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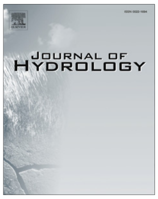

An inverse approach to perturb historical rainfall data for scenario-neutral climate impact studies

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SUMMARY

Scenario-neutral approaches are being used increasingly for climate impact assessments, as they allow water resource system performance to be evaluated independently of climate change projections. An important element of these approaches is the generation of perturbed series of hydrometeorological variables that form the inputs to hydrologic and water resource assessment models, with most scenario-neutral studies to-date considering only shifts in the average and a limited number of other statistics of each climate variable. In this study, a stochastic generation approach is used to perturb not only the average of the relevant hydrometeorological variables, but also attributes such as the intermittency and extremes. An optimization-based inverse approach is developed to obtain hydrometeorological time series with uniform coverage across the possible ranges of rainfall attributes (referred to as the 'exposure space'). The approach is demonstrated on a widely used rainfall generator, WGEN, for a case study at Adelaide, Australia, and is shown to be capable of producing evenly-distributed samples over the exposure space. The inverse approach expands the applicability of the scenario-neutral approach in evaluating a water resource system's sensitivity to a wider range of plausible climate change scenarios.

1. Introduction

Scenario-neutral approaches are being used increasingly to assess the possible impact of climate change on the performance of water resources systems (Brown et al., 2012; Brown and Wilby, 2012; Dessai and Hulme, 2004; Nazemi and Wheater, 2014), as well as social and ecological systems (Gao et al., 2016; Poff et al., 2015). The information generated from these approaches can be used to assess system vulnerability under alternative climate change scenarios, and to calculate climatic thresholds at which system performance begins to change abruptly (Brown et al., 2011; Poff et al., 2015). Scenario-neutral approaches can also accommodate changes in climate projections without the need for additional analysis (Prudhomme et al., 2010), and can help to identify the important hydrometeorological variables, or particularly critical states of these variables that affect the system under consideration. The latter feature is particularly useful for selecting: (1) climate models; (2) strategies to generate future rainfall conditions from GCM-based projections (known as statistical downscaling); and (3) alternative 'lines of evidence' (e.g. expert opinion and data from the paleo-climatic record) that can provide useful information about these variables. Ultimately, this allows for the development of a more complete set of projections that describe how these variables might change in a greenhouse gas-enhanced climate (Nazemi et al., 2013; Singh et al., 2014; Steinschneider and Brown, 2013; Vano et al., 2015).

Central to the scenario-neutral approach is the analysis of system sensitivity to a range of hydrometeorological conditions. Such analyses involve exposing the system to perturbed hydrometeorological forcing data that reflect various hydrometeorological conditions that the system may confront in the future (referred to as the 'exposure space'). To this end, it is important to consider the possible variations not only in the average states of the relevant hydrometeorological variables, such as annual average rainfall and potential evapotranspiration (see Kay et al., 2014; Prudhomme et al., 2013), but also their other attributes, including extremes, seasonality and interannual variability (Meselhe et al., 2009; Moody and Brown, 2013; Prudhomme et al., 2010; Steinschneider and Brown, 2013). Indeed, assessments of historical and/or future changes to rainfall as a result of climate change have already indicated different changes to the averages (Collins et al., 2013), extremes (Ajami et al., 2007; Alexander et al., 2006; Westra et al., 2013, 2014), temporal distribution (Rajah et al., 2014) and low-frequency variability (e.g. Johnson et al., 2011) of rainfall throughout the world. Similarly complex changes to other relevant hydrometeorological variables might also be expected, including potential evapotranspiration, and snowfall and melt.

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One approach to generating perturbed hydrometeorological forcing data is by applying scaling factors to historical records of each of the relevant hydrometeorological variables. These factors can be applied at annual or monthly scales (Kay et al., 2014; Paton et al., 2013; Prudhomme et al., 2013, 2010; Singh et al., 2014), or different factors that can be applied across different quantiles in the entire distribution (Nazemi et al., 2013). Although such approaches might be viable for perturbing a small number of hydrometeorological variables and their attributes (i.e. low-dimensional exposure spaces), the capacity of these to represent the potentially complex variations in a wider range of variables and attributes (i.e. high-dimensional exposure spaces) is likely to be limited. Consequently, when using scaling factors to perturb historical data for climate impact assessments, the resultant projections may not show the full range of variability that can be expected in a greenhouse gas-enhanced climate (Prudhomme et al., 2013, 2010; Steinschneider and Brown, 2013).

The use of stochastic generators has been proposed as an alternative to scaling factors to generate hydrometeorological data in a way that can account for a wider range of possible changes (Whateley et al., 2014). Some recent advances include the use of a multi-site weather generator that is capable of producing realistic time series of meteorological variables with shifts to the mean, standard deviation, extremes, daily-scale Markov transition probabilities and low-frequency (interannual) variability (for examples see Steinschneider and Brown, 2013; Wilby et al., 2014; Yates et al., 2015). This is achieved through the perturbation of stochastic model parameters (including the transition probabilities and the autocorrelation coefficient) and the subsequent application of quantile correction, which, in combination, can be used to generate the high-dimensional exposure space. A challenge with this approach, however, is that it is difficult to assess *a priori* which parameters of the stochastic generator should be modified to produce time series at pre-specified points in the exposure space, potentially leading to insufficient exploration of the exposure space. This challenge arises both as a result of the non-linear mapping between the parameters of a stochastic generator and the statistics of the hydrometeorological variables, as well as due to the stochastic nature of the model, which means that a single parameter set will produce hydrometeorological data that span multiple points on the exposure space (Steinschneider and Brown, 2013).

In order to address the shortcomings of existing approaches in generating hydrometeorological data to form the exposure space, we introduce the concept and framework for an inverse approach with demonstration on a case study. The proposed inverse approach enables stochastic generators to be used to generate time series that uniformly span the desired range of the hydrometeorological variables and attributes of interest, and thus provides uniform coverage of the exposure space to serve the needs of scenario-neutral climate impact assessments. Although generally applicable to any parametric weather generator, this paper focuses on applying the method to rainfall time series for the following reasons:

1. Although stochastic generators have been used to generate a range of weather variables, including temperature, humidity, and wind (e.g. Racsko et al., 1991; Semenov and Brooks, 1999), the majority of applications have focused on the generation of rainfall data, due to their importance as an input to many water resource assessments (e.g. Chiew and McMahon, 2002b; Jones and Thornton, 1993).
2. At daily or shorter timescales, rainfall is intermittent, highly skewed (with rainfall series typically exhibiting a large number of moderate rainfall days and a small number of very heavy rainfall days), and exhibits variability at seasonal, interannual and longer time scales (Bastola et al., 2011; Dubrovský et al., 2000). As a result, rainfall is often regarded as a particularly challenging variable to simulate stochastically.
3. There has been a substantial amount of work on developing stochastic generation models to both generate replicates of historical rainfall data (Beven, 1987; Boughton and Droop, 2003; Chen and Brissette, 2014; Clark and Slater, 2006; Frost, 2004; Furrer and Katz, 2008; Langousis and Kaleris, 2014; Langousis et al., 2015), as well as downscaling GCM-based climate projections (Allen and Pruitt, 1986; Bastola et al., 2011; Fowler et al., 2007; Jones et al., 2011; Kay and Jones, 2012; Wilby et al., 2014; Yates et al., 2015).

The remainder of this paper is structured as follows. In Section 2, we illustrate the alternative approaches that are currently available for generating an exposure space, including the historical scaling, forward and inverse approaches. This section also provides details of the proposed inverse approach. Section 3 introduces a case study and two stochastic generators that are used to illustrate both the proposed approach, as well as a simple forward approach that is used as a basis of comparison. The results are given in Section 4, followed by conclusions in Section 5.

2. Proposed inverse approach to exposure space generation

2.1. Rationale for an inverse approach to perturbing stochastic model parameters

As described in the introduction, a central feature of scenario-neutral approaches is the exploration of a water resource system's response to a range of different hydrometeorological conditions. This range of hydrological variables (e.g. rainfall, temperature, evapotranspiration) and the set of attributes of these variables (e.g. annual average, variance, seasonal differences, extremes) are collectively referred to as an 'exposure space', and represent the range of conditions of interest that a system may be exposed to under a future climate. For example, if a scenario-neutral approach was to be used to evaluate system sensitivity to changes in the average, variability and extremes of rainfall, then this would require generating a three-dimensional exposure space with each dimension representing one of the rainfall attributes.

Fig. 1 illustrates the conceptual approaches that could be used to generate an exposure space **E**, which consists of the plausible future changes (represented as the gray shaded region, with the origin corresponding to no change) in various rainfall attributes of interest (represented by two axes A_1 and A_2, which refer to two generic rainfall attributes or groups of attributes). Two techniques are involved in the perturbation approaches – namely scaling of rainfall time series and stochastic rainfall generation (as shown in the two green squares). We use the term 'scaling' in the figure to collectively refer to perturbations that are directly applied to rainfall time series, through the use of change factors at annual, monthly or other time scales (Kay et al., 2014; Prudhomme et al., 2010; Prudhomme and Williamson, 2013), or more complex methods, such as quantile mapping (as used in Steinschneider and Brown, 2013). Consequently, the scaling technique can only modify rainfall intensity on wet days. The term 'stochastic generation' in the figure refers to indirect modification of the rainfall time series through changing the parameters of stochastic generators (as used in Dubrovský et al., 2000; Jones and Page, 2001; Steinschneider and Brown, 2013). The parameter space Θ consists of two axes of θ_1 and θ_2, which refer to two generic parameters or groups of parameters. The plausible ranges for all parameters are represented by the gray shaded region, while the

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