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Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

Catchment multisite discharge measurements for hydrological model calibration

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Abstract

This work has the objective to find and test methodologies for distributed hydrological model calibration starting from discharge measurements. As all distributed models, also FEST-WB demands a large amount of information and parameters. To reduce the calibration effort, in this study we assign a first initial distribution of values for each parameter starting from information about soil type and usage and we let calibration change only the mean value, through a correction factor. The study area in which this methodology has been applied is Piemonte, with a total of 50 flow measurements series. With this large amount of discharge data it is possible to test a multi-site calibration approach. The results show that the use of only one measure for calibration highlight some shortcomings in the validation results, while the use of all the measures together improve model performance in all catchments levels.

Keywords: disributed hydrological models, multi-site approach, efficient parameterization, discharge measurements, model calibration

1. Introduction

In Alpine and Mediterranean climatic zone, hydrological processes are largely variable both in time and space, due to the high variability of rainfall, the influence of topography and the spatial distribution of soil typology and land use.

The use of a distributed hydrological model on this type of region can therefore be useful to take into account all that variability in simulating water resources management and in floods prediction [1]. However, when dealing with a distributed hydrological model it is crucial to adopt a rigorous

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parameterization procedure, because several are the parameters involved and it is necessary to avoid problems with over-parameterization [2]. The procedure must aim at assessing most of the parameter from field data in an objective way and at identifying a minimum number of parameters to be adjusted by calibration [3], [4].

Another important topic concerns the calibration of parameters. Distributed models can usually only be calibrated and validated against discharge data, and usually against streamflow series at the catchment outlet only. Nevertheless, when the catchment is densely monitored, and one or more gauging stations exist upstream of the outlet, they provide internal stramflow measurements and offer an opportunity for multi-site calibration [5]. So the question is: what is the value of this additional information for model calibration?

In literature, several are the example in which improvements reached by using internal flow measurements are reported. Andresen et al. [3] applied a physically based distributed hydrological model to the Senegal River Basin, and obtained improvements in model performance by calibrating against all the 10 stations in the catchment. Moussa et al. [1], reached a similar conclusion while calibrating a distributed model using data from nine internal gauging stations in a mountainous catchment in France. Feyen et al. [6], compared several calibration strategies on the Morava catchment in central Europe and concluded stating the superiority of the multi-site calibration. On the contrary, there are also some examples in which no improvement are registered with multi-site calibration. In Lerat et al. [5] they used a continuous daily lumped rainfall-runoff model to test if multi-site calibration could provide better results than a one-site calibration. They concluded that internal measurements provided limited improvement in model performance, but they also recognized that since they deal with a lumped model, this is not able to capture the spatial variability, and not able to make efficient the use of internal data.

The objectives of this study are: (1) to establish a rigorous parameterization procedure, starting from field data and without losing the spatially distributed approach; (2) to test a multi-site calibration and validation procedure.

2. Model, data and site description

2.1. The hydrological distributed model FEST-WB

The hydrological simulations are performed using the FEST-WB distributed water balance model [7], [8], [9]. This model allows to calculate the main processes of the hydrological balance: evapotranspiration, infiltration, surface runoff, flow routing, subsurface flow and snow dynamics. In Fig 1 a scheme of the model is shown. The computational domain is discretized by a mesh of squared cell, of 1 km per side, in each of which water fluxes are calculated at hourly time step. The model needs spatially distributed forcing as input: precipitation, air temperature, net radiation and the maps with the physiographic characteristics of the basin. The observed data at ground station are interpolated to a regular grid using the inverse distance weighting technique. Spatial distribution of air temperature local measurements takes into account the reduction of temperature with altitude, with a constant lapse rate of $-0.0065°C \cdot m^{-1}$.

The evapotranspiration is calculated with the Priestley Taylor equation [10] which needs only temperature and solar radiation data as input. Runoff is computed for each cell according to a modified SCS-CN method extended for continuous simulations [11].

The surface flow routing, for the cell free from snow, is computed with the Muskingum-Cunge method in its non-linear form with time variable celerity [9]. Subsurface flow routing is computed with a linear reservoir routing scheme [12] with a celerity calculated as a function of the soil saturated conductivity.

The snow module includes snow melt, accumulation and propagation into the snow pack; the melt model is based on a simple degree day depending on air temperature; the accumulation model, provides the partitioning of total precipitation in liquid and solid by using two thresholds of temperature, T_{LOW} and T_{UP}, below/above which all precipitation falls as snow/rain and they have to be found with calibration; melted water is supposed to flow into the snow pack with a linear reservoir routing scheme. All the parameters of the snow model don't vary in time and space but they are fixed values for the catchment. These parameters were calibrated comparing simulated and measured snow coverage, so in this study aren't subjected to further calibration.

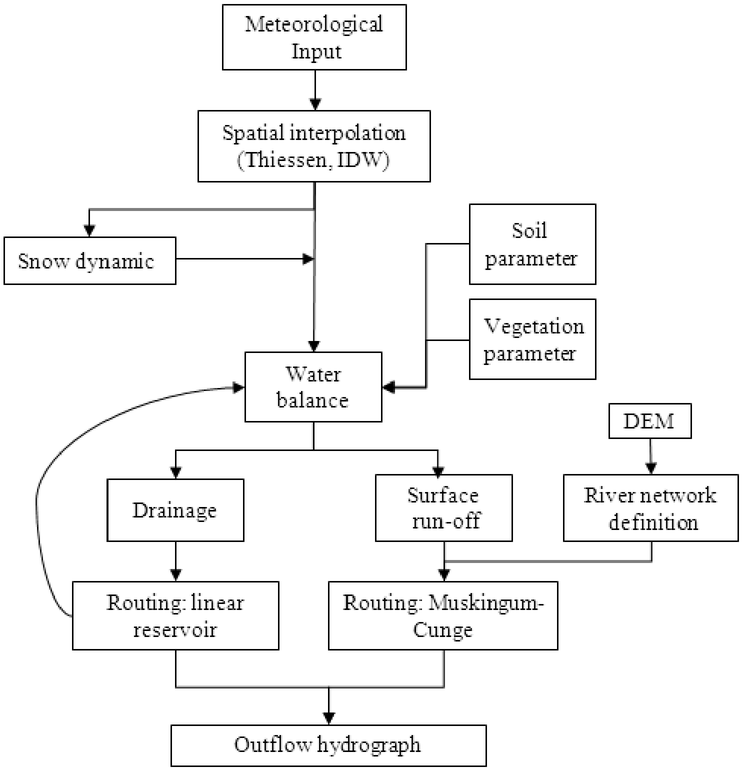

Fig. 1. Scheme of the hydrological model FEST-WB

2.2. Data available

The available meteorological data for this study consist on 12 years of data of hourly precipitation (486 stations), temperature (489 stations), solar radiation (100 stations) from 2000 to 2011. The discharge data are available at hourly time step on 50 gauging station on Piemonte region in the North of Italy from 2000 to 2011.

To run the model, soil parameters are required; the digital cartographic maps available for this study are: the Digital Elevation Model (DEM), the map of CN index [13], the map of soil typology, all with a spatial resolution of 1 km per side. To calibrate the snow sub-model, MODIS maps of snow cover with eight days resolution are available from 2000 to 2009.

2.3. Site description

The study was made on 50 catchments of the Piemonte region in the North of Italy. Several are the river interested in this study, but all of them are tributaries of the Po river basin.

In Fig. 2A the 50 catchment are represented. In this paper we focus on two river basin to explain the procedure of calibration followed for all the catchments. The first basin is the one of Orba river, located in the south-east of the region and characterized by a mostly flat area; the other basin is the one of Cervo river, located in the north-east of the region with a more mountainous area. In the Orba basin, there are two gauging stations: the upstream Basaluzzo and the downstream Casal Cermelli. In the Cervo basin, there are four gauging stations: Cossato on Strona river and Passobreve, Vigliano and Quinto Vercellese on Cervo river. In Fig. 2B all these catchments are represented.

Concerning the Orba river, the two catchments show similar physic and soil typologies characteristics, as displayed in Fig 3A, where hypsographic curve and distribution of soil typologies are shown. Regarding the Cervo river, it can be noticed that the catchments are really different from each other both from topography and soil typology point of view, see Fig 3B.

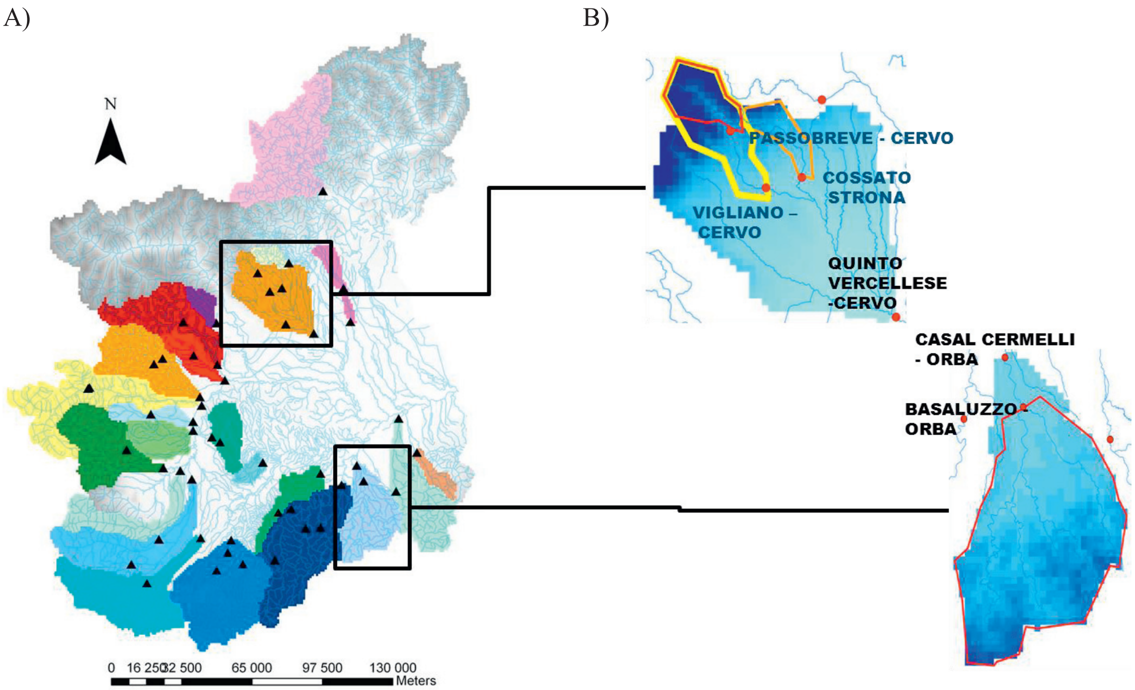

Fig. 2. Representation of the 50 catchments on Piemonte region (A); focus on the two river basin: Orba and Cervo (B)

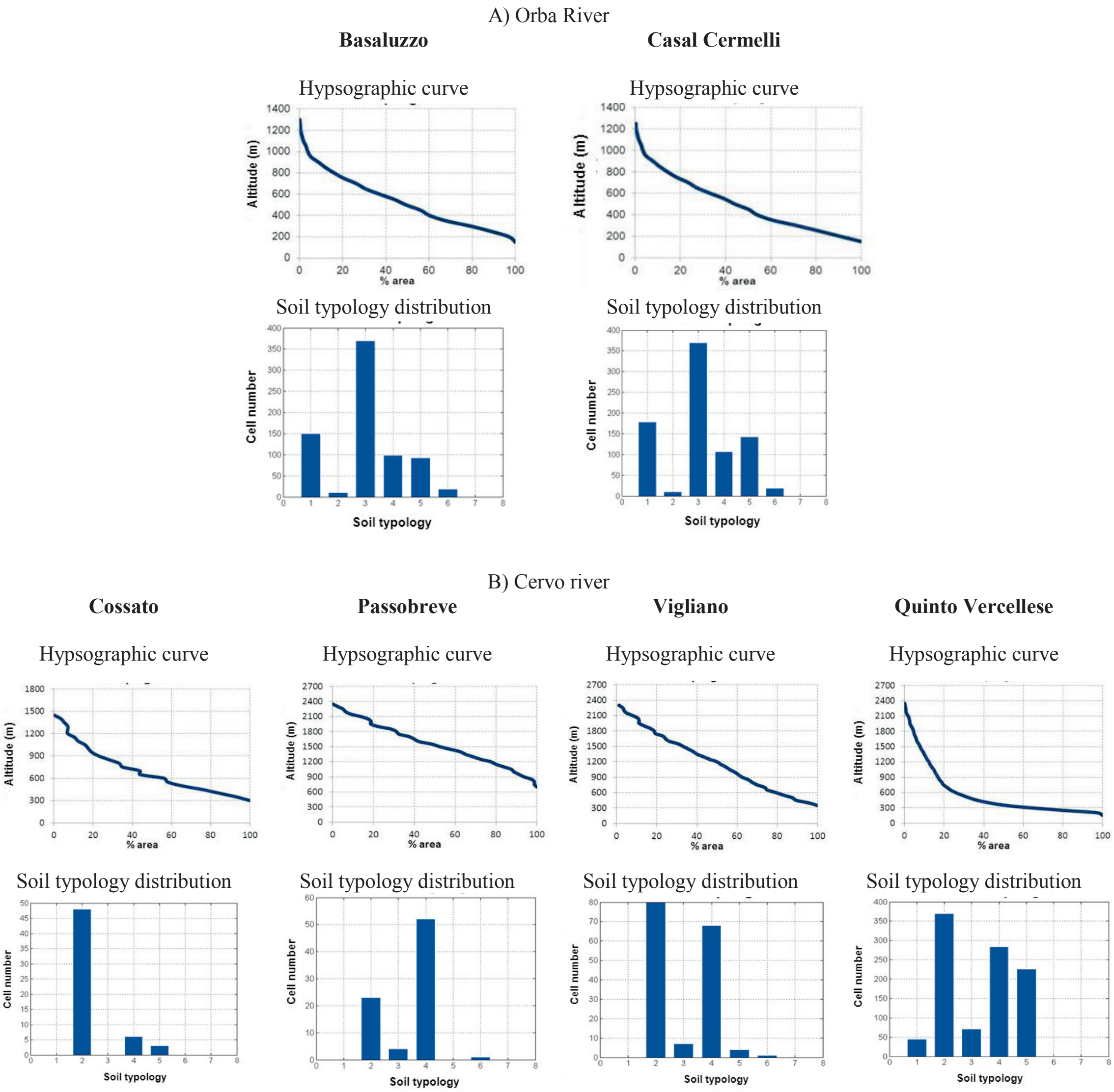

Fig. 3. Catchment characteristics: A) Orba catchments hypsographic curve and soil typology distribution. B) Cervo catchments hypsographic curve and soil typology distribution. In Soil typology distribution: 1 stands for sand soil, 2 for loamy sand, 3 for silt loam, 4 for silt clay loam, 5 for silt clay, 6 for clay, 7 for lakes.

3. Model parameterization, calibration and validation

Distributed hydrological models are surely a useful instrument to take into account the spatial heterogeneity of the main hydrological processes and inputs, but it is crucial to adopt a rigorous parameterization, calibration and validation procedure. In this section, the procedures used in this study are described.

The parameterization aims at assessing most of the parameter values directly or indirectly from field data and identifying a minimum number of parameters to be adjusted through the calibration process in order to avoid over-parameterization [1], [14]. So, two main principles were adopted in the parameterization procedure:

- a sensitivity analysis was made to identify the most important parameters of the hydrological processes, so that the number of parameters to be adjusted in the calibration procedure is kept as low as possible;
- the values of parameters were defined starting from field data observation, in this specific case, from soil typology and CN maps, and assigning a specific value of each parameter for each cell in relation to that of the input data: this ensure transparency and reproducibility of the parameterization.

Six are the parameters for each cell that undergo the process of calibration: the saturated vertical hydraulic conductivity, the saturated horizontal hydraulic conductivity, the Brook's and Corey index [15], the Field Capacity, the Wilting Point, the depth of the active soil. The values of these parameters and their range of variability are taken from literature [16] according to the class of soil typology, so that, also after calibration, all parameters maintain their physical meaning.

For each cell of the domain, six are the parameters to be calibrated and this leads to a very large amount of variables. To solve this situation, the effective parameter in each cell is split into two component: one fixed, the initial value, that expresses the spatial pattern and the physical meaning, and one variable, the correction factor, that takes into account all the modeling errors [3], [4]. In this way, the number of parameters to be calibrated is reduced from the number of parameters times the number of cells, to only the number of parameters, since the correction factor is common for all cells. This method allows to maintain both the spatial variability described a priori and the physical meaning of parameters, allowing the calibration procedure to modify the correction factors only in the admissible range of variability.

With these premises, the calibration procedure was made in this way:

- first of all, a first run of the model was made with the starting values of parameters, for all the catchments.
- the un-calibrated model, was then calibrated by considering independently each catchment (one-site calibration), so adjusting correction factors against each discharge series .
- the results obtained in the one site calibration for the two downstream catchments (Casal Cermelli and Quinto Vercellese) were validated against the upstream data.
- the one-site calibration was further calibrated by using discharge data of all the gauging station sequentially, multi-site calibration.

The model performance criteria used are: the Mean Relative Error (Mean Biased Error) on the peak discharges, Equation 1, and the Mean Absolute Error on peak discharges, Equation 2. For both indices also the standard deviation was calculated.

$$MBE = \frac{\sum_{i=1}^{n} \frac{Q_{sim,i}^{\max} - Q_{obs,i}^{\max}}{Q_{obs,i}^{\max}}}{n} \tag{1}$$

$$MAE = \frac{\sum_{i=1}^{n} \frac{\left|Q_{sim,i}^{\max} - Q_{obs,i}^{\max}\right|}{Q_{obs,i}^{\max}}}{n} \tag{2}$$

The calibration is considered satisfactory if the MBE is less than 25% that is lower than the error attributed in literature to discharge measurements [17]. For each catchment, more or less ten peak events have been detected. In most cases, a reduction of MBE implies a reduction of also MAE; in the rare cases in which this is not verified, the reduction of MAE was privileged, as long as the difference in MBE wasn't bigger than 2%.

As a measure of validation, to quantify the improvements resulting from calibration, three other indices were calculated: the Nash and Sutcliffe index [18], the Skewness coefficient (SK), defined as the ratio between mean and median discharge, that characterized general flow conditions and the Q_{10}, defined as the flow exceeded 10% of the time divided by the median flow, that is used to identify high flows conditions [19], [20].

4. Application and results

In this section application and results of the described methodology are presented.

The parameter adjustments made during calibration process were in all cases carried out manually, using a trial and error approach.

The un-calibrated model was applied using the values of parameters determined from input data and then each catchment was independently calibrated (one-site calibration) by adjusting the six correction factors corresponding to the six parameters. In Table 1A and 1B the results for the model performance respectively on Orba river and on Cervo river are summarized.

Table 1A. Model performance after first one-site calibration on Orba river

	UN-CALIBRATED MODEL				ONE-SITE CALIBRATED MODEL			
	MBE		MAE		MBE		MAE	
	Mean	St. Dev	Mean	St. Dev	Mean	St. Dev	Mean	St. Dev
Basaluzzo	-23.19	52.34	49.93	23.82	-1.68	45.12	36.35	23.91
Casal Cermelli	-24.9	50.1	44.7	31.2	-7.6	39.3	30.5	23.9

Table 1B. Model performance after first one-site calibration on Cervo river

	UN-CALIBRATED MODEL				ONE-SITE CALIBRATED MODEL			
	MBE		MAE		MBE		MAE	
	Mean	St. Dev	Mean	St. Dev	Mean	St. Dev	Mean	St. Dev
Cossato	12.5	70.0	58.15	32.31	-0.2	65.0	54.4	26.6
Passobreve	-35.9	28.3	36.7	27.1	-5.6	23.9	20.8	10.2
Vigliano	30.6	41.3	44.7	22.1	20.3	34.0	31.2	22.7
Quinto Vercellese	1.2	45.2	30.0	31.6	-1.2	39.5	28.2	25.2

Not surprisingly, the one-site calibration has improved the model performance in all stations. Now, the calibrated parameters obtained for the downstream stations, were validated in the upstream stations, by calculating the same model performances. As shown in Table 2, that reports the results for all the upstream catchments, the overall tendency is a reduction of model performances; this decrease is accentuated in particular in the catchments on the Cervo river, that, as shown in paragraph 2.3, have the major physical and topographic differences among themselves.

Table 2. Model performance for validation in upstream catchments

	VALIDATION			
	MBE		MAE	
	Mean	St. Dev	Mean	St. Dev
Cossato	2.2	62.6	52.1	25.9
Passobreve	-38.6	23.9	38.6	23.9
Vigliano	23.3	42.9	38.2	27.2
Basaluzzo	-8.0	46.8	38.8	24.1

From these validation results, appears that it is quite impossible to neglect upstream measurements in calibration procedure, because this would lead to worse outcomes, especially in upstream catchments. This effect is probably mostly due to the distributed structure of the model, that is able to capture the spatial variability.

The last calibration procedure is the multi-site procedure: all discharge data are used in the calibration process in a sequentially way, starting from calibrating against the upstream data and moving towards downstream, by fixing time to time the calibrated parameters upstream. In Table 3A and 3B the model performances for all catchments are reported.

As it can be noticed, in this way it is possible to reach good results in the upstream catchments and also to improve performances in the downstream catchments. This improvement in the downstream catchments can be evaluated also by calculating Nash and Sutcliffe index (NS), the Skewness coefficient (SK) and the Q_{10}, as defined previously. Notice that these indexes are not optimized, since they weren't used as model objective function for calibration, but only for validation. In Table 4 the values of indices are summarized. In all cases a better performance is registered, demonstrating the benefit of using all discharge data.

Table 3. Model performance after multi-site calibration on Orba river (A) and on Cervpo river (B)

A) Orba	MULTI-SITE CALIBRATED MODEL			
	MBE		MAE	
	Mean	St. Dev	Mean	St. Dev
Basaluzzo	-1.68	42.1	36.3	23.9
Casal Cermelli	-3.8	42.4	32.6	25.3

B) Cervo	MULTI-SITE CALIBRATED MODEL			
	MBE		MAE	
	Mean	St. Dev	Mean	St. Dev
Cossato	-0.24	65	54.4	26.6
Passobreve	-5.6	23.9	20.8	10.2
Vigliano	18.3	35.2	31.7	21.8
Quinto Vercellese	0.7	44.1	30.8	29.0

Table 4. Validation indexes on downstream station

	Quinto Vercellese – Cervo river			Casal cermelli – Orba river		
	NS	SK	Q_{10}	NS	SK	Q_{10}
Measured discharge	-	1.29	2.22	-	3.12	6.01
One-site calibration	0.2738	2.26	3.71	0.5760	2.90	4.86
Multi-site calibration	0.4742	1.49	2.47	0.5822	2.91	4.94

As already noticed, the improvements in Orba river are lower than those obtained for Cervo river. This fact can be explained considering the physical characteristics of the catchments: the two gauging station on Orba river are spatially close to each other and they subtend very similar catchments, so that using only downstream discharge or both, leads to comparable results. Instead, in the case of Cervo river, the catchments are really different from each other and so the calibration done with all available measurements allows to obtain better results, as the values of all model performance calculated show.

Considering all catchments together, it can be said that the parameter that needs the largest correction was the saturated vertical hydraulic conductivity, that in most cases was led to the maximum/minimum value allowed by the physical range of variability. This fact can be explained by considering the specific performance criteria used: the goal was to calibrate better high discharge than the low one, and that parameter is the one that governs mostly high flows.

5. Conclusions

This paper investigated both parameterization and calibration topics with respect to physically based distributed hydrological models, as the one used in this study. Distributed models have the advantage to take into account spatial variability of hydrological processes, but on the other hand require lots of parameters as input and an efficient procedure of parameterization and calibration must be identified.

Regarding parameterization, a simple approach was successfully used: a first initial value for all parameters and for each cell of the domain is assigned starting from soil typology maps; to diminish the number of variables to be calibrated, for each map, a correction factor, is introduced. These corrections factors are common for all cell of one parameter map and allows to change the mean value of the variables within the calibration process, but maintaining the physical meaning of the parameter and without losing the spatial variability.

This paper also investigated different strategies to calibrate a distributed hydrological model with several discharge measurements. The model was applied to 50 catchments where flow data were available at the outlet point and in several cases also at internal point. Only six catchments are presented here to show the methodology used for the whole calibration. The objective was to compare one-site calibration to multi-site calibration and to test if the use of flow data at the outlet and at interior point could produce better results. The calibration were performed with a trial and error approach and using as model performance the Mean Biased Error and the Mean Relative Error. As validation of results, the Nash and Sutcliffe index, the skewness index and the Q_{10} were calculated.

The main conclusion from this comparison is the improvement gained by using for calibration both flow data at the outlet point and at interior point. The validation results for the various calibration schemes provide indications that the model performance increase when moving to sub-catchments: the usage of all flow data measures for calibration allows to reach better results in all catchments levels. However the validation has been carried out at the river basin and at sub-catchment scales and not at scales below those, so nothing could be said for smaller scales because of lack of data. At the same time, it was not possible to test the ability of the model to simulate other variable rather than discharge. The use of multivariable approach or of remote sensing data could be a feasible way of improving model performance.

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