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Evaluating four downscaling methods for assessment of climate change impact on ecological indicators

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ABSTRACT

Assessments of climate change impacts on freshwater ecosystems are generally based on global climate models (GCMs) and ecologically relevant “time-averaged” hydrological indicators derived from long-term records. Although uncertainties from GCMs have been recognized, the influence of downscaling methods remains unclear. This paper evaluates the influence of applying different downscaling methods of increasing complexity (annual scaling, monthly scaling, quantile scaling, and weather generator method) on the assessment of ecological outcomes. In addition to time-averaged indicators, “sequence-dependent” metrics which involve ecological dynamics by considering the impacts of flow sequencing are also adopted. In a case study in Australia, the condition of river red gum forest was assessed. Results show that the choice of downscaling methods can be of similar importance as that of GCMs in ecological impact studies. Where sequence-dependent metrics are adopted, more sophisticated downscaling techniques should be used to better represent changes in the frequency and sequence of flow events.

1. Introduction

Water resources around the globe are becoming increasingly stressed as human demand for water increases (Vörösmarty et al., 2010). There is now significant evidence that climate change, exhibited through altered precipitation patterns and temperature, will alter the global hydrological cycle and local catchment hydrology to exacerbate these stresses (Arthington et al., 2006; Poff and Zimmerman, 2010; Poff et al., 2015). At the same time, there is growing awareness and understanding of the implications of hydrological alterations for freshwater ecosystem health (Dudgeon et al., 2006; Poff et al., 2010, 1997). It is important therefore to understand the implications of a changing climate for not only human water uses, but also for the instream environment those uses depend on (Döll and Zhang, 2010; Poff et al., 2015). However, when assessing the impact of climate change, it is important to consider the method used to represent those changes in the context of the objectives of most interest.

There is an extensive literature examining the impacts of climate change on water resources, however few focused specifically on ecological outcomes. A large number of these studies have focused purely on instream hydrology and long term average flow conditions (e.g. Beyene et al., 2010; Chiew et al., 2009; Lauri et al., 2012). Studies focused primarily on water availability have tended to adopt simple ecologically relevant hydrological indicators to infer ecological outcomes (e.g. CSIRO, 2008). Where studies have included environmental outcomes, the most common approach has been to assess the ecologically relevant hydrological indicators at the seasonal and annual scale (Döll and Zhang, 2010; Laizé et al., 2014; Piniewski et al., 2014). Only a handful of studies have adopted more complex approaches. For example, in addition to hydraulic indicators of direct relevance to habitat (e.g. water depth), Htun et al. (2016) and Walsh and Kilsby (2007) used a habitat-suitability based approach, and Battin et al. (2007) used a population model, where responses of fish or waterbirds were investigated. As our understanding of environmental flow requirements improves, it has been gradually acknowledged that it is difficult to characterize the dynamics of ecological response using simple hydrological flow indicators as they do not capture the complexity of the interactions involved. It thus may be necessary to adopt assessment methods based on process-oriented descriptions of

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ecological dynamics particularly at inter-annual scale, for example, the state and transition succession theory (Zweig and Kitchens, 2009), for long-lived species (Anderson et al., 2006; Hickey et al., 2015).

There has been significant scientific research aimed at representing climate change derived at the global or regional scale in a way that is relevant to the assessment of water resources at the local scale. Global climate models (GCMs) are the primary tool for understanding and projecting changes in the global climate and their outputs have been widely used in impact studies (Maraun et al., 2010). Despite their physical basis and the ability to represent historical climate, GCMs have two key limitations. Firstly, there are substantial uncertainties between GCMs and within a GCM (Peel et al., 2015); the former largely reflects the epistemic uncertainties related to model structure and parameterization, and the latter to aleatory uncertainties associated with the random nature of natural processes and the initial state and forcing variables (Beven, 2015; Ekström et al., 2015). These uncertainties can result in large differences between simulations, and are usually addressed by analyzing simulations from multiple GCMs or different ensemble members (e.g. Chiew et al., 2009; Lauri et al., 2012; Thompson et al., 2014). Secondly, GCM outputs are of too coarse a scale to be directly used in catchment-scale impact studies (e.g. see Fowler et al., 2007). Numerous downscaling techniques have been developed to derive local climate change information from large scale GCMs outputs (Maraun et al., 2010). The two primary categories of downscaling techniques are (1) dynamic downscaling, which obtains regional information by nesting a high-resolution regional climate model within a GCM, and (2) statistical downscaling, which relates large scale climate variables to local scale climate variables (Trzaska and Schnarr, 2014). Although dynamic downscaling is more conceptually appealing, it has not been popular in impact studies due to the computational cost and limitations of regional climate models (Fowler et al., 2007). In contrast, statistical downscaling has been more widely applied (Trzaska and Schnarr, 2014). Under the broad category of statistical downscaling, there are a number of methods from the simplest constant scaling method to more sophisticated regression models and weather generator methods.

Different downscaling techniques yield differences in local climate change characterizations, and these differences affect the evaluation of changes to the hydrological regime (Chen et al., 2011a; Hay et al., 2000; Mpelasoka and Chiew, 2009). Even though GCMs generally represent the largest source of uncertainty in climate change impact assessments (Kay et al., 2009; Minville et al., 2008), the influence of downscaling methods, depending on the hydrological indicators assessed, could be of a similar magnitude to that of GCMs (Chen et al., 2013, 2011b; Prudhomme and Davies, 2009; Teutschbein et al., 2011). The need to consider both GCMs and downscaling techniques on issues related to catchment hydrology has been well recognized. However, in ecological impact studies, although the uncertainty from GCMs has been considered, the influence of downscaling methods has not previously been assessed. Existing literature has tended to adopt multiple GCMs to assess the impact on instream environment derived from hydrological alterations whilst adopting only a single downscaling method (Battin et al., 2007; Döll and Zhang, 2010; Piniewski et al., 2014; Thompson et al., 2014). The majority of these studies have adopted simple statistical downscaling approaches, such as the monthly-scale constant scaling method (Döll and Zhang, 2010; Htun et al., 2016; Piniewski et al., 2014; Walsh and Kilsby, 2007).

This paper examines the implication of using different downscaling methods for the assessment of freshwater ecosystem conditions. The choice of a downscaling method – as with the choice of a GCM – introduces uncertainty into the assessment of climate change impacts. This uncertainty reflects both the differences in the ability of each method/model to adequately represent climate change (i.e. epistemic uncertainty) and the *natural variability* (i.e. aleatory uncertainty) of the system being analyzed (Beven, 2015). The latter is of particular importance to the assessment of ecological impacts as different environments or river typologies have evolved to cope with different levels of natural variability, known as the ecosystem resilience (Poff and Matthews, 2013). Climate change impacts both the frequency and variability of flow conditions, and thus methods which consider this explicitly may be expected to provide a more realistic assessment of the impacts. This paper considers three deterministic downscaling methods (constant scaling applied on the annual scale and the monthly scale, and the quantile scaling method) and a stochastic downscaling method (based on the use of a weather generator), the latter of which is able to consider the natural variability in climate sequences. We consider the type of hydrological indicators that are typically used to assess ecological impacts, and include more sophisticated metrics that consider ecological dynamics, which is important when considering the influence of natural variability (Section 2). A brief introduction to the four downscaling methods are provided in Section 3. The Ovens River, Australia, is used as a case study to explore the influence of applying different downscaling methods on ecological outcomes (Section 4). Results are presented in Section 5, and the importance of the selection of a downscaling method on the assessment of ecological impacts is discussed in Section 6.

2. Assessment of hydrological alterations affecting ecological outcomes

The natural flow paradigm is a central element of many environmental flow assessment methodologies (Acreman et al., 2014). The natural flow paradigm suggests that the entire flow regime is critical to the integrity of river ecosystems, and this can be represented through key flow components described by their magnitude, frequency, duration, timing and rate of change (Poff et al., 1997). Modifications of the components will have cascading effects on an ecosystem's ecological integrity. Although it is still unclear how the modifications transfer quantitatively to ecological responses, it has been demonstrated that the risks to ecosystem health increase with the degree of hydrological alterations (Döll and Zhang, 2010; Poff and Zimmerman, 2010). The natural flow regime thus provides the baseline for quantifying flow alterations to assess the impact of human activities and climate change on instream environment (Poff et al., 1997; Poff and Zimmerman, 2010).

There are a large variety of hydrological indicators that have been developed to characterize flow regimes and to quantify hydrological alterations (Olden and Poff, 2003). Broadly, studies have attempted to select a range of hydrological indicators that are representative of the ecologically relevant flow regime (e.g. the Indicators of Hydrological Alteration; Richter et al., 1996). Flow alterations are calculated by comparing the hydrological indicators of changed flow series to a reference flow series, which is usually representative of "undisturbed" conditions. Hydrological indicators remain the most commonly used metrics for assessing the ecological impacts at a catchment scale. In this paper, they are referred to as "time-averaged" metrics, as they are based on statistical analysis of long-term records and do not explicitly consider the sequencing of flow conditions.

River ecosystems are shaped by a combination of the flow regime and internal feedbacks that are heavily dependent on the sequencing of particular flow events (Anderson et al., 2006). This has recently led to a series of more complicated indices, which