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Regionalization for uncertainty reduction in flows in ungauged basins

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Abstract The objective of this study is to contribute to the reduction of predictive uncertainty in flows in ungauged basins through application of a regionalization method to 56 well-gauged basins in the United Kingdom. The classical approach of regionalization is adopted, where regression relationships between calibrated hydrological model (HBV) parameters and physical characteristics of the basin are established and used to estimate parameters for ungauged basins. The calibration resulted in optimum parameter sets for 48 basins of which 17 were used for the regression analysis. The results of the regression analysis showed statistically significant relationships for six out of seven parameters, and hydrologically sensible relationships for only three parameters. The validation for eight basins revealed that the regionalization model does not perform satisfactorily. The use of default parameter values seems to favour the use of regionalized parameter values. Therefore, the applicability of the classical approach of regionalization for HBV aiming at simulating all aspects of the hydrograph is questioned.

Key words calibration; HBV model; Monte Carlo analysis; multiple objective function; regionalization; uncertainty; United Kingdom; validation

INTRODUCTION

The prediction of flows for ungauged basins is the centre of attention in hydrology due to the Predictions in Ungauged Basins (PUB) initiative. One of the aims of PUB is to reduce the predictive uncertainty in modelled flows at ungauged basins. Regionalization might be one of the methods to achieve this aim. Merz & Blöschl (2004) consider two approaches for regionalization, one based on similarity of spatial proximity and the other based on similarity of basin characteristics. With respect to the second approach, a classical variant and non-classical variant exist. In the classical variant (e.g. Sefton & Howarth, 1998; Seibert, 1999; Merz & Blöschl, 2004), relations between calibrated hydrological model parameters and physical basin characteristics are established. In the non-classical variant introduced by Hundecha & Bárdossy (2004), these relations are assumed *a priori* and incorporated in to the hydrological model. Then, the parameters of the regionalization relations are calibrated. However, since satisfactory regionalization relations obtained from classical and non-classical studies are rare, the classical approach for regionalization is used here.

The objective of this study is to contribute to the reduction of predictive uncertainty in flows at ungauged basins through application of the classical regionalization method to 56 well-gauged basins in the United Kingdom. First, hydroclimatic and physiographic data are described. Next, the calibration, regionalization and validation methods are explained and, finally, results are discussed and conclusions drawn.

DATA

Hydroclimatic data

Time series of precipitation, actual temperature, dew point temperature, sunshine hours, wind speed and discharge data were used. Daily basin precipitation (mm) and daily mean discharge (m^3 s^{-1}) for 56 basins throughout England and Wales for the period 1980–1990 were used. These data originate from the Data60UK data set (Data60UK, 2006) and have undergone extensive analysis as reported in several studies (e.g. Jakeman *et al.*, 1990; Jakeman & Hornberger, 1993; Sefton & Howarth, 1998). Hourly actual temperature (°C), hourly dew point temperature (°C), sunshine hours (h d^{-1}) and hourly wind speed (mile d^{-1}) obtained at meteorological stations in England and Wales for the period 1983–1990 originating from the BADC (British Atmospheric Data Centre) database (BADC, 2006) were used. With these data, daily basin potential evapotranspiration was calculated according to the Penman-Monteith formula. This formula was recommended for general use in the United Kingdom by the UK Meteorological Office (Shaw, 1994). The basin mean temperature, dew point temperature and wind speed were calculated based on the two nearest meteorological stations with respect to the discharge observation station. The basin mean sunshine hours is based only on the nearest meteorological station.

Physiographic data

Elevation, basin size, land use and geological data for the 56 basins originating from the Catchment Spatial Information (CSI) pages of the National River Flow Archive (CSI, 2006) were used. The elevation data are derived from the Centre for Ecology and Hydrology (CEH) Wallingford Integrated Hydrological Digital Terrain Model (IHDTM), and have a horizontal resolution of 50 m and a vertical resolution of 0.1 m. The minimum and maximum average basin elevation are respectively 25 m a.m.s.l. and 431 m a.m.s.l. The smallest and largest basins have a surface area of respectively 25 km^2 and 1480 km^2. The land use data are derived from the Land Cover Map 2000 which is part of the Countryside Survey 2000. Twenty-seven land-use categories are distinguished which are grouped in seven broader classes. The most dominating land-use class in all basins is grassland (43% of surface area), followed by arable land (31%) and woodland (13%). Geological maps are derived from the 1:625 000 British Geological Survey (BGS) data sets. The CSI pages present a subdivision into six classes emphasizing the influence of hydrogeology on river flow behaviour. These classes vary between impermeable (e.g. Wales, southwest England) and permeable bedrock (e.g. south England, southeast England, west England). More information about the data can be found in Deckers (2006).

METHODOLOGY

Calibration of HBV model

The conceptual hydrological HBV model (Lindström *et al.*, 1997), lumped for each of the 56 basins in England and Wales with a daily time step, was used to simulate the continuous discharge regime. Considerations in favour of HBV can be found in Booij (2005). Moreover, HBV has been used in several regionalization studies (e.g. Seibert, 1999; Hundecha & Bárdossy, 2004; Merz & Blöschl, 2004) and demonstrated to be a suitable model. HBV describes the river basin hydrology conceptually through six routines (i.e. precipitation, soil moisture, quick flow, baseflow, transformation function, routing) and simulates the river discharge as a function of precipitation, temperature and potential evapotranspiration. Calibration of HBV for 48 basins was done using Monte Carlo simulation (MCS). The MCS is a technique where, through numerous model simulations with randomly generated model parameter sets, an optimum value for the objective function(s) is sought. Harlin & Kung (1992) and Seibert (1999) have applied MCS to HBV previously. The most important issues when calibrating using MCS are the selection of calibration parameters (other parameters have default values), their probability distributions for MCS and the objective function(s).

To derive statistically and hydrologically significant relationships between model parameters and physical basin characteristics, it is important to determine the most sensible model parameters to incorporate in to the calibration, and hence the regionalization. This determination is based on former HBV studies (Harlin & Kung, 1992; Seibert, 1999; Lidén & Harlin, 2000; Merz & Blöschl, 2004) and resulted in seven calibration parameters: three in the soil moisture routine, three in the quick flow routine and one in the base flow routine.

The uniform probability distribution is used in the MCS, because no information regarding model performance for certain parameter values is available. The ranges for these uniform distributions are determined based on the minimum and maximum values of ranges for each parameter used in nine former HBV studies (see Deckers, 2006) taking into account physical and mathematical constraints and prior knowledge about model behaviour. The ranges have been slightly adjusted according to the first MCS experiments, in particular for two parameters, i.e. the soil moisture and quick flow routines (see Deckers, 2006).

The objective function(s) measure(s) the level of agreement between the observed natural system output and the model output, i.e. the observed and modelled discharge. Since the objective of the study is to model the continuous discharge regime, the single objective functions selected should consider different aspects of the hydrograph. Following Madsen (2000), four objectives are important: a good agreement between the average observed and modelled basin discharge volume, a good overall agreement of the observed and modelled hydrographs, a good agreement between observed and modelled high flows and a good agreement between observed and modelled low flows. For each objective, a single objective function was selected, respectively: the relative volume error (RVE), Nash-Sutcliffe coefficient (NS) (Nash & Sutcliffe, 1970), Nash-Sutcliffe coefficient for high flow (Nash-Sutcliffe coefficient for 7-day flows above 5%-exceedence flow) (NSH), and Nash-Sutcliffe coefficient for low flow (Nash-

Sutcliffe coefficient for 51-day flows below 90%-exceedence discharge) (NSL). A warming-up period for the HBV model of eight months was used and thus the single objective functions were calculated from the start of the hydrological year in the UK (1 September) 1983 until 31 December 1990 (see Data section). Next, these single objective functions are integrated into one multiple objective function to which each single objective function contributes equally, as in the approach of, for example, Seibert (1997). This is done by first scaling each single objective function using its best value (out of 10 000 MCS runs) and its 1000th best value; second determining for each run the minimum of four scaled values; and finally selecting the optimum parameter set corresponding to the maximum of these 10 000 minimum scaled values. In this way, optimal parameter sets for 48 basins were determined.

Determination of regionalization model

The regionalization model comprises all relations between calibrated model parameters and physical catchment characteristics implemented in the HBV model. Three issues are of importance: the selection of calibrated basins for the regionalization relations, the selection of physical basin characteristics and the approach for establishing relationships between calibrated parameters and characteristics.

The calibrated basins to be included in the regionalization relationships were selected based on the non-scaled values of two single objective functions (frequently used in the literature): both a relative volume error ranging from –5% to 5% and a Nash-Sutcliffe coefficient above 0.75. The physical basin characteristics were selected based on previous research on regionalization using HBV (Seibert, 1999; Hundecha & Bárdossy, 2004; Merz & Blöschl, 2004), and using another model (IHACRES) for basins in England and Wales (Sefton & Howarth, 1998) and the availability of data on these characteristics for the UK basins (see Data section). This resulted in the selection of 14 characteristics: basin area, average elevation, hypsometric integral, basin shape, five land-use classes, four classes for bedrock permeability and average annual precipitation. Relations between calibrated parameters and physical basin characteristics were established using single and multiple linear regression analysis. In the single regression analysis, correlation analysis was performed first to determine significant statistical relations between parameters and characteristics. Second, the significant relations were hydrologically interpreted based on previous research and the authors' insight. Third, the relations were visually interpreted to assess whether any transformations would lead to stronger and significant relationships. In the multiple regression analysis, multiple characteristics were used to estimate model parameters. For pragmatic reasons, this is done by the forward entry method, in which the significant simple relations are optimized by adding other characteristics, and by the backward removal method, in which the initial relations incorporating all characteristics for each parameter are reduced stepwise to a significant multiple regression relation. Finally, for each parameter one simple or one multiple regression relation was selected based on statistical and hydrological interpretation together comprising the regionalization model.

Validation of regionalization model

The proxy basin test according to Klemeš (1986) was used to validate the regionalization model. This test uses data from one set of basins to calibrate the model (here 48 basins) and data from another set of basins to validate the model (here eight basins). Thus, the model parameters for these eight basins, regarded as ungauged, are estimated using the established regionalization model. Two issues need to be addressed: the selection of validation basins and the method of assessing the validation.

The eight validation basins were selected with as much hydrological and physiographic diversity as possible enabling a robust validation. The selection was based on four physical basin characteristics: basin area, hypsometric integral, bedrock permeability and average annual precipitation. The performance of the validation basins was assessed using the same four single objective functions as in the calibration. This was done for each validation basin with regionalized HBV parameter values, default parameter values (from SMHI, 1997 and several other studies) and optimized parameter values using the same methodology as for the calibration. In this way, to what extent model performance for ungauged basins with regionalized parameter values differs from model performance for ungauged basins with default parameter values and with optimized parameter values, was verified.

RESULTS AND DISCUSSION

Calibration

Seventeen basins (out of 48) satisfied the two conditions for inclusion in the regionalization relations (see Fig. 1). Corresponding non-scaled values of the four single objective functions for the optimum parameter sets are shown in Table 1. Notably, for NSH and NSL, negative values were generated. This is because the intention of the regionalization is to derive a robust regionalization model (i.e. simulating all aspects of the hydrograph) and therefore there is a trade-off between different criteria. It seems that the HBV model has most difficulty with simulating low flow behaviour for these UK basins.

Thirty-one basins did not satisfy both conditions, although four of these basins still satisfy the condition with respect to NS and only slightly exceed the condition for RVE. Considering the physical basin characteristics of these non-satisfying basins, it is found that all dry basins (average annual precipitation <800 mm) except one are included (18 basins out of 48). Also basins with a large portion (>30%) of the land use type "Mountain" are included in the group of non-satisfying basins. All these basins are situated in the northern part of England and in general have a low average annual precipitation.

Regionalization model

Statistically significant regionalization relations for all but one parameter (in the base flow routine) have been derived. Multiple regression relations have been obtained for

Fig. 1 Selected and non-selected basins for regionalization relations and validation basins.

four parameters: the maximum soil moisture storage (related to land-use class "arable" and bedrock permeability class "high"), the parameter determining the relative contribution of runoff from rain or snowmelt (land-use classes "arable" and "urban"), the parameter determining the nonlinearity of the quick flow routine (elevation, hypsometric integral and bedrock permeability class "very low") and the recession coefficient of the quick flow routine (elevation, hypsometric integral and land-use class "urban"). Simple linear regression relationships have been obtained for two parameters: the threshold value for soil moisture storage above which potential evapotranspiration occurs (average annual precipitation) and the maximum percolation to the baseflow routine (hypsometric integral).

However, three of these relations (for the first, third and fifth parameters mentioned) are still questionable on the basis of hydrological interpretation. Furthermore, different relations to those described in the literature have been found and *vice versa*, several relationships from the literature could not be confirmed. This may largely be attributed to the differences in geography and data availability between the different studies.

Table 1 Non-scaled values of four single objective functions for optimum parameter sets for 17 selected calibration basins for regionalization (see Fig. 1).

Basin	RVE (%)	NS (-)	NSH (-)	NSL (-)
27035	–1.096	0.817	–0.099	–1.858
33019	1.537	0.753	0.380	–5.853
41022	0.160	0.763	0.725	–3.644
43006	–1.300	0.796	0.718	–19.723
45005	–0.474	0.783	0.531	–73.591
48003	–0.754	0.865	0.368	–3.266
48010	–1.328	0.940	0.569	–3.602
50001	–0.401	0.813	–2.240	–1.134
52010	–4.138	0.777	0.600	–12.929
53009	–4.019	0.876	0.672	–12.380
54016	–1.914	0.790	0.362	–1.791
54029	–1.534	0.816	0.544	–0.657
55013	0.989	0.835	0.627	–3.460
55014	–0.514	0.887	0.653	–1.509
57010	0.656	0.878	0.162	0.326
60006	–2.105	0.849	0.612	0.633
66011	–4.197	0.795	–0.009	–0.038

RVE: relative volume error; NS: Nash-Sutcliffe coefficient; NSH: Nash-Sutcliffe coefficient for high flow; NSL: Nash-Sutcliffe coefficient for low flow.

Table 2 Non-scaled values of relative volume error (RVE) and Nash-Sutcliffe coefficient (NS) for optimum, regionalized and default parameter sets for eight validation basins.

Basin	RVE (%)			NS (-)		
	Optimized	Regionalized	Default	Optimized	Regionalized	Default
27034	–0.307	–1.436	1.045	0.747	0.553	0.622
27056	2.990	–12.294	12.079	–0.011	0.081	–0.735
31010	–4.875	–2.643	3.227	0.745	0.611	0.718
38029	0.056	112.121	119.356	0.646	–0.042	0.254
42008	–0.493	85.766	85.657	0.469	–19.883	–36.590
47008	–1.863	–1.465	6.943	0.845	0.832	0.844
53013	–7.900	–6.309	–6.348	0.716	0.702	0.787
60010	11.118	21.336	22.107	0.759	0.448	–0.464

Validation

The resulting non-scaled values of RVE and NS for optimum, regionalized and default parameter sets for the eight validation basins (see Fig. 1) are given in Table 2. The Table shows that in general the regionalization model does not perform satisfactorily. Regionalized RVE values are much larger than optimized RVE values for four basins, while these values are comparable for the other four basins. Default RVE values are similar to the regionalized RVE values, where a significant improvement of regionalized RVE values with respect to default values would have been expected. The situation is worse for NS values, where default values are higher for five out of eight basins. Moreover, regionalized NS values comparable to optimized values have been found for only two basins. The other single objective functions, NSH and NSL, show similar results (not shown here).

These results are not surprising given the conceptual nature of the hydrological model. Over-parameterization, input errors and a lack of systematic links between parameter precision and model efficiency complicating the calibration (Andréassian *et al.*, 2003), but also difficulties in interpreting the physical meaning of parameters and the selection of physical basin characteristics, complicate regionalization of these conceptual type of models. Moreover, Merz & Blöschl (2004) found that regionalization methods based on similarity of spatial proximity and kriging performed better than those based on physical basin characteristics.

CONCLUSIONS

The validation of a regionalization model for model parameter estimation at ungauged basins revealed that the regionalization model does not perform satisfactorily. Differences between the regionalization and optimized model are considerable for most basins. Moreover, it can be concluded that using default parameter values seems to favour using regionalized parameter values, because the default model performed better than the regionalized model for 19 out of 32 single objective functions. Therefore, the applicability of the classical approach of regionalization for HBV aiming at simulating all aspects of the hydrograph is questioned.

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