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Streamflow estimation in ungauged catchments using regionalization techniques



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ABSTRACT

Continuous streamflow regionalization in ungauged catchments is contemplated as a challenging task. In a developing country like India where the subject of prediction in ungauged basins (PUB) is not prevalent, thirty-two catchments were specified in order to analyze continuous streamflow estimation. Spatial proximity (Inverse Distance Weighted, Kriging, and global mean), regression and physical similarity were the regionalization approaches implemented in conjunction with SWAT (Soil and Water Assessment Tool) for streamflow estimation in each catchment treated as ungauged in turn. Kriging and IDW were the two methods that produced superior results than other applied techniques in terms of Nash-Sutcliffe Efficiency (NSE), RMSE-observations standard deviation ratio (RSR) Percentage bias (PBIAS) and Peak percent threshold statistics (PPTS). Physical similarity and regression approaches, which were based on catchment attributes exhibited better results than global mean approach. Sequential Uncertainty Fitting (SUFI-2) tool analyzed the uncertainty associated with regionalization techniques in terms of 95% prediction uncertainty (95PPU). The comparative assessment proposes that presence of well-gauged catchments in proximity with the ungauged catchment is more beneficial than catchments having resemblance between them in terms of physiographic attributes for continuous streamflow prediction.

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1. Introduction

Rainfall-runoff modelling is a key area of research for the global scientific community dealing with the surface water hydrology. One simple reason for this is quantitative or qualitative information about streamflow is vital for many practical applications like water allocation, long-term planning, catchment management operations, flood forecasting, optimization of hydropower production, design of hydraulic structures and others. However, modelling requires calibration, parameter estimation and validation of the model, which is likely in cases of the gauged catchments only (Bárdossy, 2007). Transfer of optimized model parameter set from one or more gauged catchments to an ungauged catchment is a way to quantify various hydrological processes occurring within the ungauged catchments. This process is called regionalization (Blöschl and Sivapalan, 1995; Oudin et al., 2010). A large chunk of total river basins present across the world are either poorly gauged or completely ungauged (Sivapalan et al., 2003; Young, 2006; Blöschl et al., 2013) and the hydrological parameter

observation networks are continuously deteriorating (Mishra and Coulibaly, 2009). In addition, the number of gauging stations compared to the large river basins is insignificant. As a result, small watersheds are devoid of water resources assessment data (Ibrahim et al., 2015). This scenario applies to all developing countries like India. Hence, regionalization is the alternative way for prediction of parameters like streamflow, sediment load and water quality in ungauged catchments. Though there are few examples of regionalization studies mentioned in the last decade of the twentieth century, the major advances in regionalization approaches have only occurred during the last decade (Blöschl, 2016; Hrachowitz et al., 2013). Hence, additional attention is needed for further improvement.

Estimation of streamflow in gauged or ungauged basins is being carried out using distributed physically-based models, conceptual and semi-distributed models and data-driven models (Razavi and Coulibaly, 2012). Usually, prediction from physically distributed models is associated with high levels of uncertainty (Razavi and Coulibaly, 2012). Therefore, it is opined to use a conceptual or semi-distributed model. In case of ungauged catchments due to unavailability of long-term discharge data, upon which model functioning is dependent, regionalization is considered a daring job (Sivapalan et al., 2003; Oudin et al., 2008; Stoll and Weiler,

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2010; Samuel et al., 2011). Regionalization approaches differ from place to place due to effect of regional climate, scale of catchment, human interventions. Thus, the notion of a universal approach for all catchments is yet to be established (Oudin et al., 2008). Regionalization methods can be categorized into two groups: hydrological model-dependent and hydrological model-independent (Razavi and Coulibaly, 2012). He et al. (2011) appraised hydrological model-dependent streamflow regionalization methods while Razavi and Coulibaly (2012) reviewed a wide range of continuous streamflow regionalization approaches covering both the categories.

Amongst the various regionalization approaches, regression analysis is one of the most widely used methods. This technique uses model parameter and physical catchment attributes as dependent and independent variables respectively. As for streamflow regionalization using hydrological models, IHACRES seems to be one of the most extensively used models throughout the world in combination with either linear, nonlinear or multiple regression techniques (Sefton and Howarth, 1998; Post and Jakeman, 1999; Kokkonen et al., 2003; Parajka et al., 2005; Young, 2006; Post, 2009; Samuel et al., 2011). Heuvelmans et al. (2006) used SWAT (Soil and Water Assessment Tool) on 25 catchments of Belgium to predict daily streamflow in ungauged catchments. Artificial Neural Network (ANN) based regionalization techniques outperformed conventional linear regression techniques. Gitau and Chaubey (2010) used global average and regression methods along with SWAT model for streamflow regionalization in 7 catchments of Arkansas. A satisfactory range of NSE values suggests the proficiency of the model for streamflow prediction in ungauged catchments. Boughton and Chiew (2007) used AWBM (Australian Water Balance Model) in combination with multiple linear regression technique on 213 catchments of Australia to estimate average annual runoff. The results were within 2.5% of real values for two-thirds of the cases. Peel et al. (2000) used SIMHYD on Australian catchments in conjunction with linear regression technique to estimate daily streamflow in ungauged basins. Reichl et al. (2009) used a model parameter averaging technique based on similarities between catchments in combination with SIMHYD model. This regionalization method fared better than spatial proximity and regression with a NS value of 0.8.

The use of spatial proximity approach is an alternative method which is widely used over the globe for streamflow regionalization in ungauged catchments (Merz and Blöschl, 2004; Parajka et al., 2005; Masih et al., 2010; Samuel et al., 2011). HBV is a hydrological model which is very popular in Europe. The researchers mentioned above used this model in combination with either spatial proximity, regression analysis or physical similarity approach to regionalize streamflow. The uncertainty of a hydrological model while predicting discharge at ungauged catchments was characterized (Sellami et al., 2014) using SWAT model combined with spatial proximity approach for Mediterranean catchments. Instead of using catchment attributes, this technique uses the geographical distance between gauged and ungauged catchments for parameter transfer with an assumption that the region is hydro-meteorologically homogeneous.

Physical similarity approach is another regionalization technique which uses catchment attributes to find out similarity between donor and receiver catchments (Nathan and McMahon, 1990; Kay et al., 2006; Parajka et al., 2005; Samuel et al., 2011). The advantage of physical similarity approach over regression technique is that it does not take the assumption of linearity (Samuel et al., 2011).

Laaha and Blöschl (2006) compared four low flow regionalization procedures in 325 Austrian sub-catchments and found that the seasonality grouping method fared better than the residual

pattern approach, weighted cluster analysis and regression trees. Götzinger and Bárdossy (2007) tested the accuracy of four regionalization approaches on HBV model in the Neckar basin of Germany. The modified Lipschitz condition estimated the most effective simulation. None of the four applied methods could be able to reproduce an acceptable range of observed discharge in some areas of river where flow is regulated suggesting the sensitivity of the model to catchment properties. Schreider et al. (2002) used streamflow data for disaggregation method while predicting streamflow in gauged and ungauged catchments in Thailand. Croke et al. (2004) combined IHACRES with CATCHCROP model while simulating daily streamflow in ungauged catchments of Thailand to assess land use impact on streamflow. Use of a completely distributed hydrological model for ungauged catchment analysis is not very common. One such example is where Makungo et al. (2010) used MIKE 11 NAM model on an ungauged catchment in South Africa to generate natural streamflow. A NSE value of 0.74 for modified nearest neighbor regionalization technique can be considered a good result. Two conceptual hydrological models, HYMOD and HBV, were used along with a new regionalization technique called RDS (robust parameter estimation, data depth, spatial proximity) in the Eastern USA catchments (Shoaib et al., 2013). Prediction efficiency was found to be more than 90% for each of the models. Pinheiro and Naghettini (2013) used a synthetic long-term FDC to enable autocalibration for parameters of RIO GRANDE rainfall-runoff model in ungauged basins of Brazil. The results show good agreement between synthetic and calibrated FDC as per low average relative error and high NSE values. Four regionalization methods i.e. Parameter set yielding maximum regional weighted average performance measures, nearest neighbor, physical similarity and regional median of optimal parameters were implemented by Hailegeorgis et al. (2015) to simulate hourly streamflow in 26 ungauged catchments of Norway. First-order nonlinear system model, HBV and basic grid model were the three hydrological models combined with the above-mentioned regionalization techniques provided satisfactory outcomes.

An extensive literature survey indicates the importance of streamflow estimation in ungauged catchments across the globe. In a developing country like India, the issue of continuous streamflow regionalization is less addressed. Taking the above situation into consideration, the focus was on estimating continuous daily streamflow in Indian ungauged catchments with an aim to quantify the relative performance, consistency and efficiency of different regionalization approaches, ultimately to distinguish the most suitable regionalization method and associated uncertainty. Spatial proximity, linear regression and physical similarity were the three different regionalization approaches used in combination with SWAT for achieving the objective. Such comparative study is a first for Indian catchments as far as our knowledge is concerned.

2. Study area and data

India is home to an extraordinary diversity of climatic regions. Thirty-two gauged catchments from the Eastern and Southern India with minimal flow regulation located in the headwater regions of nine river basins were identified as the study area (Fig. 1). Most of the ungauged catchments usually located at the upstream of the river basins (Niadas, 2005), unregulated basins (Mishra and Coulibaly, 2009) and remote areas (Makungo et al., 2010) due to a variety of reasons like unreachability or absence of development purpose. The listed thirty-two catchments spread over the following states: Jharkhand, West Bengal, Chhattisgarh, Odisha, Telangana, Andhra Pradesh, Tamil Nadu, Karnataka, and Maharashtra. One catchment (Rushikulya) was picked for repre-

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