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Development of a method to identify change in the pattern of extreme streamflow events in future climate: Application on the Bhadra reservoir inflow in India

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ABSTRACT

Study region: Bhadra basin (1968 km^2), located in peninsular India, is considered for demonstration.
Study focus: A general framework to assess the impact of climate change on the pattern of daily extreme streamflow events is proposed. Whereas, the impact is confirmed in the recent literature for most of the hydrologic variables at monthly/seasonal time scale, assessment and quantification at finer time scale, e.g. daily, is challenging. Complexity increases for the derived hydrologic variables, such as soil moisture and streamflow as compared to primary hydrologic variables, such as precipitation. The proposed general framework is demonstrated with the daily inflow to the Bhadra reservoir. Different statistical limits of extremes are defined and change in daily extreme pattern (number and magnitude) in the future (2006–2035) is assessed with respect to the baseline period (1971–2000).
New hydrological insights for the region: Demonstration of the proposed methodology with the inflow to Bhadra reservoir reveals that the daily extreme events are expected to increase in number with the increase in the threshold of the extreme. For a particular threshold, the average magnitude of the extreme events in the future is found to be higher as compared to the baseline period. However, for monthly totals the case is not the same – it remains almost similar. The methodology, being general in nature, can be applied to other locations in order to assess the future change in streamflow and other derived variables.

1. Introduction

Climate change is expected to have a substantial impact on the available water resources almost everywhere across the world. However, its impact may vary spatio-temporally depending on the topographical and climatological features of the basin (Arnell, 1999; Maity and Kashid, 2011; Maity et al., 2013; Pichuka and Maity, 2016; Rashid et al., 2016; Ashofteh et al.,

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2016a). Change in spatio-temporal pattern of primary hydrologic variables, such as rainfall, causes the variation in the other derived hydrologic variables, such as evapotranspiration, streamflow, soil moisture, ground water table etc. (Arnell, 1999; Dore, 2005; Das and Maity, 2015; Haddeland et al., 2014; Mcmichael et al., 2006; Taylor et al., 2013). However, it is difficult to generalize the extent of impact on any hydrologic variable across different locations. The complexity is even more for the derived hydrologic variables than the primary hydrologic variables. It is identified from the studies that the temperature variations are accompanied by changes in precipitation and runoff (Kabiri et al., 2015; Labat et al., 2004; Probst and Tardy, 1989). This phenomenon, after going through complex basin-hydrologic processes, leads to variation in streamflow and ground water recharge. At small temporal scale (e.g. daily), hydrological systems are expected to experience not only the changes in the average availability of water, but also changes in the extreme events (Grillakis et al., 2016; Jiang et al., 2007; Modrick and Georgakakos, 2015; Piras et al., 2016). Hence, a general framework to assess and quantify the change in daily extreme events of secondary hydrologic variables owing to climate change is utmost important, which is the focus of this study.

A plethora of studies have been carried out around the world to assess the impact of climate change on hydrological variables (Burn, 1994; Menzel and Burger, 2002; Zuo and Xu, 2015; Ashofteh et al., 2016b). For instance, Lindström and Bergström (2004) investigated the time series of runoff volumes, annual and seasonal flood peaks in Sweden. Ashofteh et al. (2013a) has investigated and confirmed the climate change impact on monthly inflow volume of the reservoir in an East Azerbaijan river basin. Tofiq and Guven (2014) attempted to predict the peak monthly discharge from statistical downscaling approach. Mishra and Singh (2010) and Mishra et al. (2011) has investigated the changes in extreme precipitation in Texas. Novotny and Stefan (2007) studied about streamflow records in five main river basins in Minnesota, USA. Aich et al. (2014) used Soil and Water Integrated Model (SWIM) to investigate the future streamflow over African river basins due to climate change. Ashofteh et al. (2013b) assessed the monthly streamflow simulations during the 21st century by using the GCM outputs and also examined the streamflow transition probabilities at each month. Liang et al. (2015) quantified the impacts of climate change on streamflow in China's Loess Plateau using a Budyko hydrological model. Jiang et al. (2014) carried out streamflow simulations at monthly and annual scales and found that the relationship between streamflow and precipitation is positive, whereas the same between streamflow and temperature is negative in the Luanhe basin of North China. Devkota and Gyawali (2015) assessed the hydrological regime of the Koshi River in Nepal and concluded that the average water availability is not much affected by the climate change. However, temporal flow variations will increase in the future. Islam et al. (2012) found that the rise of temperature results in the decreasing annual streamflow over the Brahmani river basin in India. Wang et al. (2012) explored the monthly streamflow variations under climate change conditions and concluded that the future monthly streamflow and hydrological extremes are expected to increase in the Shiyang river basin. Vicente-Guillén et al. (2012) developed a model based on the physical characteristics of the basin to predict monthly streamflow in the context of changing climate for the ungauged watersheds in Spain.

Most of the previous studies deal with the assessment of the climate change impact at monthly, seasonal and annual scales (Ashofteh et al., 2013a,b; Bennett et al., 2016; Dehghani et al., 2015; Huang et al., 2014; Jiang et al., 2007; Lindström and Bergström, 2004; Mishra and Singh, 2010; Mishra et al., 2011; Tofiq and Guven, 2014; Wang et al., 2012; Xie et al., 2015; Zamani et al., 2016; Zhang et al., 2015). Analyses at daily scale are few and mostly focus on the modeling of mean values rather than extremes (Bhagwat and Maity, 2014; Elias et al., 2015; Kopytkovskiy et al., 2015; Mantua et al., 2010; Maurer et al., 2010). However, assessment and quantification of climate change impact on the daily extremes might be more useful from management point of view. For instance, daily extreme streamflow may lead to flash floods in a basin and difficult to manage even with the existing reservoirs if such extreme events are not considered in its design. In some cases, extreme events may also cause the failure of capacity of the reservoir and it may lead to failure of the dam. Thus, it becomes vital to assess the changes in such daily extremes.

Keeping this in mind, the objective of this study is to develop a general framework to assess and quantify the change in daily extreme events of secondary hydrologic variables owing to climate change. First, a Rainfall-Runoff (RR) model is calibrated and validated using historical daily observed precipitation and inflow data. Next, the developed RR model is applied during future period using downscaled GCM data as input and to check the performance using the 'kept-aside' observed data from the considered 'future period'. Finally, different statistical thresholds of extremes are defined in order to assess the change in number and magnitude of the daily extreme pattern in future with respect to present.

The Hydrologic Engineering Center-Hydrologic Modelling Software (HEC-HMS) is used as RR model and Statistical Downscaling Model (SDSM) version 5.2 is used as downscaling tool. However, changing HEC-HMS and SDSM to some of its equivalent tools does not alter the overall approach to assess the impact of climate change on extreme events except the individual capability of the used tools. In this paper, HEC-HMS and SDSM are used for demonstration after calibration and validation with reasonable accuracy.

Two issues are important to mention here. Since the day-to-day variation in streamflow may not be much meaningful in far future (say after 30 years), the general framework is necessary to assess and quantify the change in the pattern of daily extreme (number and magnitude). Secondly, the far future is good for water management but quality of GCM simulation and reliability of emission scenarios in far future is uncertain. Assessment on daily streamflow variation next 20 years can be useful in many applications, such as flood management and watershed management in near future. However, developed approach should be general enough to be applicable for far future as well.