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Impact of parameter set dimensionality and calibration procedures on streamflow prediction at ungauged catchments

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ABSTRACT

Spatial proximity, physical similarity and multiple linear regression are implemented on 266 snowmelt dominated catchments located in Québec, Canada. This paper evaluates: (1) the impact of the parameter set dimensionality by comparing 6, 9 and 15 free parameters structures of the GR4J hydrological model coupled to the CemaNeige snow model and; (2) the impact of the parameter set calibration method by comparing SCE-UA, CMAES and a uniform random sampling procedure. Results show that physical similarity performs better than spatial proximity and that both methods outperform multiple linear regression. Among 12 catchment descriptors, the percentage of water and geographical coordinates are the most relevant for this region. Results show that 9 free parameters are globally sufficient to regionalize the snow covered catchments but that 15 free parameters are necessary for lower quality time-series or catchments dominated by arctic or subarctic climates, high water storage capacity or low annual precipitation. Compared to complex models, parsimonious models are more robust in regionalization but their lower performance in model calibration results in lower performance in regionalization. Results show a relationship between the robustness of the parameter sets generated by the calibration procedures and their dispersion within the parameter space. Uniform random sampling is the most robust calibration method but shows an overall performance that is similar to both optimization algorithms because of its weaker performance in model calibration.

1. Introduction

It is expected that climate change will increase exposition and vulnerability of human societies and ecosystems to hydrological risks (IPCC, 2014). In such a context, modelling tools become a necessity. However, they are facing a worldwide decline in hydrological data collection networks (Sivapalan et al., 2003). The usual practice that consists in optimizing the hydrological model with hydrological data becomes impossible for ungauged catchments (He et al., 2011). The ungauged catchment is defined as a catchment with an inexistent or inadequate, in terms of quality or temporal scale, record of its streamflow (Sivapalan et al., 2003). The definition extends to catchments undergoing climatic or human-induced changes that will modify their hydrological response with the consequence that existing streamflow records become non-representative of their response (He et al., 2011). Streamflow prediction at ungauged catchments addresses these issues and proposes two main model-dependent approaches to regionalize hydrological model parameters. The distance based approach involves the transfer of optimized parameter sets from gauged and similar catchments to an ungauged, and similar, catchment. The regression approach uses a regional regression model to predict the hydrological model parameters at the ungauged catchment. These model-dependent approaches suffer from limitations due to model

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structural error and equifinality of parameter sets. Model-independent approaches have been developed to overcome these limitations. An extensive review of these approaches can be found in Razavi and Coulibaly (2013) but they will not be discussed further here as this paper will focuss in assesing the impact of the model-dependent approaches' limitations.

1.1. Regionalization methods and main hypothesis

Among regionalization methods, regression methods are the most popular. They appear in about two-thirds of the studies inventoried by Razavi and Coulibaly (2013) despite that the underlying hypotheses of these methods are strongly criticized. One of these approaches is multiple linear regression in which a regional linear model is computed from the catchment descriptors and the optimized parameters at gauged catchments. The regional linear model is then used to predict the parameter at the ungauged catchment. The method's first hypothesis states that there is a well behaved relationship between the catchment descriptors and the hydrological model optimized parameter set, which contravenes the equifinality principle (Oudin et al., 2008; Beven, 1999; Bárdossy, 2007). The second hypothesis assumes that the catchment descriptors selected to compute the regional linear model are representative of the catchment main hydrological processes but their representativeness is difficult to verify (Oudin et al., 2010; Oudin et al., 2008; Peel and Bloschl, 2011). Despite the fact that some hydrological model parameters can be strongly correlated to the catchment descriptors, correlation is usually absent for most of the hydrological model parameters (Yadav et al., 2007; Lee et al., 2006; McIntyre et al., 2005). The third hypothesis is the assumption of a linear relation between catchment descriptors and the optimized parameters which is a useful simplification (Parajka et al., 2007) but unlikely to describe a natural system (Samuel et al., 2011).

A second popular method is spatial proximity in which the hydrological models' optimized parameters are transferred from gauged catchments according to their geographic proximity to the ungauged catchment. The hypothesis underlying this method is that neighbouring catchments belong to the same homogenous and geographical region which confers them similar hydrological behaviour (Samuel et al., 2011). To this hypothesis, He et al. (2011) and Ouarda et al. (2008) argue that proximity between catchments doesn't necessarily involve they share the same hydrological processes. Oudin et al. (2008) point out that the performance of this method is related to the density of the gauged catchments network.

The third popular method is physical similarity, in which the hydrological models' optimized parameters are transferred from gauged catchments according to their proximity, in terms of similarity of catchment descriptors, to the ungauged catchment. Similarly to the multiple linear regression method, representativeness of the catchment descriptors, selected to compute the similarity between catchments, is difficult to observe. The fact that catchments belong to the same homogenous region, based upon climatic and physical catchment descriptors doesn't assure them to share hydrological behavior (Oudin et al., 2010).

The performance of the distance based approaches, spatial proximity and physical similarity, increases when parameters, individually or as sets, are transferred from multiple donor catchments using multi-donor averaging schemes, rather than only from the closest donor catchment (Arsenault and Brissette, 2014; Oudin et al., 2008; Zhang and Chiew, 2009).

1.2. Equifinality and singularity of parameter sets as limitations to regionalization

Two limitations challenge the concept of parameter regionalization. The first limitation is equifinality (Beven, 2006) that states the non-uniqueness of an optimized parameter set. The consequence of such equifinality is that similarly performing optimized parameter sets in calibration may not all be equivalent in terms of transferability and sensitivity (Gibbs et al., 2012; Oudin et al., 2008; Bárdossy, 2007 B & rdossy, 2007). Equifinality also affects the repartition of parameters into an identifiable regional pattern, meaning that two similar and adjacent catchments may have different optimized parameter sets (Arsenault and Brissette, 2014; Peel and Bloschl, 2011). Equifinality finally involves the existence of interactions between optimized parameters that should be taken into account by transferring the entire parameter set instead of individual parameters (B & rdossy, 2007; Parajka et al., 2005; Oudin et al., 2008; Perrin et al., 2001).

The second limitation is the singularity of a parameter set. Singularity is here defined as the information contained in the optimized parameter set that is specific to the modelled catchment and, a priori, not interesting in terms of transfer to other catchments. Singularity has three causes. The first cause is the data error compensation that occurs when the hydrological model is optimized against streamflow observations (Oudin et al., 2006a; Andréassian et al., 2004; Lee et al., 2006; McIntyre et al., 2005; Beven, 2006). The second cause is the bias induced to the model by the optimization period and its specific climatic conditions (Merz and Blöschl, 2004; Brigode et al., 2013; Beven, 2006; Yapo et al., 1996). The third cause is the conceptual error linked to lumped hydrological models that results in a regional variation of its optimized parameters since the model adapts its components distinctly according to the catchment's main hydrological processes (Beven, 1999; Lee et al., 2006; Duan et al., 2006).

1.3. Equifinality and parameter sets dimensionality

In the context of equifinality, the hydrological model complexity should be sufficient to efficiently describe the catchment's main hydrological processes (Beven, 2006). Over-parameterized hydrological models show increased interaction between their parameters while parsimonious models might lack in ability to adapt to different catchments (Perrin et al., 2003). Parsimonious models are usually expected to be the most robust (Perrin et al., 2003) and are preferred for regionalization purposes (Razavi and Coulibaly, 2013). Current studies compare different hydrological models with distinct complexity to investigate the issue of model parsimony (Arsenault and Brissette, 2015; Perrin et al., 2001; Oudin et al., 2008; Zhang and Chiew, 2009). The main limitation of those studies is