Flow simulation in an ungauged basin: an alternative approach to parameterization of a conceptual model using regional data

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Abstract An alternative approach to parameterization of the conceptual Soil Moisture Accounting and Routing (SMAR) model for continuous simulation of flow in an ungauged basin, using daily discharge data from neighbouring gauged catchments, is presented. The methods are suited for situations where adequate data on soil, geology, land use, etc., which are required for relating model parameters to catchment-specific hydrometeorological and physiographical characteristics, are not available. Four methods, namely: regional averaging of data, regional pooling of data, transposition of data, and averaging the parameters of the model calibrated for different gauged catchments, are applied to a group of 12 catchments in France. The concept of a pseudo-ungauged basin is used whereby each catchment is first considered as ungauged for the purpose of flow estimation, and only subsequently considered as gauged to evaluate the performance of the flow estimation procedures. Performance evaluation using the Nash-Sutcliffe efficiency index shows that pooling of data is the best in this approach.

Key words conceptual model; flow simulation; rainfall–runoff; regional analysis; ungauged basin

INTRODUCTION AND OBJECTIVE

Parameters of a conceptual model, when calibrated for a catchment, are generally regarded as a potential source of information about the physiographic and hydrometeorological characteristics of that catchment. Explicit relations between the descriptors of relevant features of the catchment and perceptibly predominant processes of the hydrometorological systems on one hand, and the calibrated values of parameters on the other, are often difficult to prescribe. Yet efforts are made to link the parameters of the model with some descriptors of catchment characteristics and hydrometeorological behaviour using physically plausible and usually empirical relations. This assumed capability of producing meaningful relationships for transferring information from the gauged to the ungauged basin is often considered a prospective tool for application in ungauged basins for rainfall–runoff simulation. However, in many situations, particularly where an ungauged catchment is located in the remote headwater region of a river, adequate and reliable data about soil, geology, land use, land cover, etc., may not be available. Although important topographical and hydrometeorological data can generally be obtained with some effort, lack of complete data sets representative of all major hydrological processes, and consequent difficulty in relating, empirically or otherwise, the parameters of a conceptual model to the catchment-characteristics greatly limit the application of the conceptual model for such purposes. In such situations, however, it may not be difficult to collect hydrometeorological data from a number of gauged catchments from a homogeneous region to which the ungauged catchment under study may be considered to belong. In this context, the term "region" may not be restricted to geographical proximity. Judging on the nature of the response behaviour to rainfall inputs, and broad hydrometeorological conditions, contiguous or "local" catchments may also be included in the "region". An approach of regionalization for evaluation of parameter values of the conceptual model for subsequent use in ungauged catchments in such cases may be useful. Three methods involving regionalization of discharge data of the gauged catchments, and one method in which parameters calibrated for each of the gauged catchments are combined are presented in this study. The physically-inspired lumped conceptual Soil Moisture Accounting and Routing (SMAR) model has been used for transferring the values of the parameters from gauged basins to the ungauged basin for this purpose.

Seven years of continuous daily hydrometeorological data from 12 French catchments were generously provided by Météo France and the Direction de l'Eau, through Dr Vazken Andréassian, of Cemagref, Paris, for application in the MOPEX (Model Parameter Estimation Experiment) research project, and made available to the present authors for their contribution to the 2004 MOPEX Workshop held in Paris. The Nash-Sutcliffe efficiency index (R^2) is used for assessing the performance of the SMAR model. Results are presented, and conclusions are drawn on the efficacy of the procedure.

METHODOLOGY AND REGIONALIZATION STRATEGIES

Data gaps in discharge series of six catchments in the sub-group are first filled synthetically by using rainfall, evaporation and available discharge records with the SMAR model in an iterative scheme. With the starting values of –9.99 for the missing data, the model is calibrated, and the iterations continued until the model performance in two successive iterations converged, the discharge data used for the gaps in each iteration being the corresponding estimates obtained in the previous iteration.

For assessing relative performance of the methods in the regionalization approach, each of the 12 gauged catchments considered in the region is used initially in turn as if it was ungauged, but subsequently, after simulation of its flows from the regional analysis, as gauged (using its measured flow data) for the purpose of evaluating the simulation efficiency of the procedure of flow simulation in an ungauged catchment in the region. The catchment, thus considered, is called "pseudo-ungauged" in this study.

With the underlying assumption that regionalization reflects the general characteristics of the region, which are also representative of the ungauged basin in the region, four regionalization methods are applied for flow estimation in pseudo-ungauged catchments. The methods are described below.

Regional averaging of data

In this method, the naïve "no-model" discharge estimate of a pseudo-ungauged (equally applicable to ungauged) catchment is obtained as the average of the synchronous discharges of *N*–1 number of gauged catchments excluding the pseudo-ungauged catchment in the selected region comprising *N* catchments. The average discharge series, thus generated, is used for rainfall–runoff simulation by calibration of the SMAR model. The rainfall and the evaporation data series, as required by a model, are those observed for the pseudo-ungauged catchment, i.e. it is assumed that rainfall and evaporation data are available for the pseudo-ungauged catchment and ultimately for any ungauged catchment in the region.

Regional pooling of data

In this method, the observed hydrological data series are combined by putting the *m* years of data from all gauged catchments (*N*–1 in a group of *N*) in a region, in series, end to end, and appending the data of the pseudo-ungauged (*N*th) catchment as the last one, thereby making $N \times m$ years of data in all. Hydrological models are then calibrated by maximizing the combined R^2 value over the calibration period using the corresponding combined (end to end) input to the *N*–1 gauged catchments in a region as inputs to the "regional model" to simulate flows in this calibration period. Finally, considering the entire data set of the *N*th pseudo-ungauged catchment as that belonging to the "validation" period of the "regional model", and using the rainfall and evaporation inputs to that catchment as inputs to the model, the discharge series for the pseudo-ungauged catchment is estimated.

Transposition of data

This "nearest neighbour" approach is used when very few catchments in a homogeneous region in the neighbourhood of an ungauged catchment are gauged. The flow data series of a gauged catchment measured in volume of flow per unit time, i.e. $m^3 s^{-1}$, are scaled up or down in the proportion of catchment areas depending on whether the ungauged (pseudo-ungauged in this study) catchment is larger or smaller in area than the gauged catchment considered. Noting that for the catchments used in the present study the rainfall values within each subgroup are similar, the mean annual rainfall data of the gauged and the ungauged catchments are not used for additional scaling. By scaling of flow rates from the gauged catchments by area, it is thus assumed that for all catchments in a homogeneous region, the flow depth over the catchment during any given time interval is uniform. Taking the rainfall and the evaporation data series as those observed for the ungauged catchment, and the flow data series as that obtained by scaling of the data series of the nearest-neighbour gauged catchment, i.e. of the "index basin", the SMAR model is calibrated. For validation, the output of the model is compared with the corresponding measured discharge of the pseudo-ungauged catchment.

Regional averaging of parameters

In this method, unlike the previous three, the SMAR model is first applied to *N*–1 gauged catchments individually in a group of *N* catchments in the region obtaining the best possible fit for each catchment. The weighted average of *N*–1 values of each parameter from the *N*–1 parameter sets is obtained. The weights used in this study are based on the R^2 efficiency values, which reflect the degree of fit of the model. These weighted-average parameters are then applied, without further calibration of the SMAR model, to the *N*th catchment which is considered pseudo-ungauged, and the simulated discharge is compared with the discharge observed at the pseudo-ungauged catchment.

For simplicity, despite its shortcomings (Kachroo & Natale, 1992), only the dimensionless efficiency index R^2 (Nash & Sutcliffe, 1970) is used in this study for judging the relative performance of the SMAR model while using different methods of regionalization. Whereas $R^2 = 100\%$ would denote an ideal or "perfect" fit, it is generally agreed that $R^2 > 90\%$ is indicative of a very good model fit, while that in the range of 80–90% is a fairly good fit, and a range of 60–80% is unsatisfactory. For consistency, a "warm-up" period corresponding to first year's data is not considered for performance evaluation in calibration as well as in validation in all four methods.

ASSESSMENT OF REGIONAL HOMOGENIETY

Assessment of regional homogeneity is very important for reducing the uncertainty of estimation of flow in an ungauged catchment by regional analysis. In the group of 12 catchments, the three in the northwest are in the humid seaboard climatic zone, three in the southeast are in the Mediterranean zone, one in the northeast is in the semi-continental zone, and the remaining five are characterized by an intermediate climatic zone. A1522020 in the east is the wettest and H3613020 is the driest. The southeastern catchments, namely, V6035010, Y3514020 and Y5615030 have significant evaporation, with evaporation exceeding rainfall for almost 80% of the time. The northwestern catchments, namely, J2034010, J3024010 and J4124420 constitute a hydrometeorologically homogeneous region with very little variability in hydrometeorological data values. The contributing catchment at station K0744010 is contained within that of station K0753210, both stations being located on the same river. These two catchments are therefore considered as being hydrometeorologically homogenous for the purpose of this study.

Topographically, the mean altitude, the altitude at the highest point, and the altitude at the outlet of the three catchments in the west are of the same order of magnitude, whereas Y3514020 in the sub-group of three catchments in the southeast is located at a much lower altitude in comparison with V6035010 and Y5615030 in that sub-group. A1522020 is located at a significantly high altitude in the northeast France. Among the three catchments in the central region, H5723011 and H3613020 are located at nearly the same altitude, whereas H2001020 is at a higher altitude.

Characteristics of the hydrological data of all 12 catchments are presented in Table 1. It is seen from the table that the rainfall in three southeastern catchments, namely, V6035010, Y3514020 and Y5615030, exceeds the evaporation for only about 15–20% of the time. Although conscious that just seven years of data is hardly sufficient to adequately characterise the rainfall–runoff process in these drier catchments, this number was adopted for uniformity in application, the same number being used in the analysis for consistency with the lengths of data available for the other catchments in

Table 1 Characteristics of hydrological data (1 August 1995–31 July 2002) 2557 data values.

Station code no.	% days R>E	$R_{mean} - Q_{mean}$ (mm day^{-1})	$\frac{R_{mean} - Q_{mean}}{E_{mean}}$	$\frac{E_{mean}}{R_{mean}}$	$R_{mean} - E_{mean}$ (mm day^{-1})
J2034010	37.3	1.74	0.90	0.74	0.69
J3024010	38.7	1.33	0.71	0.68	0.90
J4124420	38.1	1.95	0.99	0.58	1.41
A1522020	40.0	2.52	1.25	0.44	2.55
H5723011	30.7	1.54	0.75	0.94	0.14
H3613020	31.6	1.87	0.93	0.91	0.20
H2001020	37.0	1.18	0.58	0.57	1.53
K0744010	34.1	1.66	0.83	0.74	0.69
K0753210	34.6	1.56	0.78	0.72	0.78
V6035010	20.1	2.07	0.70	1.02	–0.06
Y3514020	15.4	1.61	0.51	1.37	–0.86
Y5615030	17.1	1.59	0.52	0.97	0.10

the sample. It is also observed that the ratio of mean values of evaporation to rainfall is significantly greater than unity (at 1.37) for the Y3514020 catchment in the southeast, very close to unity for the two neighbouring catchments, i.e. V6035010 and Y5615030, and less than unity for the remaining nine catchments. These statistics, while indicating higher evaporation levels in the three catchments in the south-east of the country, also suggest that the catchment Y3514020 is an outlier within the group of 12 catchments. As a further indication of the heterogeneity effect of Y3514020, the mean evaporation for this catchment is seen to be higher than the mean rainfall by 0.86 mm day^{-1}, whereas it is either less than or very near to the mean rainfall in the case of the other eleven catchments. A comparison of the values in Table 1 of [(R_{mean} – Q_{mean})/E_{mean}], i.e. the ratio of the difference between the mean values of rainfall and discharge to the corresponding value of evaporation, shows that, for catchment A1522020, this ratio is significantly greater than unity (at 1.25) whereas it is less than unity for the other 11 catchments. This suggests that, in the transformation of rainfall to precipitation, quite apart from evapotranspiration losses, there is substantial unaccounted-for loss in this catchment, so that the hydrological system, represented by the observed rainfall, evaporation, and discharge data, is apparently non-conservative.

On estimation of regionally averaged “no-model” discharge for each pseudo-ungauged catchment for regional analysis, it is observed that the ratio of the mean regionally averaged discharge to the mean observed discharge for H3613020 is very high (3.79) followed by H5723011 (1.99), Y3514020 (1.77) and V6035010 (1.51), whereas for other catchments it is near to 1. This shows that in each of these four catchments, actual discharge production is much less than the regionally averaged discharge, and there may have been some component of rainfall which is not accounted for in the water-balance expression dependent on the observed data series. In the light of the above comments, the six catchments namely, A1522020, H3613020, H5723011, Y3514020, Y5615030 and V6035010 are considered heterogeneous in the group of 12 catchments.

Although initial analyses were conducted using all 12 catchments without considering regional heterogeneity, in the light of the observations regarding homogeneity presented above, the catchments A1522020, H3613020, H5723011, V6035010, Y3514020 and Y5615030 were excluded from the subsequent analyses having the objective of the parameterization of the SMAR model variant applicable to conservative systems. Thus the remaining six catchments: J2034010, J3024010, J4124420, H2001020, K0753210 and K0744010, having discarded the six apparently heterogeneous catchments, as indicated above, were used only for exploratory tests to assess the effect of homogeneity, as reflected in the sub-group within the whole sample of 12 catchments, on the overall performance of the chosen methods.

Clearly, it would be desirable from the perspective of drawing a generalized conclusion on the performance of the regional methods tested in this study to include more catchments in the whole sample and hence in the sub-group. However, for the purposes of this heuristic study, the number used was deemed sufficient and was also used to demonstrate the applicability of the methods, their relative efficiencies, and the importance of homogeneity in selection of catchments for the simulation of flow in the case of ungauged basins.

MODEL DESCRIPTION

Whereas the standard form of the model, generally indicated by SMARG and referred in this study by SMAR, was designed for conservative systems, modifications were incorporated in its structure to make it applicable to both conservative and "apparently non-conservative" systems. These variants are named SMAR-NC1 and SMAR-NC2, where "NC" denotes "non-conservative". Detailed description of the structure of the model, which is not included in this paper for brevity, may be found in Kachroo (1992) for the original version of SMAR, Goswami *et al.* (2002) for SMARG, and Goswami & O'Connor (2005) for SMAR-NC1 and SMAR-NC2.

Briefly, the SMAR model is a parsimonious nine-parameter lumped quasi-physical conceptual rainfall–evaporation–runoff model, with distinct water-balance and routing components. Using a number of empirical and intuitively assumed relations which are considered to be at least physically plausible, the nonlinear water balance (i.e. soil moisture accounting) component ensures satisfaction of the continuity equation over each time-step, i.e. it preserves the balance between the rainfall, the evaporation, the generated runoff, and the changes in the various elements (layers) of soil moisture storage. Five parameters, namely, Z (moisture holding capacity of soil layers), T (evapotranspiration conversion factor), H (fast response separation factor), Y (infiltration excess separation term), and C (factor for soil moisture depletion by evapotranspiration), control the overall operation of the water-budget component of the SMAR model. The four parameters G (saturation excess separation factor), N (shape factor of the Nash cascade model for surface water routing), NK (lag of the Nash cascade model) and K_g (linear reservoir constant for groundwater routing) control the operation of the routing component.

RESULTS AND DISCUSSION

A summary of the result of application of the SMAR model using different regionalization methods, first considering all 12 catchments and subsequently considering the sub-group of six catchments, are given in Tables 2 and 3. These tables also show the "no model" efficiencies, which correspond to the discharge series generated for a pseudo-ungauged catchment by averaging the discharges of all gauged catchments (except the pseudo-ungauged) in the region. The efficiency of the model, when applied to the actual observed discharge data of the pseudo-ungauged basin, considering this basin as gauged, is given for comparison. It is observed from Table 2 that, in comparison with the method of regional averaging of data, the regional pooling method performs significantly better in calibration and in 10 out of 12 catchments in validation. For the sub-group of six catchments, the pattern is similar, the R^2 efficiency in this case being significantly better in validation in five out of six catchments. The R^2 efficiency in validation, which really reflects the ability of the model to perform in an ungauged catchment, has a median value of 70.21% and 70.65% for all 12 catchments and for the sub-group of six catchments, respectively, which is reasonably good for an ungauged catchment. The improvement in performance in this method is attributed to the use of catchment-specific data series from each catchment in a group without

Table 2 R^2 efficiency values (%) by different regionalization methods considering all 12 catchments.

Catchment (station code) and area (km^2)	H2001020 (98)		J2034010 (125)		J3024010 (43)		J4124420 (32.1)		K0744010 (181)		K0753210 (371)	
	Calib.	Verif.	Calib.	Verif.	Calib.	Verif.	Calib.	Verif.	Calib.	Verif.	Calib.	Verif.
Regional averaging of data	68.92	17.89	60.01	63.81	51.33	65.68	55.80	66.15	62.01	64.97	61.86	67.82
Regional pooling of data	74.45	72.41	74.60	68.21	73.35	73.21	75.51	55.08	74.65	70.57	74.90	66.76
Regional averaging of parameters	---	67.86	---	49.75	---	73.57	---	45.97	---	72.96	---	72.30
"No model"	---	10.03	---	23.56	---	34.33	---	39.63	---	37.16	---	44.01
Best fit with actual observed discharge data of the pseudo-ungauged basin	---	73.42	---	83.07	---	83.43	---	87.69	---	75.76	---	75.09
Catchment and area (km^2)	A1522020 (68.1)		H3613020 (252)		H5723011 (104)		V6035010 (150)		Y3514020 (291)		Y5615030 (279)	
	Calib.	Verif.	Calib.	Verif.	Calib.	Verif.	Calib.	Verif.	Calib.	Verif.	Calib.	Verif.
Regional averaging of data	50.78	21.72	58.74	–1722	57.57	26.89	42.48	42.68	6.18	26.42	10.79	15.11
Regional pooling of data	74.58	74.42	75.01	54.57	73.77	64.82	74.91	69.85	74.31	82.37	72.17	72.68
Regional averaging of parameters	---	68.38	---	–685.31	---	54.43	---	72.15	---	68.88	---	78.34
"No model"	---	15.65	---	–2766	---	7.84	---	15.62	---	–110	---	11.89
Best fit with actual observed discharge data of the pseudo-ungauged basin	---	78.07	---	–78.23	---	68.06	---	77.50	---	79.14	---	89.30

Calib: efficiency in calibration with regionally derived data, Verif: efficiency (in verification, wherever applicable) when used for pseudo-ungauged basin

Table 3 R^2 efficiency values (%) by different regionalization methods considering six catchments.

Catchment (station code) and area (km^2)	H2001020 (98)		J2034010 (125)		J3024010 (43)		J4124420 (32.1)		K0744010 (181)		K0753210 (371)	
	Calib.	Verif.	Calib.	Verif.	Calib.	Verif.	Calib.	Verif.	Calib.	Verif.	Calib.	Verif.
Regional averaging of data	55.42	37.71	71.84	31.84	61.47	74.85	43.54	84.13	59.25	59.52	60.02	65.28
Regional pooling of data	74.45	65.69	72.05	75.04	71.58	77.75	73.55	58.26	72.09	71.42	72.61	69.87
Transposition												
Index basin												
J2034010	---	---	---	---	82.97	54.08	75.28	56.68	---	---	---	---
J3024010	---	---	76.22	43.12	---	---	76.78	82.53	---	---	---	---
J4124420	---	---	77.17	32.90	84.09	76.76	---	---	---	---	---	---
K0744010	---	---	---	---	---	---	---	---	---	---	55.90	35.75
K0753210	---	---	---	---	---	---	---	---	42.04	58.52	---	---
Regional averaging of parameters	---	63.37	---	60.00	---	75.75	---	59.39	---	69.34	---	69.29
"No model"	---	19.42	---	-9.75	---	39.90	---	44.20	---	36.00	---	50.47
Best fit with actual observed discharge data of the pseudo-ungauged basin	---	73.42	---	83.07	---	83.43	---	87.69	---	75.76	---	75.09

Calib: efficiency in calibration with regionally derived data, Verif: efficiency (in verification, wherever applicable) when used for pseudo-ungauged basin.

any averaging, and hence without dilution of the response characteristics of each of the catchments. Models calibrated to the data series generated by pooling simulate the response from an ungauged catchment in the region better because of the response of the ungauged catchment being similar to many, if not all, catchments of the region.

The method of transposition, being suitable for a small sub-group of catchments, was applied only to two relatively more homogeneous sub-groups, one comprised of the catchments J2034010, J3024010 and J4124420 in the northwest, and the other consisting of two catchments, K0744010 and K0753210. The results of the method of transposition are given in Table 3. From the results of transposition for catchment J4124420 considering J3024010 as the index basin, and *vice versa*, it may be observed that for catchments having areas of identical order of magnitude good results may be obtained by transposition. For a large difference in areas of the two catchments considered for transposition (one gauged and the other pseudo-gauged), the scaling of discharge series of the index catchment lowers the performance. This is seen from the performances of the pairs K0744010 and K0753210, J2034010 and J3024010, and J2034010 and J4124420, when considered for transposition.

Comparison of results of the method of regional averaging of parameters with those of the regional pooling method in Table 2 shows that, for the case with 12 catchments, the former performs better in five out of 12 catchments, and that the efficiency for the catchment H3613020 by the method of regional averaging of parameters is unacceptably negative. This reflects that the method of regional pooling is clearly best for the group of 12 catchments. It also shows that catchment H3613020 may have been an outlier in the group, and that the inclusion of this catchment in the regional analysis is likely to reduce the efficiency of flow modelling by any regionalization method. A similar comparison of the method of regional averaging of parameters with the regional pooling method given in Table 3 shows that, in the case of the sub-group of six catchments, the efficiencies in the pseudo-ungauged basins, although generally lower, are comparable. In the context of the regional averaging method, however, it may be noted that due to equifinality (Beven & Freer, 2001), the parameter values in the optimum parameter set, as obtained by the modelling exercise, may differ significantly in some cases from catchment to catchment in the group, and meaningful averaging of parameters may not be possible. A number of tests may be required in such a case to choose the appropriate set of parameter values giving the best fit of the model to be considered for averaging.

From Tables 2 and 3, it is found that in five out of the six catchments indicated in Table 3, the method of regional pooling of data, considering these six catchments as a homogeneous sub-group, generally performs better than when the whole group of 12 catchments is selected. Thus, although a larger volume of data is used in the case of 12 catchments, the homogeneity in the sub-group of six catchments yields better efficiency of the modelling method in the case of the test with the homogeneous sub-group of only six catchments in comparison with that with all 12 catchments. Similarly, in three out of these six catchments, the method of regional averaging of parameters, considering the six catchments in the homogeneous sub-group, performs better in comparison with the case when the whole group of 12 catchments is chosen.

From Tables 2 and 3 it is observed that, as expected, efficiency values obtained by all regionalization methods range between those achieved by "no model" and by using the model best fitted to the actual observed discharge series of the pseudo-ungauged basins except in the case of catchments H3613020 and Y3514020. In the case of these two catchments, the efficiencies in verification obtained by the method of regional pooling are higher than the corresponding values obtained by considering the observed discharge data series. This inconsistency is attributed to the peculiarity in hydrological characteristics of these two catchments as explained earlier in the section regarding assessment of regional homogeneity. As demonstrated in this study on regionalization approaches for continuous flow simulation in an ungauged basin, the conceptual SMAR model proved to be a suitable choice.

CONCLUSIONS

Assessing hydrometeorological and physiographical homogeneity is very important for reducing uncertainty of estimation of flow in an ungauged catchment by regional analysis. The method of regional pooling of data is considered to be the best when a number of gauged catchments are available in the region. When only a few gauged catchments are available, transposition of data from the gauged to the ungauged basin may be used provided the catchments are similar in characteristics and their areas are of similar order of magnitude. As expected, the lack of homogeneity in a larger sample of catchments generally reduces the efficiency of the regionalization methods for flow modelling in ungauged basins. The conceptual SMAR model is seen to be a suitable choice for regionalization studies in continuous flow simulation in an ungauged basin.

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