averages and this increases the variability of estimated growth curve (Hosking and Wallis, 1997). Fill and Stedinger (1998) and Bayazit and Önöz (2004) noted that the intersite correlation has a considerable effect on the variance of regional parameters and flood quantiles and reduces the effective length of records. However, Hosking and Wallis (1997) noted that a small amount of serial dependence in annual data series has little effect on the quality of quantile estimates. In addition,