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Comparing spatial and temporal transferability of hydrological model parameters

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SUMMARY

Operational use of hydrological models requires the transfer of calibrated parameters either in time (for streamflow forecasting) or space (for prediction at ungauged catchments) or both. Although the effects of spatial and temporal parameter transfer on catchment streamflow predictions have been well studied individually, a direct comparison of these approaches is much less documented. Here, we compare three different schemes of parameter transfer, viz., temporal, spatial, and spatiotemporal, using a spatially lumped hydrological model called EXP-HYDRO at 294 catchments across the continental United States. Results show that the temporal parameter transfer scheme performs best, with lowest decline in prediction performance (median decline of 4.2%) as measured using the Kling–Gupta efficiency metric. More interestingly, negligible difference in prediction performance is observed between the spatial and spatiotemporal parameter transfer schemes (median decline of 12.4% and 13.9% respectively). We further demonstrate that the superiority of temporal parameter transfer scheme is preserved even when: (1) spatial distance between donor and receiver catchments is reduced, or (2) temporal lag between calibration and validation periods is increased. Nonetheless, increase in the temporal lag between calibration and validation periods reduces the overall performance gap between the three parameter transfer schemes. Results suggest that spatiotemporal transfer of hydrological model parameters has the potential to be a viable option for climate change related hydrological studies, as envisioned in the "trading space for time" framework. However, further research is still needed to explore the relationship between spatial and temporal aspects of catchment hydrological variability.

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1. Introduction

All hydrological models contain parameters whose values must be calibrated by comparing the observed and simulated streamflow values from the past record (Refsgaard, 1997; Beven, 2001). Calibrated parameters represent the unique combination of climatic and physiographic factors that influence the hydrological behaviour of a catchment (Merz and Blöschl, 2004; Wagener and Wheater, 2006). However, operational use of hydrological models is always outside of the calibration period and/or catchment, which is where the parameters face their true test (Klemeš, 1986; Refsgaard and Knudsen, 1996; Coron et al., 2012). Parameter transfer away from this calibration domain can be in time (for streamflow forecasting) or space (for prediction at ungauged catchments) or both.

Temporal transfer of calibrated parameters is perhaps the most common and straightforward procedure used in catchment hydrological modelling. The first step involves choosing a specific historical time period for which all the input and output data required for running the model are available for the catchment. These data are used to calibrate the model parameters by finding the best match between the simulated and observed streamflow values. This procedure is followed by the application of the calibrated model at some other time period in the same catchment. Klemeš (1986) recommends that testing of hydrological models outside the calibration period is critical to establish their credibility as useful forecasting tools. An implicit assumption here is that the calibrated model parameters are temporally stable, i.e., they are suitable for application beyond the calibration period. However, numerous recent studies have shown that hydrological model parameters are not always temporally stable (Merz et al., 2011; Brigode et al., 2013; Westra et al., 2014), and their values depend on the duration as well as the specific physioclimatic conditions of the calibration period (Xia et al., 2004; Juston et al., 2009; Vaze et al., 2010; Razavi and Tolson, 2013). Wagener et al. (2003) used dynamic identifiability analysis (DYNIA) to estimate the

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parameters of a spatially lumped hydrological model and found that parameter values varied significantly when calibrated to different parts of the hydrograph. Merz et al. (2011) calibrated the parameters of a semi-distributed version of HBV model for six consecutive 5 year periods between 1976 and 2006 at 273 Austrian catchments, and found that (1) optimal parameter values were variable across the six calibration periods, and (2) the assumption of time invariant parameters had a significant impact on model simulations outside the calibration period. Similar findings were reported by Coron et al. (2012) in their study on temporal parameter transfer using three rainfall–runoff models at 216 catchments in southeast Australia. Razavi and Tolson (2013) compared three different calibration approaches for the SWAT2000 model at a catchment in the state of New York, USA and concluded that "…model calibration solely to a short data period may lead to a range of performances from poor to very well depending on the representativeness of the short data period which is typically not known a priori".

Spatial transfer of calibrated parameters is another widely used procedure in catchment hydrological modelling and is primarily required for streamflow prediction at ungauged basins (PUB) (Sivapalan et al., 2003). A considerable amount of research has been conducted over the years in the development and comparison of approaches to transfer hydrological model parameters from gauged to ungauged catchments (Post and Jakeman, 1999; Kokkonen et al., 2003; McIntyre et al., 2005; Young, 2006; Oudin et al., 2008; Zhang and Chiew, 2009; Patil and Stieglitz, 2014). Blöschl et al. (2013) and Hrachowitz et al. (2013) provide a comprehensive summary and synthesis of the progress made in PUB research during the International Association of Hydrological Sciences' (IAHS) PUB decade initiative (2003–2012) (Sivapalan et al., 2003). Donor gauged catchments, from which model parameters can be transferred to the receiver ungauged catchments, are typically identified using an approach that is either based on spatial proximity or physical similarity to the ungauged catchments. Oudin et al. (2008) compared the spatial proximity and physical similarity approaches at 913 catchments in France and found that the spatial proximity approach outperformed the physical similarity approach. Zhang and Chiew (2009) tested multiple parameter transfer approaches at 210 catchments in southeast Australia and found that an integrated similarity approach that combined spatial proximity and physical similarity slightly outperformed the spatial proximity approach. Patil and Stieglitz (2014) compared two different methods of spatial parameter transfer at 323 catchments in the United States and found that simulation performance at ungauged catchments is more sensitive to the types of parameters that are transferred than to the method used for transferring them. However, regardless of the chosen approach, spatial parameter transfer tends to cause deterioration in simulation performance (compared to calibration) due to the differences in physiographic properties and meteorological inputs between the donor and receiver catchments.

Although hydrological model simulation following temporal and/or spatial parameter transfer is expected to cause deterioration in catchment streamflow prediction, not many studies have focused on a direct comparison of these two approaches. A few PUB focused studies that have made such a comparison show results that range from a large performance difference between temporal and spatial parameter transfer (in favour of temporal) (Merz and Blöschl, 2004; Parajka et al., 2005) to minor performance difference between them (Oudin et al., 2008). In our view, further exploration is therefore needed on how the spatial and temporal parameter transfer approaches compare against each other, especially in the context of increasing appeal and popularity of the "trading space for time" approaches that are proposed for assessing the hydrological implications of anthropogenic climate change (Wagener et al., 2010; Peel and Blöschl, 2011; Singh et al., 2011; Ehret et al., 2014; Refsgaard et al., 2014). The trading space for time framework assumes that the spatial variability in catchment hydrological properties (including model parameters) can be used as a proxy for the climate change induced temporal variability in those properties (Merz et al., 2011). Studies such as Singh et al. (2011, 2014) have already demonstrated that the spatial parameter regionalization techniques developed for PUB can also be applied to make temporal modifications in model parameters for streamflow predictions under change (PUC) (Montanari et al., 2013). Therefore, we argue that a systematic comparison of the spatial and temporal parameter transfer approaches is likely to provide further insights into the connections between the PUB and PUC paradigms, and could even help refine the trading space for time methods.

In this paper, we compare three schemes of model parameter transfer, viz., temporal, spatial, and spatiotemporal, using a hydrological model called EXP-HYDRO (Patil and Stieglitz, 2014; Patil et al., 2014a, 2014b) at 294 catchments across the continental United States. The temporal parameter transfer scheme is implemented using a split-sample test procedure where the available data is divided into two periods, one for calibration and the other for validation. For the spatial parameter transfer scheme, we use the nearest neighbour catchment as a donor of calibrated parameters. Comparison of different spatial parameter transfer techniques is beyond the scope of this study (and has already been done by Patil and Stieglitz (2014)). In the spatiotemporal parameter transfer scheme, calibrated model parameters are transferred simultaneously in the spatial (to the nearest neighbour catchment) and temporal (to a different time period) domain.

2. Data and methods

2.1. Hydrological model

We use the spatially lumped version of EXP-HYDRO model (Patil and Stieglitz, 2014; Patil et al., 2014a, 2014b) to simulate daily streamflow (Fig. 1). This model solves the following two coupled ordinary differential equations simultaneously at each time step:

$$\frac{dS_{\mathrm{Snow}}}{dt} = P_{\mathrm{Snow}} - Q_{\mathrm{Melt}} \tag{1a}$$

$$\frac{dS}{dt} = P_{\mathrm{Rain}} + Q_{\mathrm{Melt}} - \mathrm{ET} - Q_{\mathrm{Bucket}} - Q_{\mathrm{Spill}} \tag{1b}$$

where S and S_{Snow} are, respectively, the amounts of stored water (mm) in the catchment and snow accumulation buckets. P_{Snow}

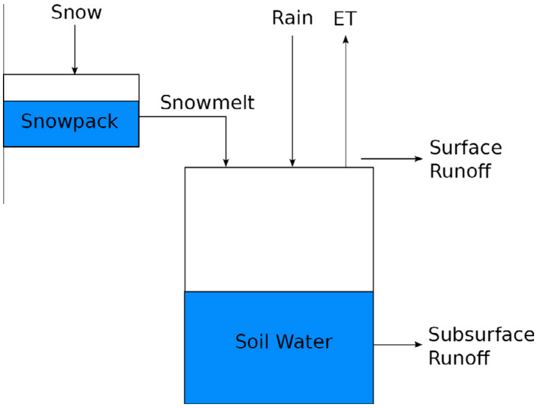

Fig. 1. Overview of the EXP-HYDRO model components and fluxes (from Patil et al. (2014a)).

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