Journal of Hydrology 517 (2014) 985–996

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Identifying dominant controls on hydrologic parameter transfer from gauged to ungauged catchments – A comparative hydrology approach

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ARTICLE INFO

Article history:
Received 30 September 2013
Received in revised form 6 June 2014
Accepted 21 June 2014
Available online 1 July 2014
This manuscript was handled by Andras Bardossy, Editor-in-Chief, with the assistance of Vazken Andréassian, Associate Editor

Keywords:
Rainfall runoff modeling
Parameter transfer
Ungauged catchment
Classification and regression trees
Streamflow signatures
Predictions in ungauged basins

SUMMARY

Daily streamflow information is critical for solving various hydrologic problems, though observations of continuous streamflow for model calibration are available at only a small fraction of the world's rivers. One approach to estimate daily streamflow at an ungauged location is to transfer rainfall–runoff model parameters calibrated at a gauged (donor) catchment to an ungauged (receiver) catchment of interest. Central to this approach is the selection of a hydrologically similar donor. No single metric or set of metrics of hydrologic similarity have been demonstrated to consistently select a suitable donor catchment. We design an experiment to diagnose the dominant controls on successful hydrologic model parameter transfer. We calibrate a lumped rainfall–runoff model to 83 stream gauges across the United States. All locations are USGS reference gauges with minimal human influence. Parameter sets from the calibrated models are then transferred to each of the other catchments and the performance of the transferred parameters is assessed. This transfer experiment is carried out both at the scale of the entire US and then for six geographic regions. We use classification and regression tree (CART) analysis to determine the relationship between catchment similarity and performance of transferred parameters. Similarity is defined using physical/climatic catchment characteristics, as well as streamflow response characteristics (signatures such as baseflow index and runoff ratio). Across the entire US, successful parameter transfer is governed by similarity in elevation and climate, and high similarity in streamflow signatures. Controls vary for different geographic regions though. Geology followed by drainage, topography and climate constitute the dominant similarity metrics in forested eastern mountains and plateaus, whereas agricultural land use relates most strongly with successful parameter transfer in the humid plains.

1. Introduction

Water management decisions often require continuous daily streamflow information for the river of interest, but this information is unavailable for most rivers of the world (Blöschl et al., 2013). In the absence of streamflow observations, inferences about the hydrologic regime can only be made from available physical or climatic characteristics of the catchments or by identifying hydrologically similar gauged catchments, potentially in connection with the use of hydrologic models. The following methods, amongst others, have mainly been used for predicting runoff in ungauged catchments in connection with a rainfall–runoff model:

(i) *Regionalization of model parameters* – This method relates the calibrated parameters of a hydrologic model with catchment characteristics using regression (Kokkonen et al., 2003; Parajka et al., 2005; Oudin et al., 2010). Once these relationships are established for available gauged catchments, the values of the hydrologic model parameters in ungauged catchments can be estimated based on its physical/climatic characteristics. Strategies based on parameter regionalization have been criticized for ignoring the covariances among model parameter estimates (McIntyre et al., 2005; Bárdossy, 2007; Parajka et al., 2007; Oudin et al., 2008), and are restricted due to parameter identifiability issues (Beven and Freer, 2001) and model structural error (Wagener and Wheater, 2006).

(ii) *Constraining hydrologic model simulations by regionalized signatures* – When regionalizing model parameters, one is invariably faced with problems such as the equifinality of

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http://dx.doi.org/10.1016/j.jhydrol.2014.06.030
0022-1694/

hydrologic model parameters (similar performance of more than one parameter set) and dependence of the calibrated parameters on the performance metrics used (Bárdossy, 2007). Regionalizing streamflow signatures and calibrating (or conditioning) the model to these estimates provides an alternative approach, which overcomes some of the issues with method (i) described above (Yadav et al., 2007; Bulygina et al., 2009).

(iii) *Transferring model parameters from hydrologically similar catchments* – This method relies on the assumption that the same parameter set should be successful in physically and climatically similar catchments (Merz and Bloschl, 2004; Parajka et al., 2005; Oudin et al., 2008, 2010; Zhang and Chiew, 2009).The transfer can be made from one or several donor catchments on the basis of a chosen similarity metric (McIntyre et al., 2005). Identifying a suitable metric of hydrologic similarity is difficult, which hinders the successful implementation of this approach.

All three strategies offer their own strengths and weaknesses (Wagener and Montanari, 2011). Weaknesses for the first and third methods generally arise from the need for model calibration (Beven and Freer, 2001). In all the above methods, the characterization of a complex and heterogeneous catchment using simple lumped descriptors of similarity is challenging. Due to these challenges in defining a consistent metric of hydrologic similarity, spatial proximity between the ungauged and gauged catchment still remains a competitive method to select donor catchments whose parameters can be transferred to the ungauged site. Several studies have tested various combinations of catchment attributes to determine hydrologic similarity and compared the different methods of predicting runoff in ungauged catchments (Merz and Bloschl, 2004; Parajka et al., 2005; Oudin et al., 2008, 2010; Zhang and Chiew, 2009). It is not clear if one method is better than the others since results vary across study areas.

1.1. Need for comparative hydrology

This study hypothesizes – similar to Falkenmark and Chapman (1989) and Sivapalan (2009) – that characterizing hydrologic processes and the similarity of those processes between catchments is best tackled by a comparative hydrology approach. By analyzing catchments across hydro-climatic gradients, it may be possible to identify the dominant controls on hydrologic model parameter transfer. There are several recent studies applying this concept and interesting trends have emerged. For example, Parajka et al. (2013) reviewed a wide range of parameter transfer studies and found that it is easier to predict runoff in humid catchments as compared to arid catchments, and in larger catchments than in smaller catchments. Oudin et al. (2008) points out that available catchment attributes may differ by region and obtaining one consistent set of attributes to define hydrologic similarity may not be feasible. These studies emphasize the need for a regional assessment of parameter transfer and for isolating the controlling characteristics for each region.

1.2. Aim of this study

The aim of this study is to diagnose the controls on parameter transfer across varying spatial scales. To achieve this aim, we apply a comparative analysis for spatial scales ranging from the sub-continental to sub-regional within the United States. We use similarity metrics based on characteristics that describe different aspects of the catchment and its boundary conditions (climate, topography, drainage, land use, and geology). However, unlike previous studies (McIntyre et al., 2005; Oudin et al., 2008, 2010; Zhang and Chiew, 2009), we do not attempt to lump these metrics into a single metric of hydrologic similarity. Instead, we identify cases of high performance of transferred model parameters between the (gauged) donor and (assumed ungauged) receiver catchments. Then, for the first time, we relate this performance to multi-dimensional regions spanned by the similarity metrics using a statistical tool called classification and regression trees (CART).

We aim to answer two questions:

(i) What are the catchment characteristics and streamflow signatures whose similarity leads to a successful transfer of parameters from one catchment to another?
(ii) Do the dominant characteristics and streamflow signatures that control the success of a parameter transfer from a gauged to (assumed) ungauged site vary across regions or scales?

The main novel contributions of this study are:

(i) We move beyond a single metric of hydrologic similarity by identifying multi-dimensional regions of the characteristics space that lead to high performance of transferred parameters. This is advantageous since it relates complex catchment response to catchment properties without losing the information content in each similarity metric as witnessed in previous studies that combined metrics.
(ii) We use information about both streamflow signatures (response characteristics derived from streamflow hydrograph) and catchment characteristics as classification variables to predict success of parameter transfer. We therefore test the relative value of knowledge regarding the expected dynamic characteristics (climate, land use) of a catchment versus knowledge of the static characteristic (soils, topography) only. The typical assumption is of course that knowledge of the latter (static characteristics such as soils) defines the former (the catchment's dynamic behavior).

2. Study area, data and similarity metrics

2.1. Study area and data

Out of 438 catchments in the MOPEX (model parameter estimation experiment, Duan et al. (2006)) dataset, we identified 87 USGS reference catchments based on the information provided by Falcone et al. (2010). These reference catchments are considered to be minimally affected by anthropogenic alterations according to the following criteria: (i) a quantitative index of anthropogenic modification within the catchment based on GIS-derived variables, (ii) visual inspection of every stream gage and drainage catchment from recent high-resolution imagery and topographic maps, and (iii) information about man-made influences from USGS Annual Water Data Reports (Falcone et al., 2010). Catchments with more than 5 years of missing data were removed resulting in 83 catchments. Fig. 2 displays the locations of these catchments. Table A-1 lists the gage identification numbers for these catchments along with their areas. The 10-year time period from 1959 to1969 has the maximum number of catchments with daily meteorological and streamflow information. The historical streamflow, temperature and precipitation data for the catchments was obtained from the MOPEX dataset (Duan et al., 2006). The catchment characteristics were obtained from the Falcone database (Falcone et al., 2010). Geologic, climatic, drainage and topographic properties were considered. Two properties describing the patterns of land use were also included in the analysis – percentage of catchment covered by agriculture and forest areas. The climate properties such as total