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How informative is land-cover for the regionalization of the GR4J rainfall–runoff model? Lessons of a downward approach

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Abstract Prediction on ungauged basins is a big issue for operational hydrology and a challenge for scientists. For regionalization objectives, the first step of the development of *a priori* parameter estimation is to look for correlations between calibrated parameters and physical catchment descriptors. This article investigates the relationships between the parameters of the GR4J rainfall–runoff model and catchment vegetation characteristics over a large sample of 221 French catchments. First, the possible links between the calibrated parameters of the GR4J model and catchment vegetation types are investigated by linear regression. Then, we try to improve these relationships by introducing a more detailed description of the evapotranspiration process, explicitly taking into account vegetation types, following a downward approach. Results show that the GR4J model parameters cannot be determined directly from vegetation characteristics, and that the situation is not improved by a more detailed approach to evapotranspiration modelling.

Key words downward approach; evapotranspiration; land use; rainfall–runoff model; regionalization

INTRODUCTION

Vegetation type is one of the most often cited driving variables of catchment behaviour. This consensus has its roots in the numerous studies implemented by forest hydrologists on small catchments during the 20th century. Several reviews are available on this topic: see for example, Bosch & Hewlett (1982) or Andréassian (2004). Mainly based on paired catchment experiments, these studies consisted of deforestation and reforestation experiments, by which it was possible to demonstrate without doubt that forest cover could have an important role in the water balance at the catchment scale. However, the fact that vegetation has a role in a water cycle does not necessarily imply that vegetation is informative for regionalization objectives. Indeed, to use land cover for regionalization applications, we must be able: (i) to quantify its impact on the water cycle at the catchment scale; and (ii) to isolate its impact from other linked factors: soils, climate.

At first sight, the most rational approach to explicitly introduce vegetation characteristics into hydrological models is to use a mechanistic approach, with a physically-based model whose parameters are directly linked with vegetation types. Several large-scale experiments have supported the development of Soil-Vegetation-

Atmosphere Transfer (SVAT) schemes that describe the vertical fluxes of water and energy on the Earth's surface and try to explicitly take into account vegetation characteristics). However, the mechanistic approaches present two main drawbacks: they are often over parameterized (Franks & Beven, 1997; Avissar, 1998) and they suffer from process scaling problems (Grayson *et al.*, 1992).

The alternative approach proposed in this article is to start with a simple (i.e. parsimonious) rainfall–runoff model and try to introduce step-by-step more complexity to account for vegetation types: modifications would be accepted only if they improve model efficiency in terms of the output simulations (the streamflow simulations in our case). This approach is known as the downward approach (Klemeš, 1983; Sivapalan *et al.*, 2003), which attempts to predict the catchment behaviour by an interpretation of the observed response at the catchment scale. Specifically, we started with a simple representation of the catchment behaviour, and made the representation more complex only in response to improved results or improved ease of regionalization.

In this article, we tested this methodology by using data from 221 French catchments and the GR4J rainfall–runoff model, the possible links between GR4J calibrated parameters and catchment vegetation-type are investigated. Then, we try to improve these relations by introducing a more detailed description of the evaporation process, in order to explicitly take into account vegetation-types.

DATA AND METHODS

Catchment sample

The 221 French catchments are part of the sample used by Oudin *et al.* (2004) to discuss the use of potential evapotranspiration (PE) in rainfall–runoff modelling. Although France has a mainly temperate climate, its climate conditions are varied in this sample: Mediterranean conditions in the south of France, oceanic influences in the west and some continental features in the eastern part of the country. Basin sizes range from small (5.2 km^2) to medium (9387 km^2), with a median size of 88 km^2. Mean annual PE varies between 690 and 1340 mm, mean annual rainfall (P) between 620 and 1940 mm and mean annual streamflow between 23 and 1740 mm. The aridity index ($\overline{PE}/\overline{P}$) varies from 0.39 to 1.93 and the runoff coefficient from 0.03 to 1.05 (the value 1.05 corresponding to a karstic system).

Using a GIS, Plantier (2003) extracted the dominant cover types from the CORINE land cover classification (CEC, 1993). This classification relies on a 250 m grid resolution and was made by visual interpretation of high-resolution satellite images, e.g. Landsat-TM and SPOT-XS, at a 1:100 000 scale. Only two dominant classes were considered: forested and arable areas (others, like urban area or lake were very scarce over the catchments). The repartition of forested and arable catchments is quite symmetric: around 20% of the catchments are covered by more than 80% of forested land and symmetrically 20% of the catchments are covered by more than 80% of arable land. Hereafter, we will present the results in terms of percentage of forested area, since results for arable areas are symmetric.

The GR4J rainfall–runoff model

When trying to identify relationships between model parameters and physical catchment characteristics, it appears essential to use a parsimonious model. This avoids over parameterization, which is always detrimental to calibrated parameter precision. It seems obvious that a relationship between model parameters and catchment characteristics, if it exists, will be detectable using a parsimonious model. We used the GR4J model, a daily lumped rainfall–runoff model with only four parameters to calibrate, belonging to the family of soil moisture accounting models. A schematic diagram of the model and its parameters are shown in Fig. 1. For a detailed discussion of the model, see Perrin *et al.* (2003). The first two parameters regulate the water balance functions and the two others, the water transfer functions. These parameters are calibrated using a local search optimization algorithm described by Edijatno *et al.* (1999), with the Nash & Sutcliffe (1970) criterion (hereafter noted *NS*) used as an objective function.

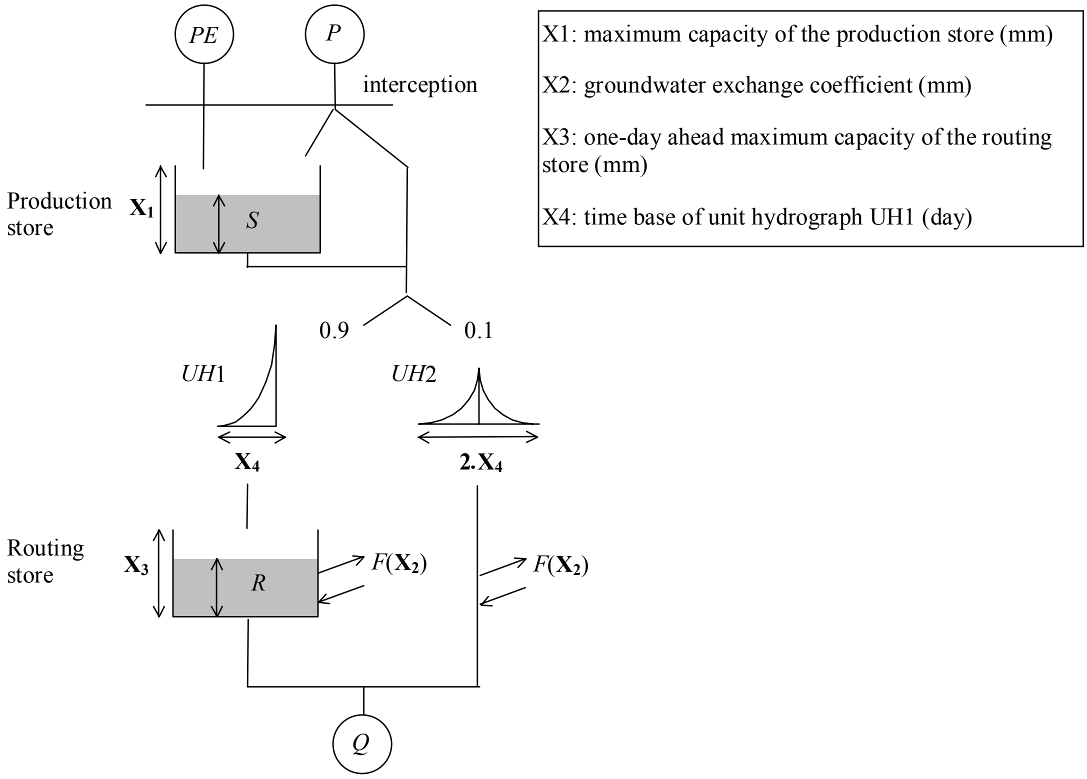

Fig. 1 Scheme of the GR4J rainfall–runoff model (*PE*, potential evapotranspiration; *P*, rainfall; *Q*, streamflow).

To assess the performance of the model, we used a split-sample test procedure (Klemeš, 1986): for each catchment, data time-series were split into two sub-periods. Then the model was calibrated on each sub-period and tested in validation mode on the other sub-periods. Two criteria were used to assess model efficiency on the validation periods. The first one is the standard Nash and Sutcliffe criterion:

$$NS = 100\left(1 - \frac{\sum_j \left(Q_{obs,j} - Q_{sim,j}\right)^2}{\sum_j \left(Q_{obs,j} - \overline{Q}\right)^2}\right) \tag{1}$$

where $Q_{obs,j}$ and $Q_{sim,j}$ are the observed and simulated streamflows on day j, and $\overline{Q}$ is the mean observed streamflow over the record period. The second criterion is based on the mean Cumulative Balance (*CB*) error of the model, written in relative terms (balance error) by:

$$CB(\%) = 100\left[1 - \left|1 - \frac{\sum_{i=1}^{n} Q_{sim,i}}{\sum_{i=1}^{n} Q_{obs,i}}\right|\right] \tag{2}$$

CB measures the ability of the model to correctly reproduce streamflow volumes over the studied period. Criterion *CB* is different from the first criterion in that it compensates for the errors at each time-step of the simulation.

A downward methodology to introduce vegetation descriptors into GR4J

The Penman-Monteith (Monteith, 1965) equation explicitly uses parameters linked with vegetation basin characteristics. Therefore, it is often considered as a first attempt to represent the soil–vegetation–atmosphere transfer and it remains the simplest SVAT scheme to implement. The Penman-Monteith formulation (with ET in m day^{-1}) can be written as follows:

$$ET = \frac{\Delta R_n + \gamma\left(e_a - e_s\right)\frac{\rho C_p}{r_a}}{\lambda\rho\left[\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)\right]} \tag{3}$$

where ET is the rate of evapotranspiration (in m day^{-1}), R_n is the net radiation (MJ m^{-2} day^{-1}), λ is the latent heat of vaporization (taken equal to 2.45 MJ kg^{-1}), ρ is the water density (1000 kg L^{-1}), e_a is the saturation vapour pressure (kPa) and e_s is the actual vapour pressure (kPa), C_p is the specific heat of the air, Δ is the slope of vapour pressure/temperature curve at equilibrium temperature (kPa °C^{-1}), γ is the psychrometric constant (taken equal to 6.6 10^{-2} kPa °C^{-1}), W is a wind speed function, r_s is the stomatal resistance and r_a is the aerodynamic resistance. Although the evapotranspiration processes may be too complex to be represented by these two resistances (Brutsaert, 1982), good correlations were obtained between modelled and measured evapotranspiration using this scheme (Allen *et al.*, 1998).

It is important to clarify a point that appears to be rather fuzzy in the literature: does the Penman-Monteith formulation refer to potential evapotranspiration, is it a formulation of reference crop evapotranspiration or a formulation of actual evapotranspiration? There are indeed multiple uses of this equation, depending on the formulation of the resistances (Wallace, 1995). For instance, the stomatal resistance may vary with the water content of the plant (Eagleson, 1978) and the vegetation-type, but in many cases, it is used as constant (equal to 69 s m^{-1}). Table 1 summarizes the rates of evapotranspiration computed with different formulations of r_s in the Penman-Monteith equation. At least, note that the original version of GR4J uses the stomatal resistance as a constant.

Table 1 Penman-Monteith equation and the corresponding rate of evapotranspiration.

Stomatal resistance	Data used for the Penman-Monteith equation			Computed rate of evapotranspiration
	Climatic data	Land use	Soil and vegetation water content	
$r_s^{RC}min = 69\ sm^{-1}$	✖			Reference crop potential evapotranspiration
$r_{s\ min}$	✖	✖		Potential evapotranspiration (surface dependent)
r_s	✖	✖	✖	Actual evapotranspiration

In order to get a more detailed representation of the evapotranspiration process, we used the Penman-Monteith equation as a formulation of potential evapotranspiration: the stomatal resistance will refer to the minimum of the stomatal resistance, which should depend on the land cover. Therefore, the term $r_{s\ min}$ is now determined by:

$$r_{s\ \min} = X_5 \tag{4}$$

where X_5 is an additional parameter to calibrate. As pointed out earlier, this formulation of r_s in the Penman-Monteith equation allows one to estimate a potential rate of evapotranspiration. Thus, the input *PE* (in m day^{-1}) is now computed by:

$$PE = \frac{\Delta R_n + \gamma(e_a - e_d)\frac{\rho C_p}{r_a}}{\lambda\rho\left[\Delta + \gamma\left(1 + \frac{X5}{r_a}\right)\right]} \tag{5}$$

where the aerodynamic resistance (s m^{-1}) is computed by as a function of the wind speed U (m s^{-1}):

$$r_a = \frac{208}{U} \tag{6}$$

This scheme was chosen because it is easy to implement in a soil moisture accounting rainfall–runoff model. Note that this implementation is fairly simple compared to other existing SVAT models. But, since GR4J's structure is initially parsimonious, we wished to propose a SVAT module of assorted parsimony. Other implementations were tested (Oudin, 2004), including more complex SVAT schemes such as the GRHUM rainfall–runoff model (Loumagne *et al.*, 1996). These investigations, not reported here, yield similar results to those presented hereafter.

Following the recommendations of the downward approach (Klemeš, 1983), two conditions are to be fulfilled to accept the modified structure:

(a) The first condition concerns the model efficiency in validation mode. Since the first purpose of an empirical rainfall–runoff model such as GR4J is to simulate streamflow, it is essential that the modifications do not degrade model performance, especially if additional parameters are added (Nash & Sutcliffe, 1970).
(b) If the two models yield similar performance, a second condition concerns the relationship between model parameters and observed vegetation types: a more detailed approach can only be justified if its additional parameters enable a physical interpretation.

RESULTS

Links between GR4J parameters and vegetation catchment characteristics

As a first step, we wanted to investigate the possible links between GR4J calibrated parameters and vegetation catchment characteristics. Fig. 2 compares the calibrated parameters and the percentage of forest cover: each point represents the parameter value averaged over the calibration periods and the error bars indicate the range of the calibrated parameters, large error bars meaning uncertain parameters values. There is no apparent relationship between catchment vegetation attributes and model parameters, even if "uncertain" parameter values are not considered. This is quite disconcerting since one would hope to find a relationship between vegetation attributes and, at least, the maximum capacity of the soil moisture accounting (SMA) store.

The absence of relationships between a catchment's vegetation descriptors and model parameters corroborates previous studies related to regionalization for a large number of catchments (e.g. Merz & Bloschl, 2004). There may be two reasons why finding relationships between vegetation characteristics and GR4J model parameters proves to be difficult:

(1) the lumped GR4J model may have a too crude representation of the evapotranspiration process to benefit from land cover information;
(2) vegetation may have only a marginal impact on catchment hydrological behaviour, and it may have served as an index for a second driving variable (such as soil) in the studies that have established a significant link.

As modellers, we focused on the first hypothesis. It is indeed possible that model parameter values hold some information from vegetation, but that the formulation of the model structure is inadequate and does not allow it to be revealed.

Would a more physically-oriented structure be more adequate?

To address this issue, we decided to compare the performance of the original GR4J model with those of a modified structure of GR4J, which presents a more detailed description of the evapotranspiration processes, involving explicit vegetation-related

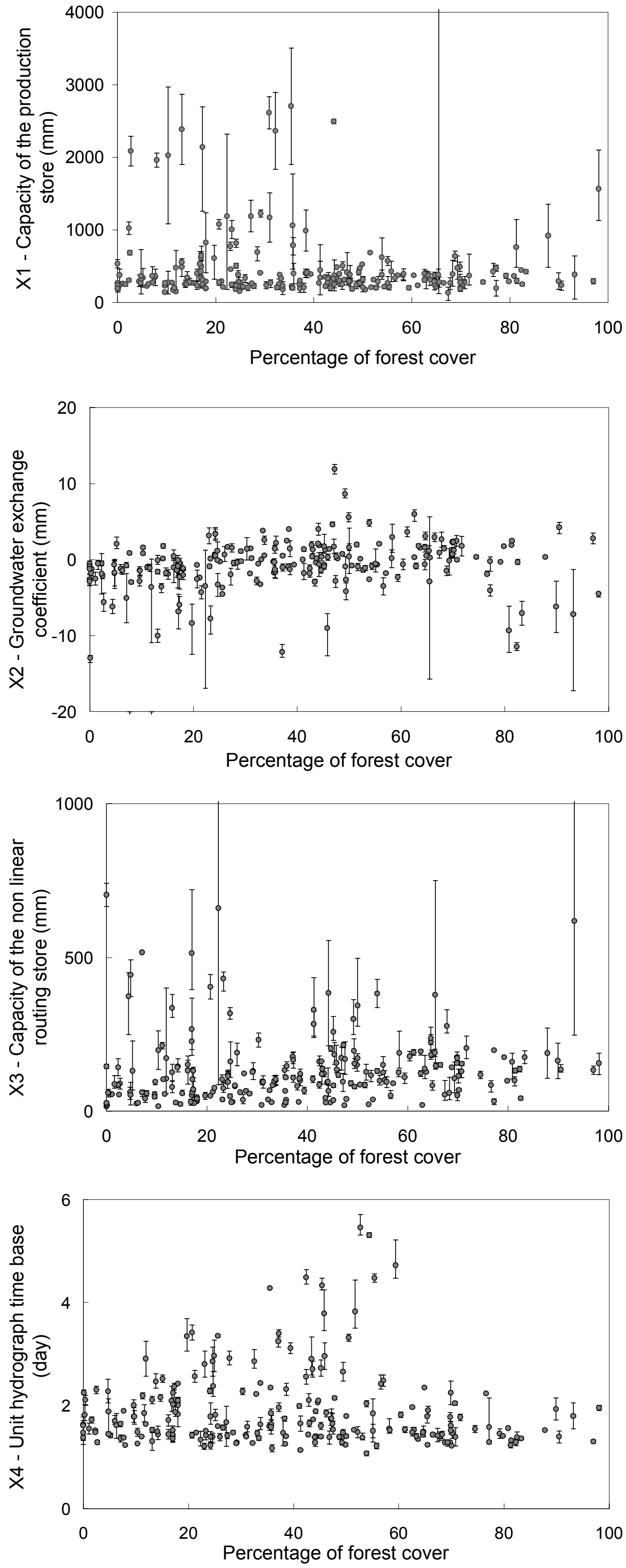

Fig. 2 Calibrated values of the GR4J model plotted against the percentage of forest cover. Error bars show the range of the calibrated parameters over one catchment.

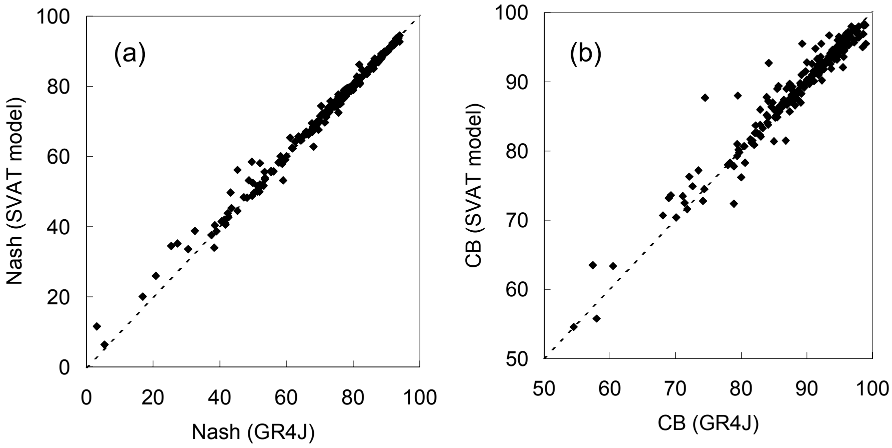

Fig. 3 Performance of the SVAT-oriented structure against the initial GR4J model, in terms of: (a) Nash and Sutcliffe criteria and (b) the water balance criterion.

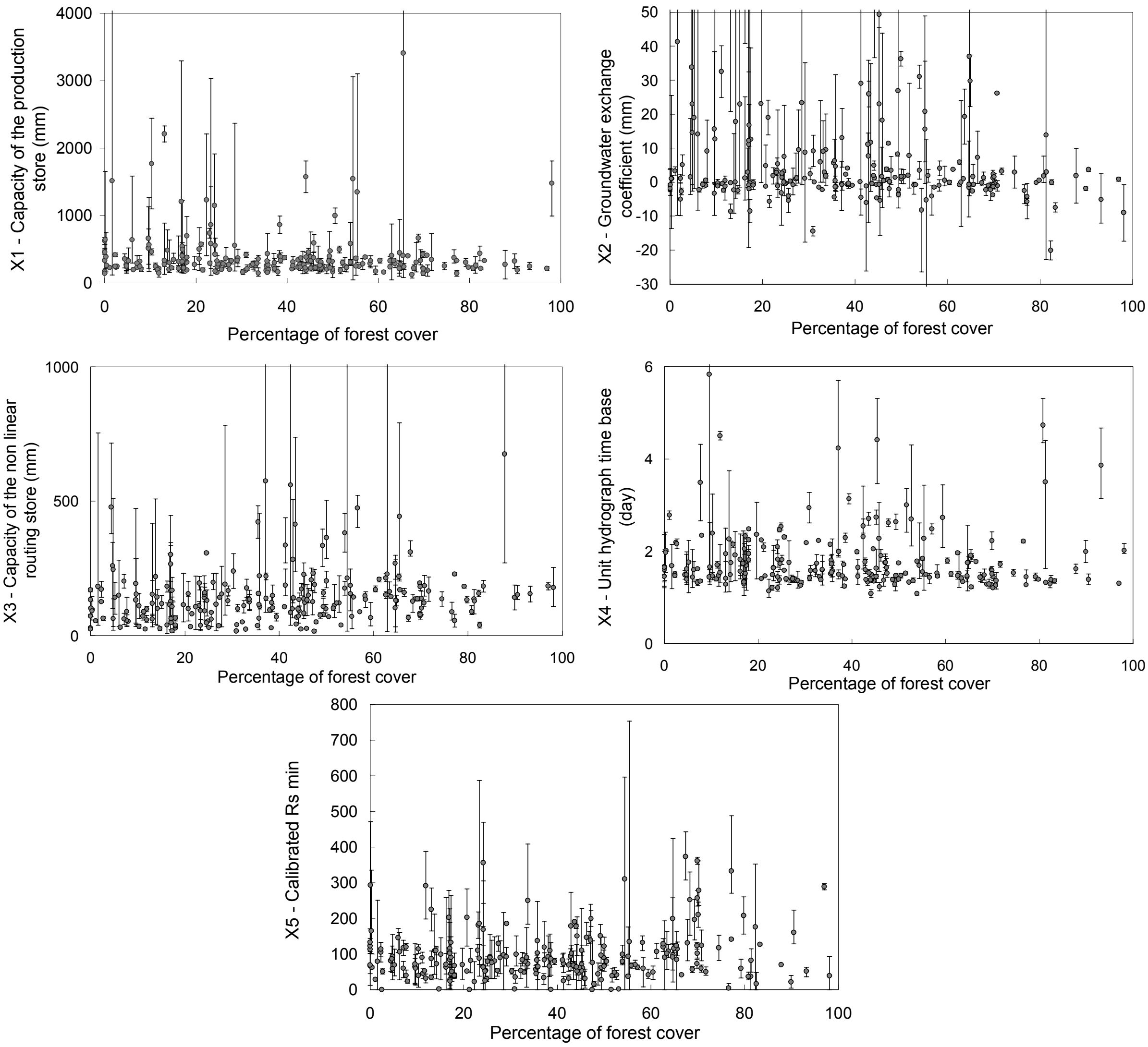

Fig. 4 Calibrated values of the SVAT-oriented model plotted against the percentage of forest cover. Error bars show the range of the calibrated parameters over one catchment.

parameters. Fig. 3 presents the Nash-Sutcliffe and water balance criteria obtained with the original rainfall–runoff model, and the modified structure over the 221 catchments in validation mode. Strikingly, the two structures perform very similarly and no systematic gain is obtained with the refined structure. These findings are supported by previous research, see e.g. Perrin *et al.* (2001) and Schulz & Beven (2003): increasing model complexity does not necessarily increase its performance.

Fig. 4 compares the calibrated parameters of the SVAT structure and the catchment attributes. In comparison with the relationships plotted in Fig. 2, the situation has not improved:

– The four initial GR4J parameters remain impossible to predict from the catchment vegetation attributes.
– The additional parameter does not appear to be related to vegetation type, while it is in theory related to the minimum value of the stomatal resistance. Besides, large error bars observed suggest that this parameter is not determined precisely, and increases uncertainty on the calibration of other parameters, particularly X2, which is related to groundwater exchanges modelling.

CONCLUSION

In this paper, we tried to establish relationships between the GR4J rainfall–runoff model parameters and catchment vegetation characteristics over a large and varied sample of 221 French catchments. We found no satisfying relationships, strengthening previous findings of similar large-scale experiments (Merz & Bloschl, 2004). Given the lack of such relationships, we modified the part of the model structure handling evapotranspiration. This new structure, based on the Penman-Monteith scheme, is more physically based and was expected to lead to more significant correlations between model parameters and catchment vegetation characteristics. However, this modification was unsuccessful since there was no improvement of the GR4J model performance in validation mode over the 221-catchment sample and the regionalization relationships were not improved.

One could argue that the model structure is still not satisfactory from a physical point of view. This may be a cause of our failure to find relationships between model parameters and catchment vegetation attributes. However, if such relationships exist, it should have been easy to detect them using a parsimonious model.

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