Hydrol. Earth Syst. Sci., 15, 3539–3553, 2011
www.hydrol-earth-syst-sci.net/15/3539/2011/
doi:10.5194/hess-15-3539-2011

Hydrology and Earth System Sciences

A review of regionalisation for continuous streamflow simulation

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Received: 15 May 2011 – Published in Hydrol. Earth Syst. Sci. Discuss.: 23 June 2011
Revised: 29 October 2011 – Accepted: 1 November 2011 – Published: 23 November 2011

Abstract. Research on regionalisation in hydrology has been constantly advancing due to the need for prediction of streamflow in ungauged catchments. There are two types of studies that use regionalisation techniques for ungauged catchments. One type estimates parameters of streamflow statistics, flood quantiles in most cases. The other type estimates parameters of a rainfall-runoff model for simulating continuous streamflow or estimates continuous streamflow without using a model. Almost all methods applied to the latter can be applied to the former. This paper reviews all methods that are applied to continuous streamflow estimation for ungauged catchments. We divide them into two general categories: (1) distance-based and (2) regression-based. Methods that fall within each category are reviewed first and followed with a discussion on merits or problems associated with these various methods.

1 Introduction

The derivation of relationships between the rainfall over a catchment area and the resulting flow in a river is a fundamental problem for the hydrologist. Rainfall-runoff models of different types provide a means of quantitative extrapolation or prediction of discharge and estimation of water balance (Beven, 2000). Two dominant types of these models are physically-based models (PMs) and conceptual models (CMs). PMs describe distributed mechanics of hydrological processes. Such models are appropriate for studying the effects of land use changes, soil erosion, surface groundwater interactions (Todini, 1996) because their parameters are (or supposed to be) reflected in the field measurements (Beven, 1989). In practice, they do not represent physical processes as they are purported to, especially in the reality of heterogeneity and complexity of water flows in the field (Blöschl and Sivapalan, 1995; Sivapalan, 2003). Beven (1989) made an interesting assertion on current PMs arguing that they are in fact lumped CMs; even if they operate at the grid scale rather than at the catchment scale of more traditional lumped conceptual models. CMs, on the other hand, are well-known for their moderate data requirement. They provide *simplified representations of key hydrological processes using a perceived system* (Dawson and Wilby, 2001). But they exhibit deficiencies when dealing with ungauged catchments because their model parameters cannot be obtained through calibration. Their conceptual basis also limits their ability to deal with climate/landuse change and other dynamic changes taking place in many catchments. This is due to the fact that they only perform reasonably well with calibration based on past data which does not necessarily reflect the future. The calibration-dependent nature and static features associated with CMs highly constrain their application for prediction in catchments that is ungauged or undergoing climate and/or physical changes (He et al., 2011). In a broad and practical sense, ungauged catchments do not only refer to the ones without past stream flow observations but also those catchments expected to experience significant change in the future.

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Table 1. Definition of regionalisation as it appears in the literature chronologically.

Authors	Term used	Definition
Riggs (1973)	Regional analysis	Extending records in space.
Gottschalk (1985)	Regionalization	Areal classification, the ability to attach to location a label or number which is hydrologically meaningful.
Blöschl and Sivapalan (1995)	Regionalization	Transfer of information from one catchment to another.
Wagener and Wheater (2006)	Regionalization or Spatial generalization	This statistical relationship and the measurable properties of the ungauged catchmentthat is used to derive estimates of the (local) model parameters.
Young (2006)	Regionalisation	Relating hydrological phenomena to physical and climatic characteristics of a catchment/region.
Oudin et al. (2010)	Regionalization	All methods allowing transfer of hydrological information from gauged to ungauged locations.

Regardless of the type of hydrological model used to derive rainfall and runoff relationships, estimation of model parameters and prediction in ungauged catchments are particularly difficult and are always associated with considerable uncertainties. Estimation of streamflow statistics in ungauged catchments is another issue that is always encountered when engineering design is needed for hydraulic structures. Research focus on prediction in ungauged catchments was formally endorsed and set out by the PUB (Prediction in Ungauged Basins) Science and Implementation Plan within the IAHS (International Association of Hydrological Sciences) Bureau in 2003 (Sivapalan et al., 2003). Regionalisation techniques have been designed to enable estimates of statistical distribution parameters of stream flow characteristics, e.g. flood frequency distribution, low flow frequency distribution, flow duration curves etc., or rainfall-runoff model parameters to simulate continuous stream flow at ungauged catchments. They aim to transfer information from one catchment or a group of catchments to another one or another group. The definitions of regionalisation (Table 1) vary depending on contexts and place emphasis on extrapolation of time series, classification or statistical relationship.

The development of regional analysis for streamflow statistics has a relatively long and rich history and much of its development has benefited the advancement of regional estimation of rainfall-runoff model parameters for continuous streamflow simulation (Vogel, 2005). Almost all methods applied to the latter are adapted from the former and hence applicable to the former, with the exception of a number of emerging methods that have only been tested with rainfall-runoff models. The focus of this paper is on studies dealing with estimation of rainfall-runoff model parameters for continuous streamflow simulation in ungauged catchments. The most intuitive regionalisation method is to identify similar or proxy catchments, be it location-wise or behaviour-wise. The concept of catchment similarity is the foundation of all distance-based methods for regionalisation. This category of methods is reviewed in Sect. 2 Distance-based regional analysis. Parameters can be related to catchment descriptors by using regression functions in which rainfall-runoff model parameters and catchment descriptors become explained variables and explanatory variables respectively. This category of methods is reviewed in Sect. 3 Regression-based regional analysis. The two categories are illustrated in Fig. 1.

2 Distance-based regional analysis

Distance-based regional analysis is essentially linked to the subject of catchment classification. If a hydrologically homogeneous region, either joint or disjoint, can be identified using various classification approaches, information can be transferred from data-rich to data-poor catchments. The most apparent and straightforward way is to use geographical distance as the basis to classify similar catchments. A slightly more sophisticated approach is to apply spatial interpolation. These approaches are reviewed in Sect. 2.1 Geographical distance. Geographical neighbouring catchments do not necessarily share similar hydrological behaviour and responses. Information transfer amongst hydrologically similar catchments is considered more sensible. Catchments are classified

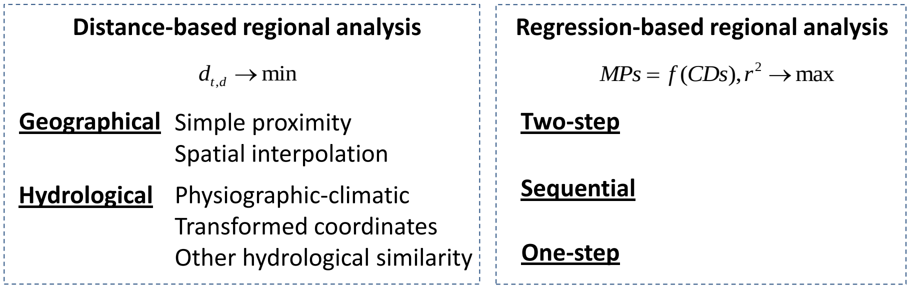

Fig. 1. The two categories of methods for regional estimation of continuous streamflow and the session structure of the paper.

based on their hydrological similarity and these methods are reviewed in Sect. 2.2 Hydrological distance.

2.1 Geographical distance

It is assumed that catchments that are close in a geographical space also behave similarly based on the premise that hydrological response is likely to vary gradually and smoothly in space and hence spatial proximity is a reasonable indicator for catchment similarity (Blöschl, 2005). Euclidean distance d is commonly used to compute the geographical distance between a pair of catchments.

$$d_{t,d} = \sqrt{(X_\mathrm{t} - X_\mathrm{d})^2 + (Y_\mathrm{t} - Y_\mathrm{d})^2} \quad (1)$$

where X_t, Y_t and X_d, Y_d are the geographical coordinates of the centroids of the target and donor catchments respectively. Target catchments here refer to poorly gauged (with some past hydrometric data), completely ungauged or pseudo-ungauged (regarded as ungauged for research purpose) catchments that require information to be transferred from donor catchments. Donor catchments are gauged catchments identified to be similar to target catchments. The entire rainfall-runoff model parameter set is transfered from the nearest catchment or a combination of a number of donor catchments to the target catchment. It assumes the differences in the set of parameters arise only from random factors (Viviroli et al., 2009).

Vandewiele and Elias (1995) use neighbouring catchments to transfer model parameters. Out of 75 catchments in Belgium, 44 % are well modelled by using neighrouring catchments. Merz and Blöschl (2004) transfer the average value of model parameters from the immediate upstream and downstream neighbouring catchments in Austria and found this approach outperforms kriging or regression method. Randrianasolo et al. (2011) use model parameters transfered from neighbouring catchments for ensemble forecast at ungauged catchments in France and show it can provide reasonably good forecasts at the target catchments. They find performance increases as the number of neighbours increases (from 1 to 20 neighbours as donors) and the best single donor is on average about 18 km away from the target. They also use neighbouring catchments as direct discharge donors for updating forecasts in addition to the use of their model parameters, but find rather poor performance.

A slightly more sophisticated procedure that makes use of parameters from neighbouring gauged catchments is to apply geo-statistical methods such as "kriging" and "inverse distance weighting" to interpolate parameter values over the geographical space (e.g. Vandewiele and Elias, 1995; Merz and Blöschl, 2004; Parajka et al., 2005; Viviroli et al., 2009). Mixed performance is reported. For example, Vandewiele and Elias (1995) found that out of the 75 Belgian catchments 72 % can be well modelled using kriging compared to 44 % using simple neighbouring catchments. But Merz and Blöschl (2004) found only tiny decrease in the model performance using kriging compared to neighbouring catchments in Austria. Using the same data sets as reported in Merz and Blöschl (2004) but an improved model version, Parajka et al. (2005) find close performance between kriging and simply neighbouring but the former is slightly better than the latter. One may look for reasons associated with the physiographic characteristics of the two populations of catchments with one located in the largely heteogeneous high alpine mountainous region and the other in low land. But the results are not directly comparable because in the two studies the adopted models are different, the temporal resolutions are monthly versus daily, and the simple neighbouring approach takes a number of close neighbours versus the immediate up/down-stream catchments. Viviroli et al. (2009) apply the kriging approach in Switzerland and report a median Nash-Sutcliffe efficientce (NSE) of 0.69 for validation. They do not compare it with regional analysis simply using neighbouring catchments. Archfield and Vogel (2010) apply kriging approach without dealing with model parameters. They interpolate correlations of pair-wise streamflow time series over the study area and select the gauged catchment with the highest correlation as the donor for the ungauged catchment. They find an improved estimation of streamflow compared to the use of the nearest neighbouring catchment. This work makes an implicit assumption that the correlation of streamflow time series represents catchments' physiographic-climatic characteristics that make up a holistic catchment response, and hence the catchments' similarity.

In most studies based on geographical distance, catchment physiographic or climatic descriptors are not taken into account because geographical distances are supposed to play a dominant role in classification of similar catchments. Merz and Blöschl (2004) find using average parameter values of the immediate upstream and downstream catchments perform the best amongst all regionalisation methods including kriging and regression methods. They conclude that *spatial proximity may be a useful surrogate for unknown controls on the runoff regime and hence the model parameters*. Sawicz et al. (2011) also find spatial proximity a clear indicator of similarity but further suggest spatial proximity may reflect similarity in other characteristics. Catchment characteristics and responses can change abruptly in space, which make spatial proximity a vague indicator. For example, McIntyre et al. (2005) find using the single nearest catchment (to define posterior likelihoods) gives the worse performance indicating UK geology often changes markedly between neighbouring catchments. Experience can also be learned from the development of regional analysis for streamflow statistics. For example, Reed et al. (1999) discuss catchment classifications based on hydrological similarities are more relevant than those based on geographical proximity. Ouarda et al. (2001) demonstrate geographical locations of catchments are not significant variables in a canonical correlation analysis and hence do not necessarily lead to hydrological similarity. Shu and Burn (2003) suggest geographical proximity cannot always be regarded as hydrological homogeneity.

It is not unexpected that spatial proximity is reported in various studies as good or poor indicators of similarity. Many studies in different regions can be carried out and a mixed outcome is anticipated. This is because we do not yet possess the knowledge of underlining reasons for catchment similarity.

2.2 Hydrological distance

A catchment is an indissoluble bond of landscape, geology, climate as well as human factors, which are generally regarded as physiographic and climatic attributes or descriptors. In practice, collection and compilation of catchment descriptors involve, to various extents, upscalling or downscalling procedures because of the *stunning degree of heterogeneity and variability in both space and time* (Blöschl and Sivapalan, 1995). The similarity concept here is considered in the space of catchment descriptors that have causative links with hydrological behaviour and make regionalisation hydrologically meaningful (Gottschalk, 1985).

2.2.1 Physiographic-climatic

The rationale of regional analysis based on hydrological similarity is that catchment physiographic and climatic characteristics can predetermine hydrological behaviour (Burn and Boorman, 1993; Oudin et al., 2010). If the donor catchment is sufficiently similar (physically) to the target catchment, the set of rainfall-runoff model parameters can be transposed (McIntyre et al., 2005). Since a number of regionalisation techniques are developed based on hydrological distances in the space of physiographic and climatic descriptors, it is necessary to reflect on the subject of hydrological similarity and catchment classification.

Many studies can be found in literature that aim at defining hydrological similarities. For example, Blöschl and Sivapalan (1995) explore similarities in association with dimensional analysis from a scalling point of view. McDonnell and Woods (2004) suggest a catchment classification scheme needs to include descriptions of fluxes, storages, and response times as explanatory variables. Wagener et al. (2007) view hydrological similarity as a joint functional response based on catchment structural and climatic characteristics and a physically meaningful classification is to map them into a functional space (see Fig. 2).

Catchment structure and hydro-climatic regimes play dominant roles in shaping hydrological responses in a natural catchment. Earlier work often takes a single feature to classify regions, e.g. isoline maps. Herbertson (1912) uses isotherm lines to classify the thermal regions of the world. It is a prototype of climatic classification leading to its development in hydrology. Budyko (1974) proposes a climatic classification based on energy balance and described the climatic condition of each area with a 3-symbol combination. The climatic dryness index defined as a ratio between average annual potential evaporation and average annual precipitation is used to classify arid regions of the world (UNESCO, 1979). Woods (2006) proposes three family indices to identify the dominant state of stored water including pore water, frozen water and open water, as the state of dominant storage impacts and affected by catchment processes and climatic conditions. The indices are more useful for catchment classification as they take into account not only climatic features but more the interaction with surface and subsurface waters. The limitations to these indices lie in the heavy data demand of soil attributes and the simplifying assumptions the indices are based on. Readers can refer to Wagener et al. (2007) for a review on more recent development of classification based on hydro-climatic regime.

With respect to catchment structural properties, Wagener et al. (2007) describe them mainly in the form of:

1. *Dimensionless number*, such as stream order (Horton, 1945; Strahler, 1957), bifurcation ratio (Horton, 1945), drainage density, hillslope Peclet number (Berne et al., 2005) and so on.

2. *Curves or distributions*, such as the hypsometric curve, first introduced by Langbein (1947) is an empirical cumulative height frequency curve for the Earth's surface or a catchment. The topographic index curve or the topographic index is conceptualized by Kirkby (1975). The index $(\alpha/\tan\beta)$ is a ratio between α – the drained

area per unit contour length and $\tan\beta$ – the slope of the ground surface at the specific location. The locations with the same index value can respond in a hydrologically similar way.).

3. *Conceptual model* defined as a simplified schematic representation of the subsurface hydrological processes. An example is the HOST (Hydrology of Soil Types) classification system (Boorman et al., 1995) which has been used to group all UK soils into 29 classes and further regionalised a baseflow index.

4. *Mathematical model* which provides a direct link between structure and response behavior. An example is the study conducted by De Felice et al. (1993) who apply a simple conceptual model to classify catchments. The model uses a variation of the Thornthwaite-Mather method which represents the catchment as two reservoirs in series. The study demonstrates one model parameter β could encompass the complex geological and morphological characteristics and differentiate catchments from low, medium to high permeability. Within each class, a surrogate value of β could be transfered to a catchment with similar geological and morphological features. The similar catchments identified by β is independent from climatic conditions.

The hydrological response of a catchment is a holistic function that integrates structural and hydro-climatic features into one signature. Wagener et al. (2007) discuss possible metrics that can best integrate similarities based on catchment structures and hydro-climatic regions to represent catchment response behaviour. They also point out similar catchment responses ought to be considered in association with spatial and temporal scales. Figure 2 illustrates the general framework of hydrological similarity based on Wagener et al. (2007).

A practical impetus behind the investigation of hydrological similarity is the need for regional flood frequency analysis (Blöschl and Sivapalan, 1995). A great amount of literature in regional streamflow statistics using physiographic-climatic distance is present. These studies are beyond the scope of this review and thus not covered here. Nevertheless, the readers are encouraged to explore related literature. As more and more spatial data and complex rainfall-runoff models are made available following the advancement in computer technology, the techniques developed in the former studies are increasingly applied to continuous streamflow simulation.

In regional studies for continuous streamflow simulation, measures of physiographic-climatic similarity are defined in slightly different ways but take the general form as follows.

$$d_{\mathrm{t,d}} = \sqrt{\sum_{i=1,I} w_i \left(\frac{X_{\mathrm{t},i} - X_{\mathrm{d},i}}{\sigma_{X_i}}\right)^2} \quad (2)$$

where $X_{\mathrm{t},i}$ and $X_{\mathrm{d},i}$ are the value of each catchment descriptor i ($i = 1, ..., I$) for the target and donor catchment respectively, w_i is the weight associated with the i catchment descriptor, and σ_{X_i} is the standard deviation of the descriptor across the entire set of catchments under study. The smaller the distance $d_{\mathrm{t,d}}$ between the target and donor catchment, the more similar they are. When a single descriptor is considered, w_i for other descriptors is set to zero. When all descriptors are considered to be equally important, w_i is set to one (e.g. Parajka et al., 2005; Kay et al., 2007; Oudin et al., 2008; Zhang and Chiew, 2009). w_i can be set to a specific value based on expert judgment (e.g. Institute of Hydrology, 1999; McIntyre et al., 2005) or optimisation (e.g. Oudin et al., 2010). The descriptor X_i can take the natural logarithm form to avoid highly skewed distribution (e.g. Institute of Hydrology, 1999; McIntyre et al., 2005; Kay et al., 2007).

Once similar catchments are identified, the entire set of model parameters calibrated on the donor catchments can be transfered from the closest donor to the target catchment (e.g. Parajka et al., 2005; Zhang and Chiew, 2009). One can also pool a number of donor catchments that have distances below a threshold value and then take a weighted average of the parameter values from the pooled catchments (e.g. Kay et al., 2007). The advantage of transferring the entire model parameter set is that it does not interfere with the integrity of model parameters as a set (see discussion by McIntyre et al., 2005; Parajka et al., 2005; Oudin et al., 2010).

Transferring a parameter set unavoidably makes two assumptions (Oudin et al., 2010): (1) the model parameter set reflects hydrological behaviour and (2) catchments classified in the space of physiographic-climatic descriptors are similar in their hydrological behaviour. The first assumption is the basis of using a rainfall-runoff model in continuous streamflow simulation. If a model does not capture the correct processes of runoff generation from rainfall over a catchment, there is no point of transferring flawed model parameters. Model reliability, as well as uncertainty, is a widely discussed topic and beyond the scope of this review. The second assumption is fundamental to the hydrological distance-based regionalisation techniques. Oudin et al. (2010) demonstrate using 893 French and 10 English catchments that similarity based on physiographic-climatic descriptors cannot necessarily be translated into hydrological similarity. McIntyre et al. (2005) also show no evidence that close physiographic-climatic distance contribute to improved simulation in ungauged catchments. More studies are needed to examine if catchments classified in the space of physiographic-climatic descriptors can truly reflect similarities in terms of hydrological behaviour and functional responses. Physically meaningful classification schemes advocated by Wagener et al. (2007) are of great importance to the improvement of regionalisation techniques.

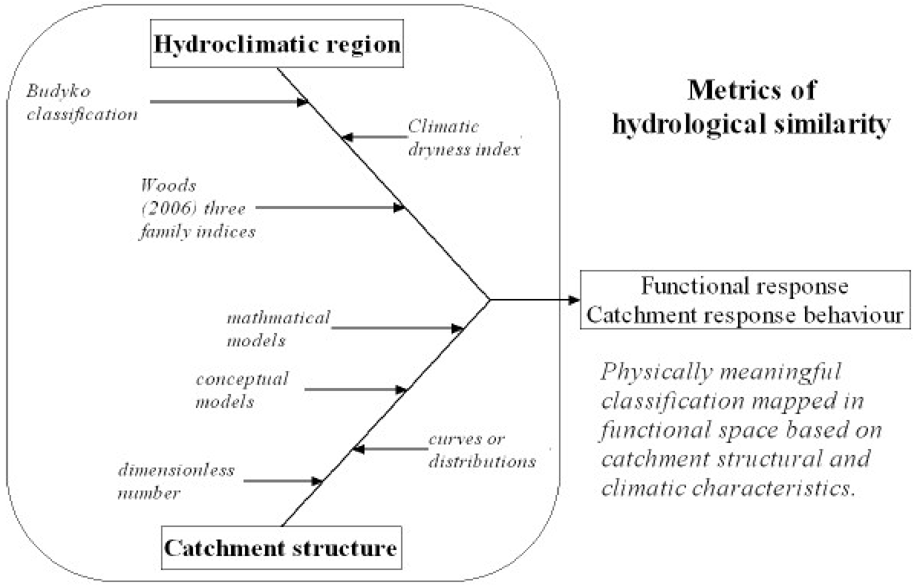

Fig. 2. The general framework of hydrological similarity and catchment classification based on Wagnener et al. (2007).

2.2.2 Transformed coordinates

A couple of valuable attempts have been made to define metrics of hydrological similarity to facilitate development of regionalisation. Methods discussed in this section measure distances or similarities between catchments in a transformed space of the physiographic-climatic descriptors.

Canonical correlation analysis (CCA) has seen a number of applications in regional statistical analysis (see Ouarda et al., 2001 for a review). CCA can be used to investigate the correlation structure between catchment descriptors and extreme streamflow (e.g. floods) or model parameters in the case of continuous streamflow simulation using a model. Readers can refer to Ouarda et al. (2001) for a full explanation of the CCA's theoretical background and its application in regional flood frequency estimation. CCA presents a typical instance where regional statistical analysis has benefited the development of continuous streamflow simulation in ungauged catchments. Hundecha et al. (2008) test an approach based on the previous work of Ouarda et al. (2001) and Hundecha and Bárdossy (2004). The relationships between catchment descriptors and model parameters are defined with a linear canonical correlation and replaced by canonical variables. A very useful property of canonical variables is that they are uncorrelated and orthogonal to each other, which makes it possible to be defined as coordinate axes. The distance between catchments can be then computed using the Euclidean metrics in the space defined by canonical coordinate axes. The spatial structure of the model parameters is considered in the canonical space using geostatistical approach. The overall performance is better than using a regression-based method reported in Hundecha and Bárdossy (2004). CCA is subject to limitations: (1) the original variables should follow normal distributions, (2) nonlinear components of these relationships are not recognised and hence not captured, (3) the solution of the linear correlation is not unique, and (4) the derived linear correlation is hard to be interpreted. A number of multivariate statistical methods can be used in a similar way to define transformed coordinate axes that are orthogonal, for example principal component analysis. But the bivariate correlation formulated by CCA makes it easy to perform metrics calculation and is therefore particularly attractive.

The distances or similarities between catchments presented in this paper thus far describe dependences or bivariate relationships between random variables. The relationship will change if the marginal distribution of the random variables change. To study the relationship or dependency without being influenced by marginal distribution of each variable, the concept of copula can be introduced to provide a similarity measure. Copula is a multivariate distribution with uniform marginal distributions, a measure describing dependency disregarding the marginals.

Samaniego et al. (2010) formally investigate three variants of a copula based similarity measure. The two random variables are streamflow time series for a pair of catchments. The first similarity measure takes into account the degree of symmetry of the empirical copula density. The second and third not only consider the degree of symmetry, but also the correlation coefficient of the two random variables. The empirical copula is estimated on the basis of streamflow because it is regarded as a holistic functional response of all the physiographic-climatic descriptors to have on a catchment. The similarity metrics are defined in a transformed space u

of catchment descriptors by using a transformation matrix **B**, which relates the m-dimensional space of the catchment descriptors X into a k-dimensional space u measured with coordinates of U. The **B** is obtained using a so called local variance reducing technique (LVR). The LVR is described in full details by Bárdossy et al. (2005) and applied in a number of regional studies (e.g. Bárdossy et al., 2005; Hundecha et al., 2008; He, 2008; Samaniego et al., 2010).

Samaniego et al. (2010) show the copula based similarity measure reduces considerably the 90 % confidence interval of the streamflow prediction and outperform the Euclidean metrics for the overall NSE. The copula based similarity measure has also been applied to regional analysis of streamflow statistics (e.g. Chowdhary and Singh, 2010). The measure seems very promising because it is able to describe the full stochastic dependence or relationship between catchments. There are a number of outstanding issues to be addressed that can potentially help to improve the method: (1) how to formally determine the dimension of the transformed space u, and (2) which copula based similarity formulation is the most robust measure.

2.3 Other similarity measures

There are a couple of studies that consider hydrological similarity without using formally defined coordinates and do not directly transpose model parameters from gauged catchments. For example, Oudin et al. (2010) uses hydrological models to measure hydrological similarity. If a number of parameter sets all lead to satisfactory model performance for a pair or group of catchments, they are considered as hydrologically similar catchments. To prove this similarity is not dependent on the model used, Oudin et al. (2010) also compare similar catchments obtained by using two different models and conclude they identify similar pools of hydrologically similar catchments for most target catchments. McIntyre et al. (2005) apply an ensemble approach to estimate streamflow time series based on a weighted average of a number of selected models and a number of donor catchments. The weights computed from each donor catchment using each selected model are used as prior and posterior likelihoods in a similar manner as the framework of the generalized likelihood uncertainty estimation (GLUE) (Beven and Binley, 1992). The prior likelihoods reflect the model's goodness-of-fit on the gauged catchments. A threshold value is set to select the satisfactory models or parameter sets. The higher the prior likelihood, the more chance the particular model or model parameter set can stand out to contribute to the weighted streamflow value. The prior likelihoods is to directly measure the suitability of a particular model or parameter set for the gauged catchments. They indirectly represent a model based similarity. The posterior likelihoods take into consideration the hydrological similarity on the basis of physiographic-climatic descriptors (as discussed in Sect. 2.2.1). This study presents an example whereby the hydrological similarity integrates the model based similarity measure and the measure based on physiographic-climatic descriptors. It is a promising approach because it eliminates or minimises influence of unsuitable or poorly calibrated models (possibly due to unreliable input data or model structure), and at the same time, it selects donor catchments in a way that they do not have physiographic-climatic characteristics that deviate too far from the target catchments.

3 Regression-based regional analysis

Another general category of regionalisation methods to estimate rainfall-runoff model parameters for continuous streamflow simulation is based on regression. The most notable early research of regionalisation using regression-based methods was probably carried out by Nash (1960) who attempted to derive empirical correlations between unit hydrographs and the characteristics of the catchment. And almost at the same time, Dalrymple (1960) reported a regionalisation procedure to obtain flood frequency curve for sites with or without gauging station records. Since then, a plethora of studies have been carried out in estimating rainfall-runoff model parameters or stream flow statistics for ungauged catchments. This section discusses three variants of regression-based regionalisation methods.

3.1 Two-step regression

The two-step regression method is the most widely used regionalisation method. In the regional study conducted by Nash (1960), two parameter values of the instantaneous unit hydrograph (Nash, 1957) were estimated for an ungauged catchment by using regression relationship obtained from 60 other gauged catchments in the UK. The parameters are expressed as linear functions of a number of topographic characteristics such as catchment area, slope and length of the main channel. It is a valuable attempt although the streamflow prediction at the ungauged catchment is rather poor. Ross (1970) and James (1972) demonstrate significant correlations between certain model parameters and catchment characteristics using the Kentucky Fortran Version of the Stanford Watershed Model IV (Crawford and Linsley, 1966). James (1972) further propose a similar linear regression-based approach to be used on an ungauged catchment, that is to relate the model parameters to measurable catchment characteristics with a regression function, but does not in his paper engage in predicting streamflow using the parameters assessed from the regressions. Dozens of studies follow this school of thought to predict streamflow in ungauged catchments using relationship found between certain model parameters and catchment descriptors (e.g. Jarboe and Haan, 1974; Heerdegen and Reich, 1974; Weeks and Ashkanasy, 1983; Waylen and Woo, 1984; Weeks and Boughton, 1987; Karlinger et al., 1988; Servat and Dezetter, 1993; Tung et al., 1997; Abdulla and Lettenmaier, 1997a,b; Kull and Feldman, 1998; Sefton and Howarth, 1998; Post et al., 1998; Post and Jakeman, 1999; Xu, 1999; Seibert, 1999; Kokkonen et al., 2003; Mwakalila, 2003; Xu, 2003; Merz and Blöschl, 2004; Wagener and Wheater, 2006; Heuvelmans et al., 2006; Young, 2006). They carry out regionalisation with two steps: (1) calibrate model parameters (MPs, hereafter) for each catchment and (2) relate MPs to catchment descriptors (CDs, hereafter). In other words, the method starts with maximising the goodness of fit between observed and simulated discharges for each individual catchment and then proceed to obtain an optimal correlation between each MP and one or a number of CDs. Multiple regression is commonly used to formulate relationship between MPs and CDs and solved by least square solutions. In the case of regional streamflow statistics, it is the statistical distribution parameters instead of MPs that are related to CDs.

The method seems effective and straightforward in estimating the MPs of ungauged catchments but relationships found between MPs and CDs are often weak and prediction in ungauged catchments achieves limited success (Fernandez et al., 2000; Hundecha and Bárdossy, 2004; Kim and Kaluarachchi, 2008). Various formulations of objective functions and a number of optimisation algorithms have been employed in an attempt to better calibrate the rainfall runoff models, unfortunately the models suffer from the same problems, namely existence of *multiple optima* and presence of *high interaction* between model parameters (Kuczera and Mroczkowski, 1998). This is the so-called "equifinality" issue discussed by Beven (1993, 1996, 2001); Beven and Freer (2001). In addition, multiple catchment characteristics may be highly correlated with each other or with some linear combination of them and reduce reliability and stability of regression coefficients (Hirsch et al., 1993; Blöschl, 2005).

3.2 Sequential regression

Sequential regression is designed to address the particular problem of poor identifiability of model parameters. The method essentially modifies the calibration procedure. Instead of calibrating all model parameters simultaneously in one go, it is executed sequentially from the most identifiable parameter to the least one. In each calibration round, different objective functions can be used to give consideration to certain aspects of hydrological response mostly represented by a specific parameter. This is reported as a multistep automatic calibration scheme in Hogue et al. (2000). The sequential order of parameters to be calibrated in each round can be based on hydrological judgment as well as the resulted response surface in the dotty plots of the objective function versus the parameter (Calver et al., 2005). Within each calibration round, the most identifiable MP is related to the selected CDs using regression functions. The parameter value takes the result from the fitted regression and is fixed in the next calibration round. The calibration and regression continue until the last parameter is calibrated and its regression function is obtained. Detailed explanation of the method and case studies can be found in (Lamb et al., 2000; Lamb and Kay, 2002, 2004; Wagener and Wheater, 2006). An outline flowchart of the sequential regression procedure can be found in Lamb and Kay (2002, p.70). Calver et al. (2005) present a modified version of this method. It adds a so-called "second pass" to repeat the same sequential procedure once again, but the order of parameters remains the same as that of the "first pass". Detailed procedure is illustrated in Calver et al. (2005, p.48).

The advantage of sequential regression is that it enhances the identifiability of the model parameter. Wagener and Wheater (2006) demonstrate the improvement in the parameter identifiability after each round of calibration, but unfortunately, the improved identifiability does not lead to stronger relationship between MPs and CDs. In general, sequential regression is reported to perform better than the two-step regression (e.g. Lamb et al., 2000; Lamb and Kay, 2002, 2004; Calver et al., 2005). Wagener and Wheater (2006) report worse performance of sequential regression compared to the two-step regression, which is likely due to the single objective function they use in the sequential calibration.

3.3 One-step/simultaneous regression

The one-step regression method was developed based on the two-step regression method described in Sect. 3.1. The method combines two steps into one and calibrates the model with all objective functions at the same time, hence it is also referred to as simultaneous regression.

Fernandez et al. (2000) present the one-step method and test it with a monthly water balance model in the southeastern region of the United States. Unlike the two-step method, the model is not calibrated independently from the catchment descriptors but with an objective function simultaneously taking into consideration the performance of the multiple regression measured with the coefficient of determination R_x^2 and the goodness-of-fit R_i^2 between predicted discharge $\hat{Q}_{\mathrm{t}}$ and observed discharge Q_t at the time step t for each catchment ($i = 1, ..., N$). The generalized reduced gradient algorithm is used to optimize $30 \times 4 = 120$ variables (30 catchments used for calibration). The regression relationships are found to be nearly perfect. These optimized relationships are tested with 3 other catchments. The results do not show any improvement from the traditional 2-step approach. The loss of model performance from calibration to validation catchments with the proposed one-step approach is almost the same as with the two-step approach. Based on these results, they suggest multivariate regression analysis is not able to uncover basic physical laws and regional studies will not advance unless the basic relationships between catchment characteristics and model parameters are formulated physically and correctly.

Hundecha and Bárdossy (2004) adopt the one-step method presented by Fernandez et al. (2000) but select a different study region, model, temporal resolution, and CDs. An aggregated objective function O_H is established to maximize the model performance in the form of the Nash-Suctliffe efficiency coefficient R_i^2 and punish the individual with the worst model performance. Drainage area, slope, shape, soil properties and land use are related to the model parameters according to their relevance to the processes of runoff generation and runoff response. Instead of calibrating the model parameters, the linear coefficients relating the model parameters and catchment descriptors are calibrated. The generalized reduced gradient algorithm is also used to find the optimal solution. In this way, the regional study can be performed in one step. The relationships established with 30 catchments are tested with 15 other catchments. Most of them obtain a Nash-Suctliffe efficiency above 0.8. With these relationships, the method is further implemented to study the impact on streamflow under three different future land use scenarios.

It is worth noting here that Fernandez et al. (2000) seek to implicitly improve R_x^2, i.e. the MP-CD relationships, while Hundecha and Bárdossy (2004) do not implicitly calibrate R_x^2 for each model parameter. The MP-CD relationships established in the latter study may be not as perfect as the former, but the improvement in predictability in the latter study is evident. The former uses CDs which require analysis of discharge data and the study is intended on formulation of the one-step approach and finding strong relationships but not necessarily its implementation in ungauged catchments. On the contrary, the CDs selected in the latter study all fall within the six most popular CDs ranked out of 15 studies listed in Table 3 with "shape" as an exception. The CDs in the latter study are selected in such a way is also because it aims to estimate impact of land use change on the ungauged catchments.

3.4 Comparison of the three methods

The three regionalisation methods use different procedures to identify optimal model parameters, relate model parameters to catchment descriptors, and account for uncertainties. Their general procedures are outlined in Fig. 3. Two-step regression methods have been widely tested in different parts of the world using various catchment descriptors, hydrological models, and regression functions. In comparison, a relatively small number of case studies can be found that use sequential regression or one-step regression. Sequential regression is reported to perform generally better than the two-step regression, as discussed in Sect. 3.2. Hundecha and Bárdossy (2004) show one-step regression produces very good performance (with goodness of fit above 0.8) using validation catchments in both calibration and validation time periods. But there is no guarantee the same method can be adopted and same good performance regained in other regions because catchments may exhibit very different behaviour. Hundecha and Bárdossy (2004) do not provide a comparative study between the two-step and one-step regression, unlike Fernandez et al. (2000) who compare the two approaches and demonstrate equivalent performance. Performance could even be worse in the case of one-step regression since parameter values may be constrained by the MP-CD relationship functions assumed a priori. It is therefore unclear if one-step regression can lead to significant improvement over two-step regression. Future studies that apply multiple methods will be very welcome to make comparison possible. And more studies in different hydro-climatic regions are needed to test the two less popular methods.

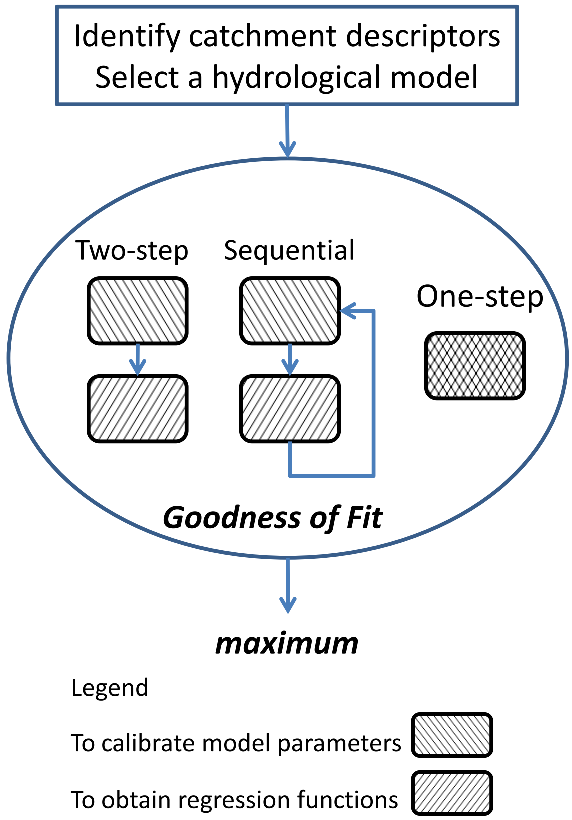

Fig. 3. General procedures of the three regression-based regionalisation methods.

Reliability of prediction in ungauged catchments seems to depend on the type and quality of catchment descriptors selected to formulate regression relationship. Riggs (1973) suggests some commonly used CDs may not prove significant in a particular regression if the range in the CD is small (e.g. all streams in a region have very similar slopes), and further notes a CD is not necessarily insignificant if it is infrequently used. In order to collate various CDs that have been used in literature, a total number of 15 regression-based regional studies (see Table 2) are randomly selected. The CDs used in these studies are summarised and listed in Table 3. One can see a large number of physiographic characteristics ranging from elevation, soil properties, land use to meteorological and climatological attributes. Out of the

Table 2. Summary of authors, year, the model, and number and location of catchments used in 15 regional studies. They are randomly selected and listed in a chronological order as they appear in literature.

No.	Authors (year)	Model	Total number of catchments, location
A	Abdulla and Lettenmaier (1997a,b)	VIC-2L	40, Arkansas-Red River basin
B	Sefton and Howarth (1998)	IHACRES	60, England and Wales
C	Post and Jakeman (1999)	IHACRES	16, Victoria, Australia
D	Xu (1999)	MWB-6;3	26, central Sweden; 24, northern Belgium
E	Seibert (1999)	HBV	18, Sweden
F	Fernandez et al. (2000)	abcd	33, USA southeast
G	Kokkonen et al. (2003)	IHACRES	13, North Carolina, USA
H	Hundecha and Bárdossy (2004)	HBV-IWS	45, Rhine basin
I	Merz and Blöschl (2004)	HBV	308, Austria
G	Wagener and Wheater (2006)	pd4-2pll	10, England southeast
K	Heuvelmans et al. (2006)	SWAT	25, Scheldt river basin, Belgium
L	Young (2006)	PD	260, UK
M	Kim and Kaluarachchi (2008)	2L WB	18, Blue Nile
N	Viviroli et al. (2009)	PREVAH	140, Switzerland
O	Samuel et al. (2011)	MAC-HBV	111, Ontario, Canada

39 descriptors, "drainage area" stands out as the most frequently used descriptor followed by land use, slope, soil classification and elevation. Apart from evident links between these catchment descriptors and hydrological response, another reason for them to be popular is due to easy access to these data. In practice, ungauged catchments often do not come with descriptors that are not easily measurable, e.g. storm intensity or annual relative humidity. It is therefore in favour of engineering practice to develop methods of prediction in ungauged catchments using easily accessible catchment descriptors. Nevertheless, it is very important to study the MP-CD relationship for those less popular CDs and obtain more insight on the governing physical processes that take place in a catchment and how they can be best described by MPs. Emphasis should be placed more on the subsurface descriptors that are particularly less well understood.

Ultimately, improvement of regression-based methods rest with improved understanding of physical processes in a catchment. Regression-based methods are not a means to an end, in other words, they are unable to uncover underlining physical laws. Wallis (1965) demonstrate it by using an example of a person calculating the weight of hollow cylinders without knowing the mathematical formula. The person might collect many cylinders, measure some of their descriptors, choose a model, and subject the resulting data to a multiple regression analysis. The person may come up with a number close to the true weight with random errors, but may also end up with a wrong weight. The example clearly shows regression-based methods can be used as a useful estimation method but the ultimate solution would be to understand the underlining functional relationship.

4 Conclusions

Obtaining reliable streamflow time series is of great importance to a wide range of applications from engineering design of hydraulic structures to restoration of ecosystem services. A hydrological model can be used to derive streamflow from rainfall over a catchment. But when there is no past streamflow observation for a catchment, the model becomes useless because its parameters cannot be calibrated against observation and hence unable to produce reliable streamflow simulation for the catchment in question. This limit is not only true for conceptual hydrological models, but also true to some extent for the current versions of physically-based models. Catchments without past streamflow observation are generally referred to as ungauged catchments. Catchments that are poorly gauged or subject to potential changes that make them virtually ungauged in the future tense are also broadly considered as ungauged catchments. To overcome the hurdle of having no observation to calibrate a hydrological model and produce reliable estimation of streamflow for ungauged catchments, a remarkably large number of studies have been devoted to find solutions.

Amid all the methods, the paper divides them into two general categories, namely distance-based and regression-based regionalisation methods for estimating continuous streamflow simulation. An intuitive and straightforward method is to "borrow" model parameter values or streamflow time series from neighbouring catchments that are situated geographically close to ungauged catchments. Many mathematically more sophisticated methods are also used to perform spatial interpolation. Geographical proximity between catchments does not necessarily mean close functional behaviour. It may be more sensible to search for similar hydrological

Table 3. CDs that have been used in 15 regression-based regional studies. "Total" refers to the total number of usage of each CD. The top six most frequently used CDs are highlighted in bold. This table needs to be read in conjunction with Table 2 for the 15 studies denoted from A to O.

	A	B	C	D	E	F	G	H	I	G	K	L	M	N	O	Total	Catchment descriptor definition
1															x	1	geographic coordinates (latitude, longitude)
2		x	x		x		x	x	x	x	x	x	x	x		11	area
3			x	x			x	x	x	x	x		x	x	x	10	slope
4										x						1	aspect
5			x					x			x					3	shape
6							x		x				x	x	x	5	elevation (catchment average, or elevation at the weir)
7			x										x			2	channel gradient
8			x													1	wetted area: percentage of the catchment adjacent to the stream channel
9		x					x							x		3	topgraphical index
10		x	x	x					x		x					5	stream frequency/drainage density
11												x				1	longest drainage path
12							x									1	mean overland flow distance to a stream
13							x									1	mean flow distance in a stream
14		x										x				2	HOST soil percentage
15						x				x		x				3	baseflow index
16						x										1	baseflow recession constant
17	x	x						x	x		x		x			6	other soil classification, e.g. sand, clay etc.
18										x						1	Index of proportion of time that soils are wet
19												x				1	regression residuals from a regression between BFIHOST and SPRHOST (see Young, 2006)
20	x															1	porosity
21	x															1	field capacity
22	x													x		2	hydraulic conductivity
23	x			x		x										3	permeability
24		x		x	x			x	x	x	x		x	x	x	10	percentage of the area covered by e.g. forests, urban land use, pastures etc.
25	x															1	average temperature
26	x															1	mean max temperature
27									x							1	average precipitation
28									x							1	mean max precipitation
29							x									1	solar radiation index
30	x															1	season interarrival time
31	x													x		2	storm intensity
32	x															1	storm depth
33	x															1	mean annual number of events
34		x														1	annual relative humidity
35										x						1	1961–1990 standard period average annual rainfall
36												x				1	fraction of months within a year in which the 35th descriptor exceeds precipitation
37										x						1	median annual maximum 2-day rainfall
38													x			1	mean annual potential evapotranspiration
39														x		1	relief energy of intermediate 80 % altitude range (see Viviroli et al., 2009)

behaviour and transfer parameter values or streaflow time series from gauged to ungauged catchments when their similarity in functional behaviour can be identified. Be it geographical or functional distance, they are all classified as distance-based methods. Another large amount of studies attempt to relate model parameters to catchment descriptors. These methods all use multiple regression approaches but differ in when they optimise model parameters and/or regression relationship. They are classified as regression-based methods.

Within each general category of methods, the paper reviews a number of variants and then makes an intra-comparison with regards to their associated problems or advantages. The majority of methods use hydrological models for streamflow simulation and transfer model parameters calibrated on donor catchments to target catchments. There are a number of methods that do not directly transfer model parameters. They make direct use of past streamflow time series at gauged donor catchments. They may not be applicable in a non-stationary context because the donor and target catchment relationship established by similarity/distance may be invalid when catchments are subject to changes.

Through discussing the category of distance-based methods, this paper touches aspects on the notion of catchment classification. Regionalisation or regional analysis is to identify a homogeneous region that can be either joint or disjoint and within which catchments have the least variance among themselves. The catchments within this region can represent each other due to their similarity. From this point of view, the notion of regionalisation is not different from that of catchment classification. But the former perhaps puts more emphasis on the application side while the latter is more about the theoretical basis and the organising principle. Catchment classification sets out an important foundation for regionalisation to move forward. To achieve a successful catchment classification, more research is needed to find proper similarity metrics that can integrate catchment physiographic-climatic descriptors and derive a physically meaningful classification. The similarity metrics do not have to be defined in the usual Euclidean space. We can possibly transfer coordinates of catchment descriptors and map them into another space using different distance measures. A number of valuable attempts discussed in Sect. 2.2.2 have been made to find a space that can better describe the stochastic dependence between catchments. Further research is needed to improve these methods and test them with catchments located in different parts of the world. The latter needs a collaborative action because the difficulty of research often lies in sharing data. This is particularly true for regionalisation work as the nature of the work requires as many catchments as possible but all with good quality data.

The notions of hydrological or functional similarity and physical similarity are often not distinguished. Catchments are assumed to be hydrologically similar when they appear to be physically similar based on one or a number of catchment descriptors. The model parameters or parameter sets are then automatically assumed transferable. The assumption of the two being equal may only be valid if the model parameters are able to represent certain catchment functional behaviour. Physically based model parameters are probably more capable of representing hydrological processes, provided that they really do capture field physics correctly. Conceptual model parameters are mostly obtained by calibration and do not necessarily have physical meanings. They are limited by a number of factors including errors in observation data, inappropriate model structures, model parameter interaction, or low identifiability of optimum model parameters. These factors are shown in regression-based studies as reasons that possibly lead to weak relationship between MPs and CDs.

A number of studies have suggested that regionalisation should not focus on relating relevant CDs to each individual MP, but on relating relevant CDs to MPs as a set because it maintains the integrity of the parameter set. When hydrological similarity is judged through the use of hydrological models, it is necessary to (1) understand why certain catchments exhibit similar behavior by sharing a large portion of behavioural MP sets for a given model, (2) investigate to what extent similarity depends on the model used and to what extent on the CDs, and (3) examine if the notion of hydrological similarity is equivalent to physical similarity.

No single method so far can be shown as the best solution to regionalisation. An in-depth understanding of hydrological processes and similarity as well as ability to model them hold the key to improvement of all regionalisation methods. This is considered as *the first step in the process of scientific analysis and synthesis* for studying the complex hydrological system (McDonnell and Woods, 2004). The efficacy of regionlisation methods can only be improved *until hydrologists formulate the basic theoretical (physical) relationships between watershed model parameters and watershed characteristics* (Fernandez et al., 2000). Regionalisation may eventually become unnecessary when a perfect physically-based hydrological model together with all its required input data becomes available. The goal may be too far distant to be achieved by many generations of scientists, but many different methods used in regionlisation may hopefully converge in the future and contribute to the advancement of hydrological sciences.

Blöschl (2005) concludes his review jokingly but perhaps points out one of the right directions. He highlights the best way to handle the issue of rainfall-runoff modelling in ungauged catchments would be to *install a stream gauge*. Indeed, limited or incomplete data can still be extremely valuable because one can use it to constrain model calibrations. Many studies have demonstrated usefulness of limited data (e.g. Vogel and Kroll, 1991; Burn and Boorman, 1993; Binley and Beven, 2003; Wagener et al., 2003; McIntyre and Wheater, 2004; Laaha and Blöschl, 2005; Rojas-Serna et al., 2006; Perrin et al., 2007; Seibert and Beven, 2009; Randrianasolo et al., 2011). On one hand, more research is needed to improve techniques in regionalisation and prediction in ungauged catchments, on the other hand, instrumentation and data assimilation technologies need to be advanced, along with other advancement in hydrological science, to reduce the number of completely ungauged catchments, improve understanding in physical processes of a catchment, and minimise predictive uncertainties.

Acknowledgements. The work was supported by a scholarship from the German Federal Ministry of Education and Research (BMBF) as well as the Tyndall Centre for Climate Change Research. The scholarship is administered by the International Bureau (IB) under the program of the International Postgraduate Studies in Water Technologies (IPSWaT). The authors gratefully acknowledge Yeshewatesfa Hundecha, Thorsten Wagener, Peter Troch, Murugesu Sivapalan and Dermit Daramanpran for their valuable comments on this manuscript.

Edited by: H. Savenije and R. Woods

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