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CHIMERA WATERSHEDS TO UNDERSTAND THE RELATIVE IMPORTANCE OF RAINFALL DISTRIBUTION IN SEMI-DISTRIBUTED RAINFALL-RUNOFF MODELS

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1 INTRODUCTION

Rainfall-runoff (RR) models are highly appreciated tools in the domain of hydrological engineering. Operational applications are very demanding, as they request both efficiency and robustness. Therefore, no one can tell a priori which modeling approach should be used: modeling choices must be justified through extensive testing, and for robustness considerations, simple solutions must be preferred to more complex ones when they are of equal efficiency.

In this context, the choice between a lumped and a spatially distributed approach for RR modelling is not a trivial one. Indeed, lumped RR models have proved over the years their robustness. On the other hand, distributed models potentially have a greater ability to take into account the spatial heterogeneity of both rainfall and soils, and this could contribute to an improvement of models efficiency and especially of streamflow forecasts.

In this paper, we consider the most basic sort of semi-distribution, which consists of a watershed that can be split into two sub-watersheds. To help modellers decide of the most appropriate equilibrium between lumped and distributed approaches in RR modelling, we introduce what we call “chimera watersheds”, which result from the association of two “actual” watersheds, similar in size, but located away from each other on the drainage network.

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In section 2, we first present the method used to produce chimera watersheds, and justify the interest of such an approach in hydrologic modeling. In section 3, we present the watershed sample and the RR model used in this study. Then, in section 4, we describe the three levels of spatial aggregation, which will be compared to assess the respective importance of rainfall and watershed behavior for a distributed description of the rainfall-runoff relationship. Last, results are discussed in section 5.

2 BUILDING CHIMERA WATERSHEDS

A chimera watershed is a virtual watershed built by combining two actual watersheds (Figure 1) similar in size, but not necessarily located in the same area: runoff of the resulting watershed is obtained by addition of sub-watersheds runoff (Figure 2); rainfall and evaporation input are a weighted average of sub-watersheds rainfall and evaporation respectively.

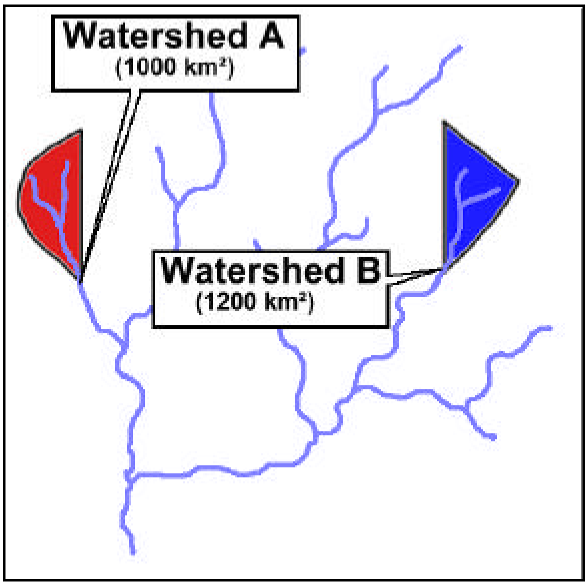

Figure 1: *constitution of chimera watersheds. First phase: selection of two watersheds similar in size*

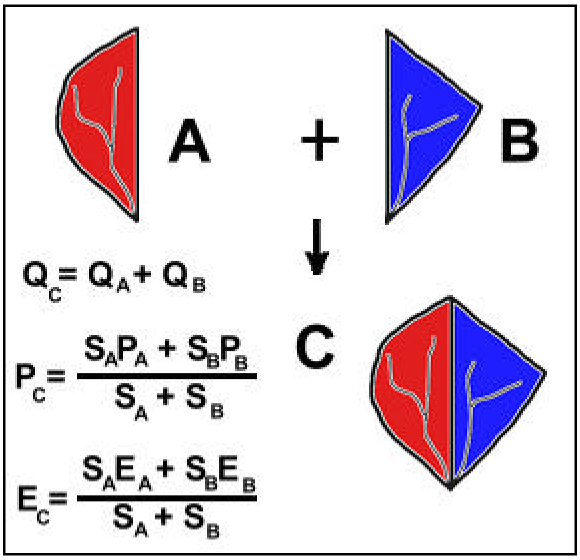

Figure 2: *constitution of chimera watersheds. Phase 2: virtual combination of flows to build chimera C (P stands for daily precipitation input, Q for daily runoff, E for daily potential evapotranspiration, and S for watershed area)*

In this study, the size was the only limitation to watershed combination into chimeras: the ratios of subwatershed areas was kept between 0.5 and 1.5.

Why did we resort to building chimeras, instead of using actual watershed pairs? Essentially for two reasons:

- First, because there is only a very limited number of watersheds where a downstream gaging station has two upstream gaging stations allowing to actually measure disaggregated (spatialized) flows (Baudez, 1997);
- Second, because previous studies, based on the very limited number of gaging station triplets available, had been unconclusive. Loumagne et al. (1999) concluded that, from a streamflow simulation point of view, there was no sensible difference between semi-distributed and lumped approaches. This rather surprising conclusion lead us to look for <u>a larger sample of more contrasted watersheds</u>, and this is the reason why we decided to use chimeras.

By using chimeras, we aimed to create conditions, which would be much more contrasted than on actual watersheds, and which would give a definite advantage to the semi-distributed approach. Therefore, chimera watersheds may contribute to assess to what extent semi-distribution is interesting to account for the heterogeneity of physical processes. The goal here was not to establish the conditions of an objective comparison between the lumped and the semi-distributed approaches, but rather to provide directions for operational hydrologists, who wish to understand the relative importance of the different sources of hydrological spatial variability.

3 WATERSHEDS AND MODEL

3.1 Watershed sample

For this study, we used a database of 307 French watersheds (Figure 3 and Table 1) for which rainfall, runoff and potential evapotranspiration were available at the daily time step. Following the procedure presented in section 2, we used all possible combinations to produce a total of 4,500 chimera watersheds, for which we will compare the performances of the lumped and of various semi-distributed approaches (section 4).

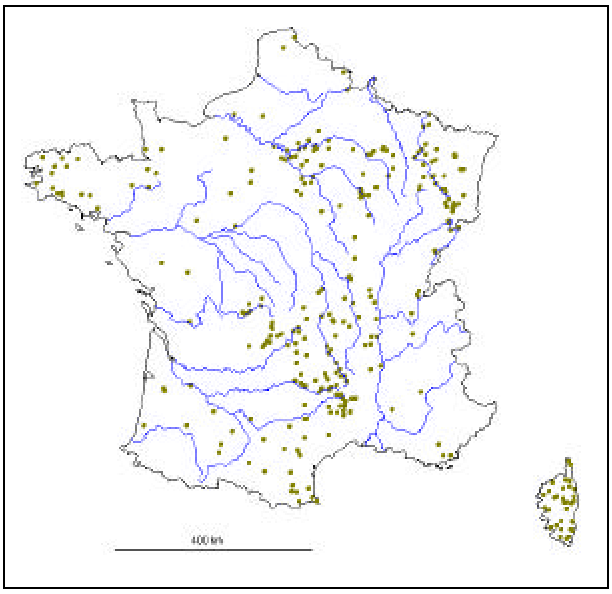

Figure 3: *location of the 307 French watersheds used to build chimeras*

Table 1: *characteristics of the watershed sample used in this study*

Number of watersheds	307
Average watershed area	580 km²
Median watershed area	85 km²
Maximum watershed area	43800 km²
Minimum watershed area	1 km²

3.2 Rainfall-Runoff model used: GR4J

We used GR4J, a parsimonious, continuous lumped rainfall-runoff model functioning at the daily time step and having just four calibrated parameters (Edijatno et al., 1999; Perrin, 2000).

A detailed discussion of the model structure is outside the scope of this paper; its structure is shown in Figure 4, and a list of its parameters is given in Table 2.

The structure of the GR4J model was developed by following an empirical approach and by testing it on a large sample of catchments. GR4J (or slightly different versions) was successfully applied in several countries and used by different authors in various hydrological studies (Kuczera and Parent, 1998; Servat and Dezetter, 1993; Yang and Michel, 2000; Yang and Parent, 1996).

The GR4J model structure is simple, with a soil moisture accounting reservoir and a water exchange function in the production module, and two unit hydrographs and a non-linear routing store in the transfer part of the model. The model showed satisfactory versatility and robustness in the comparative study proposed by Perrin et al. (2001), which comes partly from its extreme parsimony with only four parameters to be optimized. These parameters accounts for water balance (X1: water exchange coefficient; X2: capacity of production store) and water transfer (X3: capacity of the non-linear routing store; X4: unit hydrograph time base).

Given GR4J low number of parameters, it can be calibrated with simple techniques. Here model calibration was performed by a local optimisation algorithm called the 'step-by-step' method. The principle of the method is detailed by Edijatno et al. (1999).

Table 2: *list of the parameters of the GR4J rainfall-runoff model*

Parameter	Parameter signification
X1	Water exchange coefficient (mm)
X2	Capacity of the production reservoir (mm)
X3	Capacity of the non-linear routing reservoir (mm)
X4	Unit hydrograph time base (day)

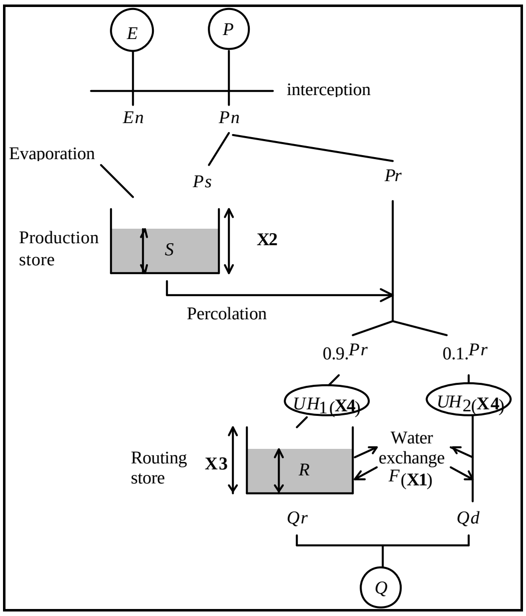

Figure 4: *Diagram of the GR4J rainfall-runoff model*

4 METHOD

To assess the efficiency of streamflow simulations, we computed the Nash and Sutcliffe (1970) criterion in control mode for each level of spatial aggregation. Parameters, which had been calibrated on a first period, were used in simulation on a second period, as recommended by Klemeš (1986). The efficiency of each approach was described by the distribution of the 4500 values of the Nash and Sutcliffe criterion.

Three approaches, differing only by their level of spatial disaggregation, were compared.

4.1 Lumped approach

In the lumped approach (described in Figure 5) the vector *X* of parameters of the RR model is calibrated on aggregated precipitation (*P*) and runoff (*Q*) time series. In simulation mode, the rainfall-runoff model is fed with aggregated precipitation to yield directly an estimate of the chimera's runoff.

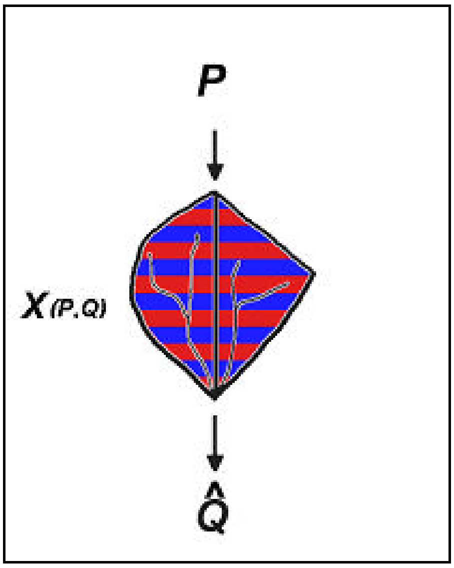

Figure 5: *schematic representation of the lumped approach of rainfall-runoff modeling on a chimera watershed. Only one vector of parameters, X, calibrated on aggregated series P & Q.*

4.2 Fully semi-distributed approach

In the fully semi-distributed approach described in Figure 6, two RR models are run in parallel, their parameters being calibrated separately using the precipitation and runoff series of the two original watersheds. In simulation mode, each side of the watershed is fed with its own precipitation input, and simulated flows are aggregated at the end to yield an estimate of the chimera's runoff.

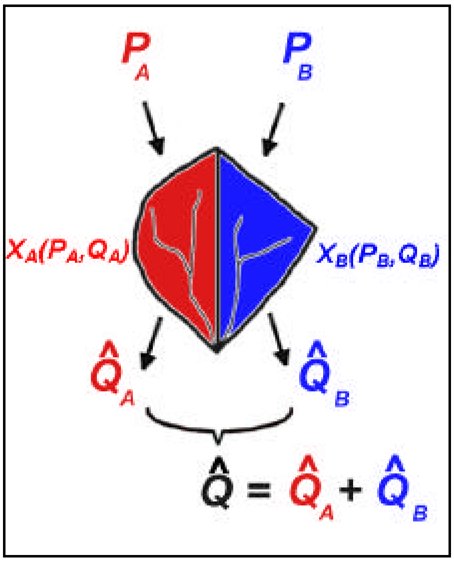

Figure 6: *schematic representation of the fully semi-distributed approach of rainfall-runoff modeling on a chimera watershed. Two vectors of parameters, X_A (calibrated on series P_A & Q_A) and X_B (calibrated on series P_B & Q_B).*

4.3 Partially semi-distributed approach

In the partially semi-distributed approach described in Figure 7, two RR models are run in parallel, but the same set of parameters is imposed during calibration. There is therefore a single parameter vector *X* describing the chimera, as in section 4.1. However, the situation differs from the lumped one, as *X* is obtained from a multiobjective calibration. In simulation mode, each side of the watershed is fed with its own precipitation input, and simulated flows are aggregated at the end to yield an estimate of the chimera's runoff.

This third approach should allow distinguishing between the effects of *precipitation disaggregation* and *watershed behavior disaggregation*. In principle, this approach should give results of lesser efficiency than the fully semi-distributed approach, as we force both sub-watersheds to have the same parametrization. But results should be better than those obtained with the lumped approach, since we can at least exploit the knowledge of rainfall heterogeneity.

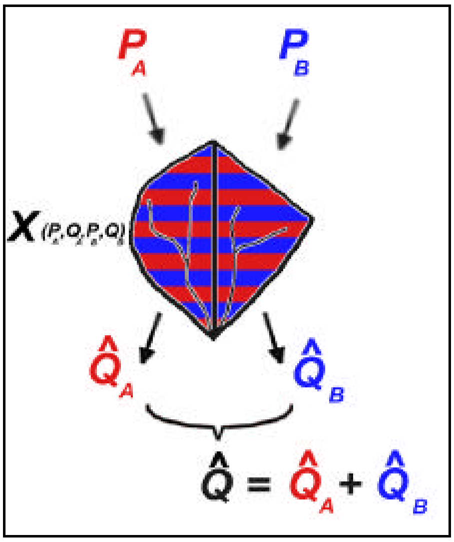

Figure 7: *schematic representation of the partially (restricted to precipitation) semi-distributed approach of rainfall-runoff modeling on a chimera watershed. Only one vector of parameters, X, calibrated on disaggregated series (P_A,Q_A)and (P_B,Q_B).*

In the following section, we now analyze the results of simulations obtained with the three approaches described above.

5 RESULTS AND DISCUSSION

5.1 The fully semi-distributed approach shows a definite superiority over the lumped approach on chimera watersheds

Our first analysis will focus on the difference between the results of the lumped and semi-distributed approaches. In Figure 8, most of the cluster (79 % of the points) is situated above the 1:1 line, showing that the GR4J performs better in semi-distributed mode than in lumped mode on chimera watersheds. This was an expected result, as our aim in building chimeras was clearly to create very contrasted situations, where a semi-distributed approach would benefit of a clear advantage. What was less expected is that, notwithstanding the superiority of the semi-distributed approach, there is still a significant number of watersheds under the 1:1 line (21 %), where the lumped approach appears to give better results than the semi-distributed one.

When facing such results, modellers may ask themselves whether the improvement brought by spatial disaggregation comes from the possibility to take into account distributed rainfall, or distributed watershed behavior? To try to answer this question, we will consider in the following section the partially semi-distributed variant of GR4J (described in 4.3).

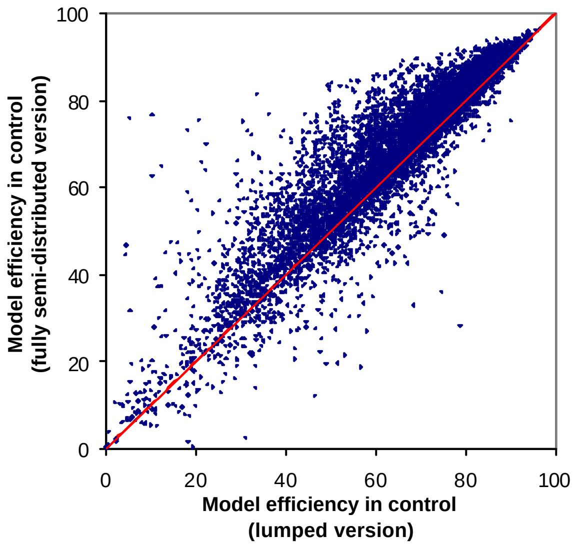

Figure 8: *efficiency of GR4J: lumped vs semi-distributed approaches (efficiency measured by the Nash and Sutcliffe criterion in control mode)*

5.2 75 % of the advantage of semi-distribution is due to the account of rainfall variability

Figure 9 presents the distribution of model efficiency ratings (in control mode), for the three level of aggregation considered in this paper. The fully semi-distributed approach (in red), has its distribution on the right hand side of the graph, which means that it yields the best results. The lumped distribution (in blue) is on the left side: its results are poorer. The partially semi-distributed approach (in green), is intermediary between the two preceding approaches.

However, the most important result on Figure 9 is that the green distribution is much closer to the red one than to the blue one. This means that most (75 % at the median) of the gap between lumped and fully spatialized can be filled by taking into account the spatial variability of rainfall. Spatialization of watershed behavior has thus only a minor effect on the improvement of simulations. This finding is consistent with the conclusions of Boyle et al. (2001) for example.

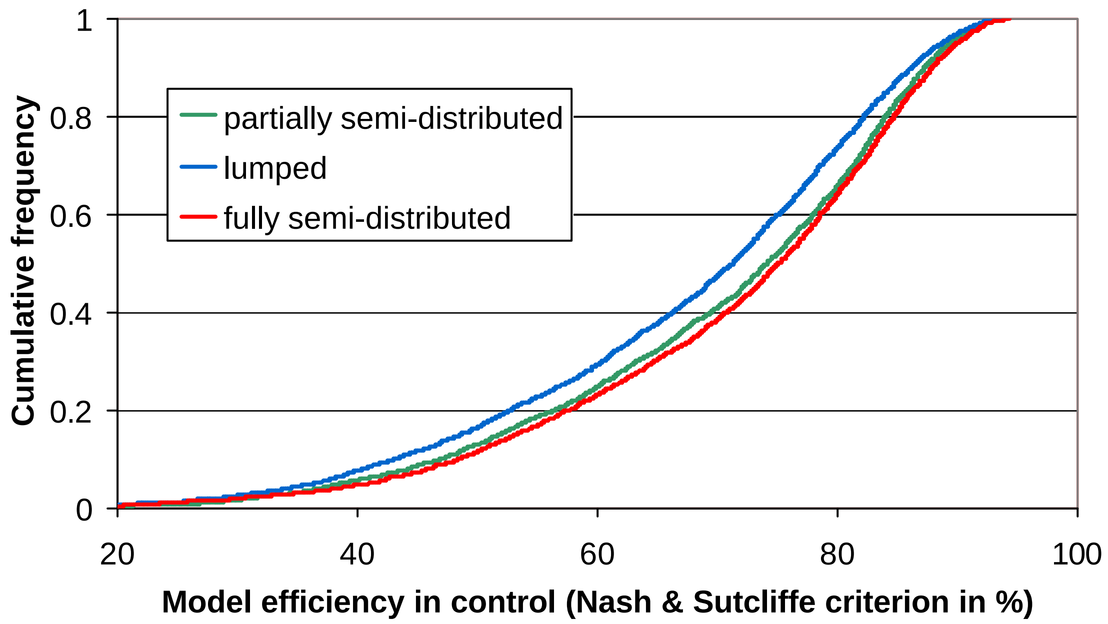

Figure 9: *distribution of GR4J efficiency (in control mode), while used in lumped, partially semi-distributed and semi-distributed mode*

6 CONCLUSION

The aim of this paper was to determine the relative importance of rainfall distribution versus parameter (i.e. hydrological behavior) distribution in rainfall-runoff models. We introduced the concept of "chimera watersheds", where two actual watersheds of similar size are associated. We believe that the use of chimera watersheds, by providing very contrasted hydrological situations, can be useful to help identify those factors, which are relevant to determine the most appropriate level of spatial distribution for a RR model.

For this study, of particular interest was the fact that the largest part of the improvement that can be brought by spatial distribution is due to rainfall variability: this means that if spatial distribution is considered to be a useful direction to improve the reliability of hydrological models, efforts should be directed in priority towards the use of spatially distributed rainfall data and not so much to the spatialization of catchment (land-surface) parameters.

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