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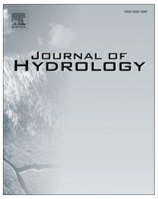

Research papers

Influence of three common calibration metrics on the diagnosis of climate change impacts on water resources

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ABSTRACT

Uncertainties associated to the evaluation of the impacts of climate change on water resources are broad, from multiple sources, and lead to diagnoses sometimes difficult to interpret. Quantification of these uncertainties is a key element to yield confidence in the analyses and to provide water managers with valuable information. This work specifically evaluates the influence of hydrological modeling calibration metrics on future water resources projections, on thirty-seven watersheds in the Province of Québec, Canada. Twelve lumped hydrologic models, representing a wide range of operational options, are calibrated with three common objective functions derived from the Nash-Sutcliffe efficiency. The hydrologic models are forced with climate simulations corresponding to two RCP, twenty-nine GCM from CMIP5 (Coupled Model Intercomparison Project phase 5) and two post-treatment techniques, leading to future projections in the 2041–2070 period. Results show that the diagnosis of the impacts of climate change on water resources are quite affected by the hydrologic models selection and calibration metrics. Indeed, for the four selected hydrological indicators, dedicated to water management, parameters from the three objective functions can provide different interpretations in terms of absolute and relative changes, as well as projected changes direction and climatic ensemble consensus. The GR4J model and a multimodel approach offer the best modeling options, based on calibration performance and robustness. Overall, these results illustrate the need to provide water managers with detailed information on relative changes analysis, but also absolute change values, especially for hydrological indicators acting as security policy thresholds.

1. Introduction

Climate change already has several noticeable impacts on many components of the continental water cycle, especially on precipitation, snow cover, soil moisture, surface runoff, atmospheric water pressure, and evapotranspiration (Bates et al., 2008). Despite expected progress in terms of reduction of the emission of greenhouse gases, the scientific community broadly agrees that adaptation measures must be urgently evaluated and considered (Refsgaard et al., 2013). Moreover, a clear consensus appears that adaptation strategies to climate change should be largely oriented towards water resources concerns (Ludwig et al., 2009; Huntjens et al., 2012), since it impacts environmental, security, industrial, and economic issues related thereto, requiring water stakeholders to redefine their management tools and to identify adaptation strategies (Minville et al., 2009).

Evaluating the impacts of climate change on water resources is typically centred around Global Climate Models (GCM) driven by consensual greenhouse gases concentration scenarios (Representative Concentration Pathways, RCP) locally post-treated with bias correction and/or downscaling methods. These scenarios are then used as inputs to impact models, namely hydrologic models in this specific context (Kay et al., 2006; Boé et al., 2009; Teng et al., 2012).

Uncertainties associated to this process are substantial, from multiple sources, which make diagnoses sometimes difficult to interpret. The quantification of these uncertainties is therefore a key element to yield confidence in the analyses and to provide water managers with valuable information (Wilby, 2005).

Most of previous studies illustrated that the major sources of uncertainties are located in the first steps of the modeling process (e.g. Kay et al., 2009; Chen et al., 2011) and mentioned that uncertainties associated to hydrological modeling are also of concern

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(e.g. Ludwig et al., 2009; Bae et al., 2011; Seiller and Anctil, 2014) because they generate "grey areas in the interpretation of future hydroclimatological projections" (Oyebode et al., 2014). As a consequence, hydrologic model uncertainties must consistently be evaluated, and robust methodologies should be implemented for this purpose. They are mostly due to errors in input and calibration data, choice of model structure (conceptualization, complexity), parameters identification, and transposability in time. Errors in input and calibration data have been widely studied, like for example the impact of precipitation (Andréassian et al., 2001; Oudin et al., 2006b), evapotranspiration (Andréassian et al., 2004; Oudin et al., 2006b), or streamflow (Perrin et al., 2007) errors. However, in a climate change context, less attention has been given to model structure and parameter identification, until recent years.

Hydrologic models are imperfect and simplified mathematical representations of the complex, dynamic, and non-linear processes of the rainfall-runoff transformation, and are essential tools to assess runoff changes. They range from conceptual to physically-based and from lumped to distributed, representing several levels of complexity. For climate change impact assessment, no clear consensus exists on the suitable level of complexity or type of hydrologic model, but conceptual ones have been the preferred tools in many studies when discharge must be computed at a gauged outlet, mainly because of their low computational cost and easy operation. Such models are known to capture the dominant hydrological processes, at the expense of a needed estimation of their empirical parameters, which cannot be directly inferred from field measurements (Merz et al., 2011).

Calibration is a crucial step in lumped modeling processes. It generally consists in estimating model parameters by comparing observed and simulated discharges, resulting most of the time in an optimization challenge towards greater predictive abilities and reduction of simulation uncertainty. Of course, due to their conceptualization level, it is difficult to consider the best parameter set as the true descriptive one, possibly leading to the right answers for the wrong reasons, in opposition to Kirchner's "right answers for the right reasons" (Kirchner, 2006). Moreover, the definition of an accurate representation of the catchment outlet discharges can vary widely based on the project goals and modeling objectives (Refsgaard, 1997).

The choice of calibration strategies, together with the hydrologic model selection and management plans, is often considered as the only part of the hydroclimate chain potentially operated by water managers, since climate data as well as post-treatments are typically performed by national agencies. This emphasis the importance of selecting the best calibration strategies, which is not as trivial as one may consider. For a small number of free-parameters, manual calibration may be an option, but for a large number of parameters or simulations (many catchments and/or hydrologic models) automatic search algorithms are generally preferred (Gupta et al., 1999). They rely on calibration metrics (hereinafter also referred to as objective functions) expressing the goodness-of-fit of the model to be maximized or minimized.

Consequently, the parameter identification step, which requires subjective and objective estimations, is challenging mainly because there exists no consensus on a universal measure of performance. The selection of an appropriate objective function, based on the modeling goal and required predictive qualities, remains quite subjective while it may potentially influence future streamflow projections and climate change diagnosis on water resources.

Few researches illustrate the importance of the calibration process on climate change impacts. However, they all highlight the need to evaluate this procedure within an uncertainty framework. For example, Najafi et al. (2011) demonstrated that both structural and calibration uncertainties may influence climate change diagnoses, especially for low flows, after evaluating three lumped and one semi-distributed models on a US catchment. Vansteenkiste et al. (2014) shared the same conclusion, especially for low flows, when evaluating five hydrologic models of different complexity and submitting one of them to nine calibration approaches, on a Belgian catchment. Mendoza et al. (2016) also confirmed that parameter estimation and model structure conjointly influence the direction and magnitude of projected changes, from four hydrologic models and three US catchments.

The wide number of available calibration metrics (e.g. Nash-Sutcliffe efficiency, Root Mean Squared Error, Kling-Gupta efficiency) leaves hydrological modellers with the challenge of identifying the best option for their particular application and of providing a meaningful and appropriate indicator of the strengths and limitations of their model(s) (Jakeman et al., 2006). Modeller's decisions must be well-reasoned and clearly acknowledged. Multiobjective approaches (Efstratiadis and Koutsoyiannis, 2010) are a possible way to tackle this question, but open up to an even larger number of possible candidate combinations. Consequently, single objective approaches are still largely preferred in practical applications, and often result in the calculation of a unique metric (value) for an entire time series (Muleta, 2012). Many authors also illustrated that streamflow transformation, before optimization, is a simple way to dedicate a model to a practical application such as flood control, ecological management, or water demand, and may help to identify parameters that target specific hydrograph sections (high flows, low flows). As an example, Pushpalatha et al. (2012) strongly recommend the Nash-Sutcliffe efficiency with an inverse discharge transformation for low flow applications. These results, obtained on a set of 940 French catchments, revealed that this function mainly focuses on the 20% lowest flows and has a low sensitivity to high-flow events. Oudin et al. (2006a), when comparing four objective functions with two lumped conceptual models on 308 catchments located in Australia, the United States of America, and France, showed that the root-squared transformation used in conjunction with the Nash-Sutcliffe efficiency led the most balanced simulations, making this objective function suitable for multi-purpose applications. By design, calibration metrics based on the mean squared error (e.g. Nash-Sutcliffe efficiency), without data transformation, put more emphasis on higher streamflows, largely neglecting lower values, making these metrics good candidates for high-flow applications such as flood warning (Muleta, 2012).

According to the cited studies, objective functions are a potential source of uncertainty when projecting the future of a hydrologic regime. Although this uncertainty, in the cascade of the hydroclimatic modeling chain, is presumably lower than the climate modeling steps, it shall not for that reason alone be considered insignificant. As a comparison and to comment previous results from a wider perspective, we propose to test this hypothesis with a large number of lumped conceptual hydrological modeling options. This will allow structural uncertainty evaluation, as part of the total uncertainty, multiple interpretations as well as ensemble deterministic simulations. Indeed, several studies revealed that even for hydrologic models with the same level of conceptualization, large differences can be found in future projected streamflows, even when similar behaviors are observed on the historical period (Jiang et al., 2007; Seiller and Anctil, 2014). The multimodel (ensemble) approach also demonstrated continuous improvement in terms of efficiency and uncertainty description, based on the concept that individual model contains (inevitable) errors that can be somehow compensated by other model structures (Shamseldin et al., 1997; Ajami et al., 2006; Seiller et al., 2015).

This work aims to evaluate the responsiveness of future water resources projections. It is based on twelve lumped conceptual models, three common objective functions, and thirty-seven