Journal of Hydrology 547 (2017) 544–556

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

Regionalization of runoff models derived by genetic programming

M. Heřmanovský *, V. Havlíček, M. Hanel, P. Pech

Faculty of Environmental Sciences, Czech University of Life Sciences Prague, Kamýcká 129, 165 21 Praha 6 - Suchdol, Czech Republic

A R T I C L E I N F O

Article history:
Received 25 August 2016
Received in revised form 9 February 2017
Accepted 11 February 2017
Available online 16 February 2017
This manuscript was handled by A. Bardossy, Editor-in-Chief

Keywords:
Genetic programming
Physical similarity
PUB
Regionalization
Runoff modelling

A B S T R A C T

The aim of this study is to assess the potential of hydrological models derived by genetic programming (GP) to estimate runoff at ungauged catchments by regionalization. A set of 176 catchments from the MOPEX (Model Parameter Estimation Experiment) project was used for our analysis. Runoff models for each catchment were derived by genetic programming (hereafter GP models). A comparison of efficiency was made between GP models and three conceptual models (SAC-SMA, BTOPMC, GR4J). The efficiency of the GP models was in general comparable with that of the SAC-SMA and BTOPMC models but slightly lower (up to 10% for calibration and 15% in validation) than for the GR4J model. The relationship between the efficiency of the GP models and catchment descriptors (CDs) was investigated. From 13 available CDs the aridity index and mean catchment elevation explained most of the variation in the efficiency of the GP models. The runoff for each catchment was then estimated considering GP models from single or multiple physically similar catchments (donors). Better results were obtained with multiple donor catchments. Increasing the number of CDs used for quantification of physical similarity improves the efficiency of the GP models in runoff simulation. The best regionalization results were obtained with 6 CDs together with 6 donors. Our results show that transfer of the GP models is possible and leads to satisfactory results when applied at physically similar catchments. The GP models can be therefore used as an alternative for runoff modelling at ungauged catchments if similar gauged catchments can be identified and successfully simulated.

1. Introduction

1.1. Hydrological regionalization

Runoff simulation on ungauged catchments continues to be a subject of interest among hydrologists (Hrachowitz et al., 2013). Various approaches collectively termed hydrological regionalization and associated with estimating hydrological characteristics on ungauged catchments are used.

The term hydrological regionalization describes methods allowing transfer of information about hydrological behaviour between catchments (Oudin et al., 2008). However, this definition varies in the context of the studied problem (compare Gottschalk et al. (1979) with Blöschl and Sivapalan (1995)). He et al. (2011) provide a brief overview of how the definition of hydrological regionalization has developed.

Some of the first works in the field of hydrological regionalization were published by Jarboe and Haan (1974) and Magette et al. (1976). Using regression, they endeavoured to relate the Kentucky watershed model parameters with measurable catchment descriptors (CDs). Subsequently, three basic approaches to hydrological regionalization have been used frequently: the regression approach (Jarboe and Haan, 1974; Magette et al., 1976; Xu, 1999; Merz and Blöschl, 2004; Heuvelmans et al., 2006; Wagener and Wheater, 2006), the spatial proximity approach (Vandewiele and Elias, 1995; Merz and Blöschl, 2004; Parajka et al., 2005; Oudin et al., 2008) and the physical similarity approach (Acreman and Sinclair, 1986; Burn and Boorman, 1993; Parajka et al., 2005; Oudin et al., 2008; Zhang and Chiew, 2009). Detailed description of these regionalization approaches can be found in He et al. (2011) or in Blöschl et al. (2013). In the physical similarity approach (which is used further in our study) it is assumed that catchments with similar values of important CDs have similar hydrological behaviour. Transfer of model parameters from a gauged catchment (donor) to a physically similar ungauged catchment (acceptor) should lead to meaningful results (McIntyre et al., 2005; Blöschl et al., 2013), due to the existing links between CDs and the hydrological behaviour of catchment. These links were explored by Oudin et al. (2010) who showed that relationship between physical and hydrological similarity exists for 60 % of catchments of their catchment set.

* Corresponding author.
E-mail addresses: hermanovsky@fzp.czu.cz (M. Heřmanovský), havlicekv@fzp.czu.cz (V. Havlíček), hanel@fzp.czu.cz (M. Hanel), pech@fzp.czu.cz (P. Pech).

http://dx.doi.org/10.1016/j.jhydrol.2017.02.018
0022-1694/

The three basic regionalization approaches (regression, spatial proximity and physical similarity approach) have been compared in terms of model simulation efficiency on ungauged catchments (Merz and Blöschl, 2004; Parajka et al., 2005; Oudin et al., 2008; Zhang and Chiew, 2009). These approaches have also been combined in order to improve model efficiency (Burn and Boorman, 1993; Merz and Blöschl, 2005; Zhang and Chiew, 2009). Parajka et al. (2013) compared these regionalization approaches on the basis of 34 previously presented studies (encompassing 3,780 catchments from different climatic conditions). Their results show that physical similarity and spatial proximity provide similar model efficiencies and that these model efficiencies are better than those based upon regression. They also presented catchment conditions where regionalization performs well.

1.2. Genetic programming in runoff modelling

Genetic programming (GP) is an evolutionary machine learning technique that automatically solves wide range of problems without requiring the user to specify the structure of the solution in advance (Poli et al., 2008). Since GP's introduction by Koza (1992), it has been applied frequently (Poli et al., 2008). The fields of GP applications are e.g. optimization, data mining, signal processing and control (for more see Koza (2010); Poli et al. (2008)).

Genetic programming is a general optimization method, and its main objective is to discover the relationships between the input and output data. In runoff modelling, GP is used most frequently as a symbolic regression tool, which means that equations describing the relationships between inputs and outputs are derived by a simulated evolution process (a GP run). The derived equation represents a runoff model for a given data set. No prior information about the structure of the model (equation) is needed. In a GP run, the population of individuals (candidate solutions) is progressively improved from generation to generation by selection and variation of the best individuals, whose offspring proceed to the next generation (often together with the best parents). A GP run is described in more detail in 2.5.

Standard GP began to be used in rainfall-runoff modelling during the second half of the 1990s in the work of Babovic (1996) and Cousin and Savic (1997). Synthetic rainfall-runoff series were used for modelling in these studies. In the first decade of this century, more works were published which included real data. Combination of GP and conceptual models in the sense of calibrating the conceptual model using GP and error correction was presented by Babovic and Keijzer (2002). Studies testing GP for 1 day runoff forecasting were published by e.g. Jayawardena et al. (2005, 2006) and Charhate et al. (2009). Rabuñal et al. (2007) applied a combined approach using GP and artificial neural networks to rainfall-runoff modelling on an urbanized catchment. In a study by Makkeasorn et al. (2008), GP and artificial neural networks were compared for their ability to predict runoff while using assorted variables (including radar data) as inputs. GP also appears in comparative studies of data-driven models (Elshorbagy et al., 2010; Elshorbagy et al., 2010; Londhe and Charhate, 2010). In these comparative studies, GP has generally been considered the most successful technique.

1.3. The study objectives

Models derived by GP (GP models) can be suitable alternatives to conceptual models. Optimization of model structure is the main advantage of GP models. Thus, a model's structure may vary when runoff is simulated in different hydro-climatic conditions.

The main objective and novelty of this study lies in testing transferability of GP models between catchments. Such testing has yet not been carried out, and in particular not for daily hydrograph prediction in ungauged catchments. The specific objectives include to:

1. test GP models' appropriateness for runoff simulation on a sample of MOPEX (Model Parameter Estimation Experiment) catchments and compare simulation efficiencies of GP models and conceptual models,
2. investigate relationships between GP models' efficiencies and CDs, and
3. test transferability of GP models between catchments on the basis of their physical similarity.

To address objective 1, we test whether GP models can reasonably simulate runoff. Furthermore, simulation efficiencies of GP models are compared with those of conceptual models. The overriding objective here, then, is to test whether GP models are capable to capture different aspects of catchment hydrological behaviour similarly to how conceptual models do so.

The intentions for objective 2 are to examine which CDs significantly affect the quality of GP model simulations and to identify catchment conditions in which GP models perform well.

Objective 3 involves testing GP models' transferability in implementing the physical similarity approach. Single-donor and multiple-donor techniques are used for estimating total runoff on ungauged catchments. Also considered are the effects of various combinations of CDs. The results of the physical similarity approach are compared with results from the naive method, which is the application of a general model of catchment behaviour.

The paper is organized as follows: 2 presents catchments and data sets used in the tests and describes the methodology. The donor catchment searching method, GP setup, and combination of the GP and physical similarity approach in regionalization are described in this section. In Sections 3 and 4, the results are presented and analysed. The paper closes with conclusions.

2. Materials and methods

2.1. Input data

Time series of daily precipitation (P in mm/day), potential evaporation (PE in mm/day) and runoff (R in mm/day) for 176 catchments in the US for period 1970–1989 were considered in our analysis. The data originate from the MOPEX project (Duan et al., 2006). The period from 1 January 1970 to 31 December 1979 was used for model calibration (i.e. identification of optimal model structure and its parameters). The period from 1 January 1980 to 31 December 1989 was then used for model validation. We selected catchments not significantly affected by snow accumulation in order to avoid regionalization of models from entirely distinct hydrological regimes.

To quantify the physical similarity, 13 catchment descriptors (CDs) were considered. Those CDs, together with definitions of the acronyms used and with summary statistics, are presented in Table 1. The CD values were taken from the MOPEX project data sets. Their origin is briefly given below. Values of P were computed using PRISM, the Parameter-elevation Regressions on Independent Slopes Model (Daly et al., 1994) for the period 1961–1990. Aridity index (defined as the ratio PE/P) for each catchment was estimated from gridded values of P and PE. The abbreviation PE stands for mean annual potential evaporation from the NOAA Evaporation Atlas (Farnsworth et al., 1982). The saturated hydraulic conductivity (SHC) was developed from 1 km STATSGO soil data provided by the Penn State Earth System Science Center (Miller and White, 1998). United States Department of Agriculture soil type classifications (Miller and White, 1998) provided the basis for the descriptor