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Regionalization of a conceptual rainfall–runoff model based on similarity of the flow duration curve: A case study from the semi-arid Karkheh basin, Iran

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SUMMARY

The study examines the possibility of simulating time series of streamflows for poorly gauged catchments based on hydrological similarity. The data of 11 gauged catchments (475–2522 km^2), located in the mountainous semi-arid Karkheh river basin of Iran, is used to develop the procedure. The well-known HBV model is applied to simulate daily streamflow with parameters transferred from gauged catchment counterparts. Hydrological similarity is defined based on four similarity measures: drainage area, spatial proximity, catchment characteristics and flow duration curve (FDC). The study shows that transferring HBV model parameters based on the FDC similarity criterion produces better runoff simulation compared to the other three methods. Furthermore, it is demonstrated that the FDC based regionalization of HBV model parameters works reasonably well for streamflow simulations in the data limited catchments in the mountainous parts of the Karkheh river basin. In addition, it could be demonstrated that the parameter uncertainty of the model has little impact on the FDC based regionalization approach. The methodology presented in this paper is easy to replicate in other river basins of the world, particularly those facing decline in streamflow monitoring networks and with a limited number of gauged catchments.

1. Introduction

1.1. Problem statement

Streamflow data are a prerequisite for planning and management of water resources such as design of dams and hydropower plants, assessment of water availability for irrigation and other water uses, assessment of flood and drought risks, and examining the ecological health of a river system. However, in many cases, observed streamflow data are not available or are insufficient in terms of quality and quantity. This undermines the informed planning and management of water resources at a specific site as well as at the river basin scale.

Hydrologists have responded to this challenge by developing various predictive tools, which are commonly referred to as regionalization methods (e.g. Sivapalan et al., 2003; Blöschl and Sivapalan, 1995; Yadav et al., 2007). These methods can be broadly classified into two groups based on their temporal dimension. The first group deals with the estimation of continuous time series of streamflows (e.g. Magette et al., 1976; Merz and Blöschl, 2004). The second group estimates selected hydrological indices, such as the mean annual flow and base flow index (e.g. Nathan and McMahon, 1990), or various percentiles of the flow instead of continuous time series (e.g. regionalization of the flow duration curve – FDC) (Castellarin et al., 2004). Further classification can be done within each group. For example, Castellarin et al. (2004) classified regionalization methods for FDC into statistical, parametric and graphical approaches. The methods used for estimating the time series of streamflows can be further categorized into three sub-groups: (i) *model parameter estimation* by developing regression relationships between model parameters and catchment characteristics (e.g. Magette et al., 1976); (ii) *transfer of model parameters*, whereby a catchment similarity analysis is conducted and parameters of gauged catchment are used in simulations for similar ungauged or poorly gauged catchment (e.g. Kokkonen et al., 2003; Wagener et al., 2007); and (iii) *other regionalization techniques* such as spatial interpolation of parameters (e.g. Merz and Blöschl, 2004) or regional pooling of data for parameter estimation for ungauged catchments (e.g. Goswami et al., 2007).

Despite considerable progress in hydrology, the prediction of streamflow for ungauged or poorly gauged catchments still remains

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a major challenge (Sivapalan et al., 2003; Wagener and Wheater, 2006). A brief review of some key studies involving commonly used regionalization methods applying conceptual rainfall–runoff models for streamflow estimations in ungauged or poorly gauged catchments is presented in the following section. In this paper, we defined a catchment as ungauged when no streamflow records exist, whereas a data limited or poorly gauged catchment is defined as a catchment where some measured streamflow records are available that are usually short, have many gaps and of poor quality. These records are not enough to achieve a satisfactory level of model calibration for streamflow simulation.

1.2. Review of regionalization methods using conceptual rainfall–runoff models

An overview of some applications of the rainfall–runoff models for regionalization in different parts of the world is given in Table 1 and briefly discussed below. The selected studies estimated continuous time series of streamflows using a rainfall–runoff model and reported the performance measures in terms of at least one of the three evaluation criterion, namely, Nash–Sutcliffe efficiency (*NSE*), coefficient of determination (R^2) and the mean annual volume balance (*VB*). These points were considered in the selection in order to keep consistency in comparison of this study and the presented literature in Table 1, as we also used the above mentioned three performance measures. Moreover, on the whole, the presented studies attempted to represent wide range of hydro-climatic environments and provide reasonably good coverage of most of the regionalization methods.

Magette et al. (1976) used 21 catchments (0.02–12 km^2) in USA for regionalization of six selected parameters of the Kentucky Watershed Model (KWB). They used 15 catchment characteristics in developing regression equations and found that a multiple regression technique used in stepwise manner was successful in developing equations to estimate model parameters from catchment characteristics, but simple linear regression models were totally unsuccessful. They randomly selected five out of 21 catchments for validation. Although the validation results showed significant variations, they concluded that the approach was useful and should be further developed. Vandewiele et al. (1991) used 24 catchments (16–2160 km^2) in Belgium for developing regression equations to estimate three parameters of a monthly conceptual rainfall–runoff model using the basin lithological characteristics. They concluded that their regionalization approach was capable of generating reliable monthly time series for ungauged sites within the region.

Servat and Dezetter (1993) evaluated the performance of two conceptual rainfall–runoff models (GR3 and CREC models) for possible applications to ungauged catchments in the north-western part of the Ivory Coast. They were able to relate all model parameters to catchment characteristics (rainfall and land cover) with varying degree of success. The regionalization results in terms of R^2 and *NSE* were variable, particularly for the *NSE* which was quite low (i.e., close to zero) in some cases.

Ibrahim and Cordery (1995) applied a monthly water balance model for predicting stream flows in New South Wales, Australia. The used model had four parameters, of which three were estimated from rainfall data. Abdulla and Lettenmaier (1997) regionalized seven of the nine parameters of a large scale model (VIC-2L) for Red and White river basins in USA. They estimated two of the model parameters from STATSGO soil data. For other parameters, they used 28 catchment variables, related to soil and climate, for developing multiple regression equations between model parameters and catchment variables. Their regionalization results were generally good in most cases, although they noticed better performance in humid and sub-humid catchments and poorer in semi-arid to arid catchments.

Seibert (1999) used the HBV model for a regionalization study using 11 catchments in Sweden and found that six of the 13 model parameters could be estimated from the land cover features (i.e., forest and lake areas). However, the application to ungauged catchments was achieved with varying degree of success, with daily *NSE* ranging from 0.23 to 0.72. Merz and Blöschl (2004) compared eight regionalization methods using the HBV model with data sets from 308 catchments in Austria. Parajka et al. (2005) conducted a follow up study of the Merz and Blöschl (2004) by improving the model structure (i.e., by dividing catchments into elevation bands of 200 m interval), adding snow cover data and conducting similarity analysis on the basis of catchment attributes. They concluded that the methods based on similarity approaches produce reasonably good regionalization results. This finding is also consistent with Kokkonen et al. (2003) who concluded that "*When there is reason to believe that, in the sense of hydrological behaviour, a gauged catchment resembles the ungauged catchment, then it may be worthwhile to adopt the entire set of calibrated parameters from gauged catchment instead of deriving quantitative relationships between catchment descriptors and model parameters*".

McIntyre et al. (2005) proposed a regionalization method of ensemble modelling and model averaging and tested it using a five parameter version of the probability distributed model (PDM) on 127 catchments (1–1700 km^2) in the United Kingdom. They selected donor catchments based on catchment similarity analysis for which three catchment characteristics, i.e., catchment area, permeability and rainfall were used. In this approach more than one donor catchment is selected, which is different from the usual approaches of using a single donor catchment for streamflow simulations at an ungauged site. Then the full parameter set of each of the donor catchment is used to predict streamflows at the ungauged catchment, thereby, generating an ensemble of flow values. Then the average streamflow could be taken from the weighted average with weights defined based upon the relative similarity. They found that the proposed method performs reasonably well as compared to the established procedure of regressing parameter values from the catchment descriptors. However, they also noted that the new method estimated the low flows better as compared to high flows for their study area. They recommended further testing of the model, especially to test different model types and improved definition of similarity.

Goswami et al. (2007) developed a methodology that uses a regionalization and multi-model approach for simulating streamflows in ungauged catchments. Like other methods, their methodology did not involve transfer of model parameters from gauged catchment to ungauged catchment, and model parameters need not to be related to physical catchment descriptors. They used seven different models for regionalization and for each tested the three methods that involve the use of the discharge series by taking regional averages, regional pooling of data and transposition of discharge data of the nearest neighbour. They used 12 gauged catchments in France to illustrate their methodology and each time considered one of them as ungauged for the application of the method and then compared the results with observed time series of daily discharge using the *NSE* criterion. The results indicated a mix of success and failure for the individual catchments and tested methods. However, they concluded that the pooling method of regionalization coupled with the conceptual soil moisture accounting and routing model (SMAR) was the best approach for simulating flows in ungauged catchments in that region. The second best method was the transposition of data from the nearest neighbour provided the catchments are similar in the hydro-meteorological, physiographic characteristics and drainage area.