How To Account For Groundwater Exchanges In Rainfall-Runoff Models?

[1]N. Le Moine, [1]V. Andréassian, [1]C. Michel and [1]C. Perrin

[1]CEMAGREF, Hydrosystems and Bioprocesses Research Unit, Antony, France
Email: vazken.andreassian@cemagref.fr

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EXTENDED ABSTRACT

Rainfall-runoff models sometimes have to deal with hydrological systems for which the water balance cannot be closed without taking into account the relation between surface and groundwater. In this study we intend to clarify in which kind of situations surface hydrologists should worry about these relations. We also conduct a preliminary study about how underground exchanges could be integrated into a conceptual (reservoir-type) lumped rainfall-runoff model. We examine the different options which modellers use to close the water balance, and we study the likelihood of each solution. We show that both from the hydrological likelihood as well as from the modelling efficiency point of view, it is better to use explicitly a groundwater loss representation. Commonly used correcting factors applied to the climatic input data (rainfall and evapotranspiration) must be avoided in rainfall-runoff models, as they may lead to obviously unrealistic parameter values and yield a similarly unrealistic fluxes distribution.

1. INTRODUCTION

For many years, catchment modellers have been considering surface (i.e. topographic) catchments as watertight systems. Over the long term and at the catchment scale, total runoff Q is seen as the difference between rainfall P and actual evapotranspiration AE. This assumption, that we can call the 'watertight substratum' hypothesis, led to the development of many models based on interannual water balance closure ($P = Q + AE = Q + \alpha\, PE$ with $\alpha < 1$).

However, this assumption does not lay on any physical basis. Beven (2001) emphasizes that "*[...] we cannot currently close the water balance by measurement. Traditionally, there was no direct way of measuring actual evapotranspiration, so errors in the long term measured water balances tended to be assigned to the evapotranspiration term, despite the fact that we know that rainfall inputs, discharge outputs and changes of storage are not always accurately measured. [...] There is still no way of checking whether the catchment is indeed watertight. The continuity equation is the most fundamental law in hydrology, but as a hypothesis it would appear that we cannot currently verify it at the catchment scale.*"

Indeed, some theoretical developments as well as many field studies based on hydrogeological, geochemical or isotopic analysis tend to question the 'watertight substratum' hypothesis in many physiographical settings. This evidence for interbasin groundwater flows (IGF) will be discussed in section 2. For surface hydrologists, such 'pathological cases' may be of minor importance since it is quite rare to find *obviously* non conservative systems, i.e. catchments for which maximum PE rate cannot even account for the total discharge deficit $P – Q$. In section 3, we discuss the possible ways to account for these groundwater losses in lumped rainfall-runoff models and we explain the purpose of the tests performed in this study. Section 4 introduces the monthly and daily time step models as well as the large set of French catchments used for these tests, and the results are presented in section 5. In section 6 we present an attempt to link the parameter of an explicit 'groundwater exchange' function with some physical characteristics of these catchments. Believing that the computation of a 'realistic' water balance – i.e. a right distribution between discharge, evaporation and groundwater loss terms – is a way to improve rainfall-runoff models, we discuss the perspectives of our work in section 7.

2. REJECTING THE 'WATERTIGHT SUBSTRATUM' HYPOTHESIS?

In many geological settings, hydraulic connections with lower geological horizons, or neighbouring catchments, prevents use of a conceptual watertight boundary isolating a given topographic catchment. The connection can be of two types: continuous or discrete.

Hydraulic connection through continuous porous media can lead to the development of regional groundwater flows and diffuse leakage from surface catchments. Theoretical analysis by Toth (1963, 1995) shows that even in homogeneous continuous permeable medium, appropriate topographic settings will allow regional flow systems to develop and cross-out local topographic boundaries. In the large Paris sedimentary basin in France, many rivers have a low water yield (annual discharge about 100-200 mm for a total rainfall about 800 mm) which is related with the presence of the Chalk aquifer.

But connection can also occur through discrete structures such as fractures in crystalline bedrock, or solution sinkholes and channels in karstified limestone (Goswami and O'Connor, 2005; Latron, 2003). These localized gains or losses will sometimes be materialized by karstic resurgences or artesian springs. Thyne *et al.* (1999) show that igneous and metamorphic rocks cannot be considered as flow barriers where there is extended faulting and fracturation. Tectonic discontinuities could allow ascending or descending drainage by connecting different confined bedrock aquifers (Carrillo-Riveira, 2000; Carillo-Riveira *et al.*, 1996) as well as karstic aquifers (Hudson and Mott, 1997).

We can sum up these conclusions in few words which will sound trivial to hydrogeologists: in all cases where either continuous or discrete permeable pathways connect the catchment's saturated domain with lower/higher hydraulic head regions, substantial groundwater loss/gain is likely to occur and affect the surface water balance.

3. HOW CAN WE CLOSE THE WATER BALANCE AT THE CATCHMENT SCALE?

Accepting that any surface catchment cannot be considered *a priori* as a watertight system, catchment modellers may however ask the following question: how important is this issue for us surface hydrologists, and how can we take it into account in our lumped rainfall-runoff models?

At the catchment scale, we hardly have any clue to guess what type of physical fluxes the discharge deficit represents. Is it evapotranspiration only, or does it include a groundwater loss component? How can we even be sure that there is no bias due to the wrong estimation of rainfall, potential evapotranspiration or catchment area?

Many rainfall-runoff models now include functions which are supposed to represent groundwater losses or gains (mainly for the modelling of karstic catchments). Among them we can mention SMAR (Goswami and O'Connor, 2005), IHACRES (Ivkovic *et al.*, 2005) or GR daily and monthly models (Perrin *et al.*, 2003; Mouelhi *et al.*, 2005) which are all using one-parameter functions. Figure 1 gives an illustration of how useful a loss function can be for a non-conservative catchment.

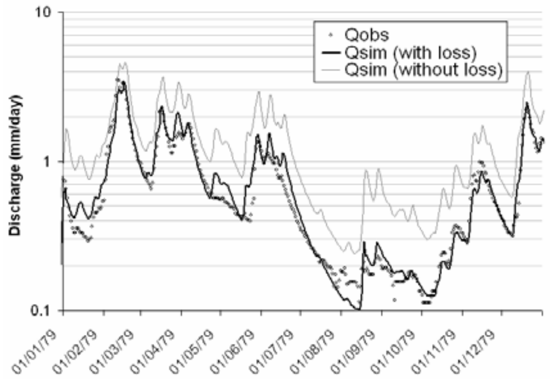

Figure 1: Effect of removal of the loss function on simulated hydrograms
(Rivers Laignes, France, year 1979)

But from a hydrological point of view, we would like to be sure that groundwater gain/loss functions yield the right distribution between atmospheric and underground fluxes, and that the additional parameter is not just a "fudge factor". And from a pragmatic point of view, we can wonder how different the efficiency would be if the additional parameters were dedicated to the scaling or correction of input data, rather than to the representation of extra phenomena. For this reason we tried to replace the existing one-parameter groundwater exchange functions by input data corrections (alternatively rainfall, PE and catchment area using the extra parameter), in two parsimonious rainfall-runoff models developed at Cemagref. These are namely the two-parameter monthly time step GR2M model (Mouelhi *et al.*, 2005) and the four-parameter daily time step GR4J model (Perrin *et al.*, 2003) presented in the next section.

The purpose of our tests is to answer the following two questions:

- Does the explicit representation of groundwater exchanges improve runoff simulation, both in a sense of efficiency (calibration) and robustness (control)?
- How likely are the alternative solutions (mainly the distribution of scaling / correcting parameters)?

4. MODELS AND DATA

In the monthly time step GR2M model (Figure 2), the first parameter X_1 is the capacity of the production reservoir (soil moisture accounting). The second one X_2 is dedicated to the computation of a groundwater exchange F formulated as a linear function of storage in the routing store: $F=X_2.R$. The development of this model showed that this parameter was much more sensitive than the capacity of this routing reservoir, which was finally set as a constant.

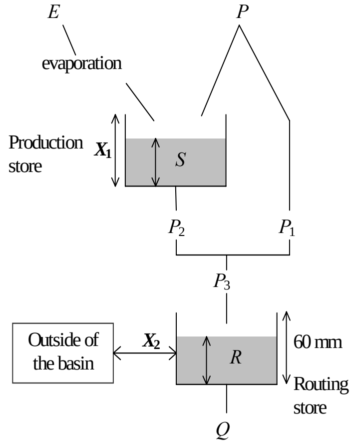

Figure 2: Structure of the GR2M model

In the GR4J daily time step model (Figure 3), the daily water exchange is calculated from the storage ratio in the routing reservoir with the function: $F = X_2 (R/X_3)^{7/2}$. The significance of the parameters is given in Table 1.

Table 1: list of the parameters of the GR4J rainfall-runoff model and their signification

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

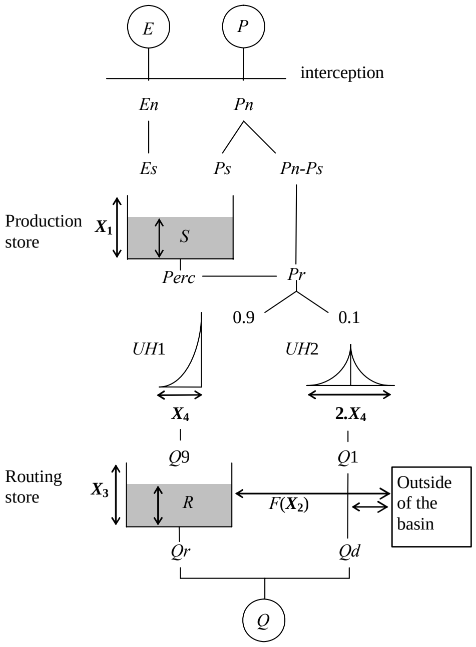

Figure 3: Structure of the GR4J model

The data set used in this study includes 102 French catchments. Information about this set is provided in Table 2 and the location of these catchments is shown on Figure 4.

Table 2: characteristics of the catchment set used in the study

Number of catchments	102
Average catchment area (km²)	1494
Median catchment area (km²)	457
Maximum catchment area (km²)	43700
Minimum catchment area (km²)	11

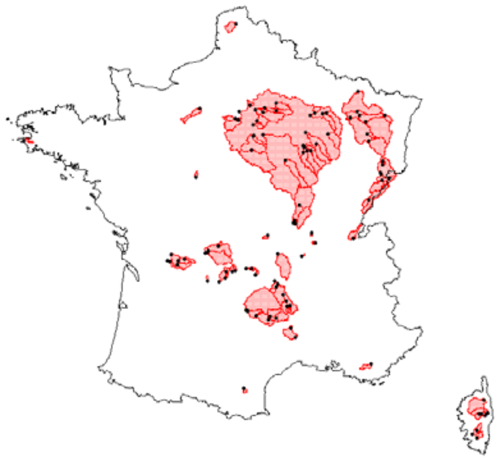

Figure 4: Map of the catchments used in the study

Table 3: Summary of the modifications tested on the models

	PE correc-tion	Rainfall correc-tion	Catchment area correction	Ground-water exchange function
GR4J daily model	$E' = X_2.E$ ($X_2 > 0$)	$P' = X_2.P$ ($X_2 > 0$)	$S' = X_2.S$ ($X_2 > 0$)	No modifica-tion ($X_2 > 0$ or < 0)
GR2M monthly model	$E' = X_2.E$ ($X_2 > 0$)	$P' = X_2.P$ ($X_2 > 0$)	$S' = X_2.S$ ($X_2 > 0$)	No modifica-tion ($X_2 > 0$ or < 0)

5. RESULTS

5.1. Efficiency of the solutions tested

Figure 5 shows the distribution of Nash criterion values in calibration and verification periods for the solutions tested. The test performed for each catchment is a split sample test in which each half record is used once for calibration and once for verification.

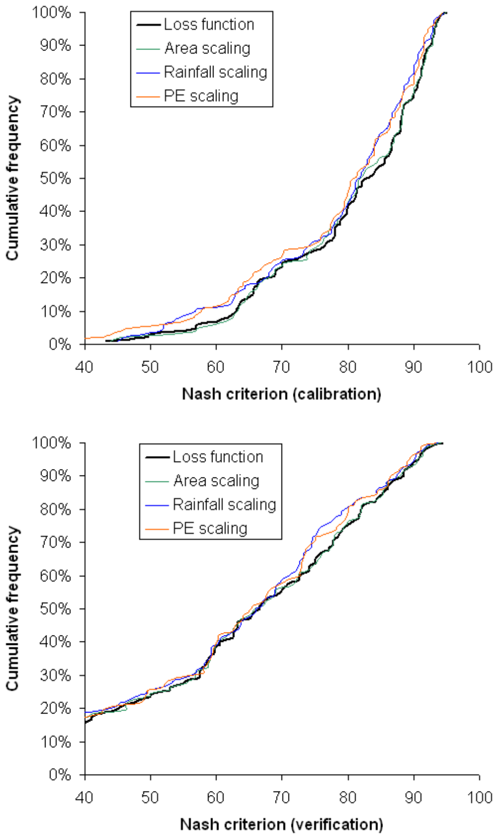

Figure 5: Distribution of Nash criterion for the solution tested: results in calibration periods (left) and verification periods (right). Results obtained with the daily GR4J model.

The use of the groundwater exchange function appears to be both the most efficient and robust solution. Statistics about these distributions are presented in Table 4. However, we must recognize that the differences are not very large and may not be significant. This is why we have to examine now the physical likelihood of each numerical solution.

Table 4: Efficiency statistics of the solutions tested, while replacing the groundwater exchange parameter of GR4J by a scaling parameter

	Calibration		Verification	
	Mean	Median	Mean	Median
Groundwater exchange function	80.1	83.3	63.3	66.6
Area scaling	80.0	82.1	62.9	66.5
Rainfall scaling	78.5	81.9	61.2	66.5
PE scaling	77.9	81.2	60.8	65.4

5.2. Hydrological likelihood of tested solutions

The difference between climatic data scaling (Rainfall and PE) and area scaling is worth being analysed: it seems more sensible to consider that only a part of the catchment contributes to the observed discharge (or an outside extra part if there is a gain), than to consider that the climatic inputs are very badly estimated and need to be scaled. Given the fact that topographic and groundwater drainage basins may not perfectly overlap, scaling the catchment's area is not very far from introducing a groundwater exchange function: the first solution would be the hydrogeological approach (looking for the *actual* drainage system explaining the discharge with current climatic data), whereas the second one keeps the topographic catchment as the main hydrological object.

This point may be confirmed by the analysis of scaling factor distributions shown on Figure 6. Indeed if Rainfall or PE input data is badly estimated due to measurement errors and/or non-representativeness of the climatic stations, the resulting scaling factor distribution should follow a kind of Gaussian distribution centred on 1 (or a bit higher for rainfall since rain gauges tend to underestimate the actual rain). In contrary, mean Rainfall correction is about 0.91 which would mean that rainfall is overestimated in average. PE scaling seems unlikely as well, the necessary increase exceeding 30% of the initial value for 24% of the catchments. Since PE is never integrally 'converted' into discharge deficit, using a PE correction to correct the water balance leads to increase it in a rather excessive way (highest PE often occurring during lowest water availability periods).

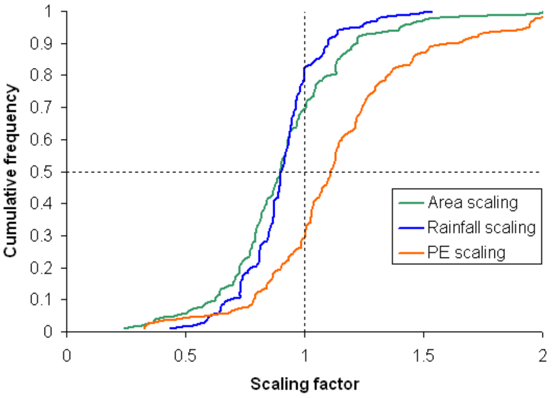

Figure 6: Cumulative frequency (occurrence distribution) of parameter value in the different solutions tested.

Consequently, we may say that considerations about the hydrological likelihood of the different solutions confirm the conclusions based on the efficiency of the respective solutions.

6. PHYSICAL CONTROLS OF GROUNDWATER EXCHANGES

This section presents an attempt to use topographical and geological information to infer the parameter controlling the groundwater exchange function in the monthly (GR2M) and daily (GR4J) models tested here.

Spatial analysis with GIS allows determining which lithology is dominant over each catchment (in terms of area). Table 5 as well as Figures 7 and 8 show that the dominant lithology is able to discriminate between different values of the exchange parameter, at least in the sense of an *a priori* distribution. The curves plotted appear to be easily distinguished and even seem to match the typology of interbasin groundwater flows defined in section 2:

- Lowest values (high losses) are observed for chalk, alluvia or limestone catchments. The first two categories may allow diffuse leakage while the third one is subject to karstification.

- For crystalline bedrock catchments, the exchange parameter distribution is centred on zero, with much less variability than the previous ones. It is more likely a pure random correction which may – this time – account for uncertainties in rainfall estimation, especially since many of these catchments are located in the Massif Central highlands.

Of course this information is not enough to assess directly the value of the parameter, since it is only qualitative. Inside each class of lithology some variability remains. But it can help us constrain the range in which to look for the best parameter during calibration. Moreover, the use of other data on the physical controls of recharge and groundwater flow could lead to an even narrower range.

Table 5: Distribution of exchange parameter for class of lithology

Lithology	Number of catchments	Mean parameter value (GR4J model)	Mean parameter value (GR2M model)
Alluvia	8	-1.04	-0.274
Chalk	4	-4.41	-0.197
Massive limestone	28	-1.18	-0.162
Crystalline bedrock	38	-0.15	-0.058

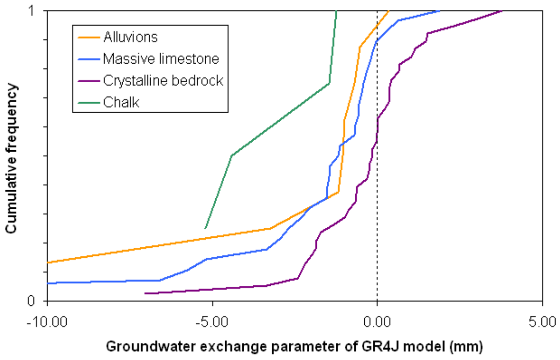

Figure 7: Groundwater exchange parameter distribution for each class of lithology, GR4J daily time step model

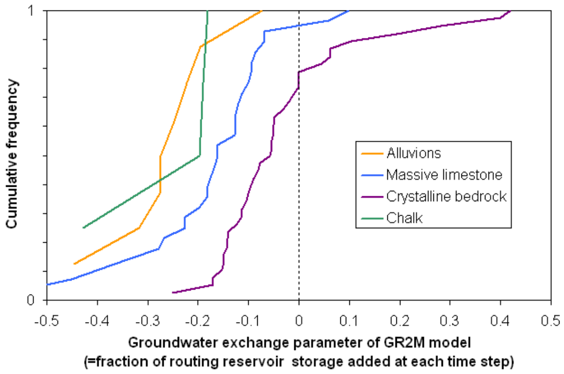

Figure 8: Groundwater exchange parameter distribution for each class of lithology, GR2M monthly time step model

7. CONCLUSION

This study aimed to investigate several options allowing adjusting the water balance in a rainfall-runoff model, to verify that explicitly accounting for groundwater exchange fluxes is necessary for rainfall-runoff models. Further work to improve the formulation of an exchange function using one or two parameters, could be one of the way to reduce uncertainty in water balance estimation and indirectly in the estimation of other parameters. Correlation between exchange fluxes/parameters and physical characteristics of the catchments is still worth being investigated (especially geology, topography and soil occupation which control recharge and thus the amount of water made available for groundwater flow) in order to constraint the calibration process. The development of such a 'realistic' function could temporarily necessitate additional data, like groundwater levels, in order to provide information on internal state variables of the model, but the resulting structure should remain efficient over large sets of catchment and parsimonious both for the number of parameters and the amount of data used in calibration.

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