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Parameter Estimation of a Conceptual Rainfall Runoff Model and Application to Mediterranean Catchments

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Abstract: Development of methodologies to achieve a priori parameter estimation of hydrological models is fundamental in ungauged basins, to reduce the number of parameters to be calibrated or to obtain parameter values where calibration is not possible. This work shows that conceptual rainfall-runoff models can be applied to ungauged watersheds by developing relationships between model parameters and watershed characteristics. In fact, the calibration of MEDOR, a four parameter daily lumped conceptual rainfall-runoff model specific for the Mediterranean catchments, is affected by the equifinality issue. Systematic scanning of the Nash criterion objective function demonstrates that a Production Equifinality Relationship (PER) exists between loss function parameters. This basin-specific relation can be determined using the annual balance of rainfall-runoff and daily rainfall data generated by a stochastic model calibrated for the region. Moreover, the analysis shows the importance of the stochastic structure of rainfall in the calibration of MEDOR. Thus, the parameters cannot be determined solely from the physical properties of the basin. Coupled to a stochastic model of rainfall of a given region, MEDOR generates equifinality relations between runoff coefficients ($C_E$) defining a surface in the parameters space. Several large areas have been identified in the Mediterranean region having a single reference $C_E$ surface (e.g., East coast of the Mediterranean Sea). The runoff coefficient of a given watershed located in one of these areas constrains the specific equifinality relation. In a case study, the PER of two Lebanese watersheds were determined using the same single reference $C_E$ surface and spatial soil depth information. Thus, it is possible to evaluate the predictive uncertainty for the streamflow at the catchments outlet.

Keywords: Hydrological modeling; Regionalization; Equifinality; Ungauged basins

1. INTRODUCTION

Access to daily stream flow data, at a river reach scale, is an operational requirement and necessity for water resource management. However, a large number of the catchments are ungauged, which is the case of several Mediterranean catchments. Hence, there is an urgent need to have easy, consistent, robust and reliable methods for simulating streamflow discharges within ungauged catchments. Thus, prediction of ungauged basins is one of the most challenging issues in the hydrology of this century. One of the difficulties of the prediction is the transfer of information from gauged to ungauged areas. Generally, catchments with similar characteristics show similar hydrological behavior. Thus, it is possible to regionalize model parameters on the basis of catchment characteristics, i.e., to provide a regional parameter set where parameter values vary with measurable catchment characteristics [Seibert, 1999]. This regionalization can be made using relationships between the parameters of the model and the catchment characteristics. The research methodology for determining relations between parameters and catchment descriptors usually employs multiple regressions [Hughes, 1989; Post and Jakeman, 1996]. Their differences lie essentially in the nature of the selected descriptors. Typically, the obtained results are not good enough to allow...
reliable application on ungauged catchments [Perrin et al., 2001]. Most of the studies focus on descriptors related to the topography, e.g., slope, drainage network, vegetation, often in relation with the remote sensing. Other studies take climate into account in these relations using climate characteristics, e.g., mean rainfall, average temperature, etc. These global climate characteristics do not use the fine permanent characters of the rainfall, which are represented by its stochastic structure.

This work shows the role of the stochastic structure of the rainfall in the a priori estimation of the parameters of a simple conceptual rainfall-runoff model, MEDOR, working at a daily step. The objective is to reduce the number of parameters of the model by taking into account the location of the catchment in a given geographical area having homogeneous climate. The introduction of the stochastic rainfall modeling [Hreiche et al., 2003], helps in the regionalization of model parameters, and in the determination of predictive uncertainty.

2. THE MODEL AND ITS CALIBRATION

2.1 The model

The MEDOR model [Hreiche et al., 2002] is a conceptual rainfall-runoff model which simulates daily streamflow using only daily rainfall as input. It was especially developed for the Mediterranean climate.

The structure of the model is represented in two separated functional modules: a production module and a transfer module, each having two parameters (its structure is given in Figure 1). This separation allows analysis of the respective roles of parameters: Two production parameters ensure the exactness of the streamflow balances and two transfer parameters modulate the realization of the simulated daily streamflow.

This specific structure results from two properties of the Mediterranean climate:
- A cold “rainy season” during which the actual evapotranspiration (ET) is at a minimum; and whose variations do not impact on the production function. Daily ET can be represented by a constant EVL.
- A dry season which leads to very low streamflow and has negligible interannual carry-forwards, which emphasizes the independence of hydrologic years.

2.2 The criterion

The criterion chosen in this paper is the Nash-Sutcliffe criterion [Nash and Sutcliffe, 1970], which is widely used and may be represented as follows:

$$Nash = 1 - \frac{\sum (q_{mes} - q_{sim})^2}{\sum (q_{mes} - \bar{q}_{mes})^2}$$  \hspace{1cm} (1)

($q_{mes}$: daily measured streamflow, $q_{sim}$: daily simulated streamflow, $\bar{q}_{mes}$: mean measured streamflow)

2.3 Study catchments

The model was successfully tested on six Mediterranean catchments, located in Lebanon and France. The data comprised daily volumes of mean rainfall from several rain gauge locations, and concomitant daily streamflows from the catchment.

Table 1. Optimized parameters, Nash-Sutcliffe criterion values and runoff coefficient $C_E$

<table>
<thead>
<tr>
<th>Catchment</th>
<th>H (x10^-3)</th>
<th>EVL</th>
<th>R</th>
<th>T</th>
<th>$N_{cal}$</th>
<th>$N_{val}$</th>
<th>$C_E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nahr Beirut</td>
<td>0.56</td>
<td>4</td>
<td>0.6</td>
<td>28</td>
<td>0.73</td>
<td>0.75</td>
<td>0.41</td>
</tr>
<tr>
<td>Nahr el Kelb</td>
<td>0.14</td>
<td>3</td>
<td>0.16</td>
<td>76</td>
<td>0.72</td>
<td>0.62</td>
<td>0.61</td>
</tr>
<tr>
<td>La Mimente</td>
<td>0.14</td>
<td>6</td>
<td>0.96</td>
<td>10</td>
<td>0.73</td>
<td>0.70</td>
<td>0.57</td>
</tr>
<tr>
<td>G. de Mialet</td>
<td>0.1</td>
<td>4.5</td>
<td>0.72</td>
<td>22</td>
<td>0.68</td>
<td>0.67</td>
<td>0.5</td>
</tr>
<tr>
<td>La Vis</td>
<td>0.21</td>
<td>3</td>
<td>0.68</td>
<td>10</td>
<td>0.83</td>
<td>0.81</td>
<td>0.64</td>
</tr>
<tr>
<td>La Muze</td>
<td>0.22</td>
<td>3</td>
<td>0.24</td>
<td>10</td>
<td>0.57</td>
<td>0.54</td>
<td>0.4</td>
</tr>
</tbody>
</table>

The MEDOR model applied on these watersheds gives acceptable Nash-Sutcliffe values. Table 1 shows for each catchment the runoff coefficient ($C_E$), the optimized production parameters (H,EVL) and transfer parameters (R,T), and the criterion values, in calibration ($N_{cal}$) and validation ($N_{val}$) respectively.

3. CALIBRATION AND EQUIFINALITY

The calibration procedure used involves the identification of a number of parameters that are identified by calibration methods using a series of measured rainfall-runoff data. One of the difficulties of this method is due to equifinality problems where a number of sets of model parameters may lead to equivalent results [Beven, 1993]. Equifinality is common in hydrologic models. It has been demonstrated [Hreiche et al., 2002] that the MEDOR model has an equifinality problem. In the current case there was an exhaustive search of the criterion function in a reasonable grid of the parameters: 1,476,800 simulations were made by using High Performance Computing and Networking. The surface objective function within the (H,EVL) space possesses a ridgeline that separates the two sides of the surface. The Nash values along this line are sufficiently close to make it possible to regard them as equivalent. Its projection on the (H, EVL) space...
represents a relation of equifinality between the parameters of production, or PER. It was demonstrated that the PER is independent of the transfer parameters. Thus it is possible to determine the production parameters in advance, independently of those of transfer.

4. DETERMINATION OF THE PER

The independence of the annual chronology was verified by checking that results are unchanged if the order of the data is changed on a yearly scale. As a consequence, the "production" at the annual time step does not depend on the transfer, but depends only on two parameters H and EVL.

The use of a Nash-Sutcliffe criterion with variable term allows the PER to be determined from the annual balances or the total balance. Indeed, if daily accumulations are correctly modelled, those at 2 days, 8 days, 1 month and 1 year will also be accurate. An average agglomerated streamflow over n days is defined using mean streamflow at a daily step: \( q_{agglo} = \frac{1}{n} \sum q_{daily} \). These “agglomerated” series give a criterion of “agglomerated Nash”:

\[
N_{agglo} = 1 - \frac{\sum (q_{applicant} - q_{calculated})^2}{\sum (q_{moyen} - q_{applicant})^2} \tag{2}
\]

At a daily time step, this expression corresponds to the usual Nash-Sutcliffe criterion. At the annual step, \( N_{agglo} \) expresses the variations of the annual volume of streamflow. The evolution of PER was analyzed with an agglomerated criterion using accumulations on the scales of 2, 4, 16, 30 and 365 days. This PER changes slightly until the annual step is reached (Figure 2). This variation is very small and does not affect the results of this analysis.

The agglomeration on the whole set of the data series gives a relation of total balance by the equality between the total volume of measured streamflow on all the period and the simulated one given by:

\[
B_T (H, EVL, rainfall data) = B_T (streamflow data) \tag{3}
\]

and can be compared to the whole set of the PER at variable steps. Figure 2 shows that different PER (monthly, annual and total) are similar to the daily PER. Therefore, the PER of the daily model, which is determined by an exhaustive scanning of the parameters of the model in the criterion space by using daily rainfall-runoff data, can be determined by using the daily rainfall and the annual discharge or the total discharge. The agglomeration of the streamflow data decreases the quantity of information used to fix the PER. Since the agglomeration involves only the streamflow, the PER is determined by the daily rainfall and annual discharge or total discharge. In the absence of daily values of streamflow, individual rainfall values cannot yield relevant information for the calibration of the model. However, useful information can be obtained from the stochastic structure of the rain and its annual accumulations and it allows the determination of the PER.

5. DEPENDENCE OF THE PER OF THE STOCHASTIC RAINFALL MODEL

The local rainfall time series constitutes a particular realization of a stochastic process. The stochastic model of daily Mediterranean rainfall [Najem, 1988] was used in this work. The adjustment of the local parameters of the model with the available rainfall data series for a Beirut station allows to generate rainfall data series of arbitrary length. The real rainfall series is replaced by a generated series of the same stochastic model having the same annual totals. A sorting of the generated years was made in order to retain the years to which the totals are closest to those of the real series. The two annual PER for both the measured and generated series, which are obtained by exhaustive scanning of the criterion in the parameters space, are similar. This shows that the only relevant information in the rainfall data is its stochastic structure. Thus the PER can be determined from only the annual balance and the stochastic structure of rainfall.

6. A PRIORI DETERMINATION OF THE PRODUCTION PARAMETERS

6.1 MEDOR: a non-dimensional stochastic generator of streamflows

The criterion of total balance expresses the equality between the total simulated flow which depends on the parameters H, EVL and of the rainfall data series and the total volume of discharge resulting from streamflow measurements.
MEDOR generates a surface iso-balances, $B^*_r = B^*_r (H, EVL)$ by systematic scanning of all the $H$, $EVL$ space. This surface, which depends only on the stochastic structure of rainfall, can be generated independently of any input data from a given basin. Expressed in meters per year, it constitutes a climatic characteristic associated with MEDOR. The value of the mean annual measured streamflow $B^*_T$ defines the cut of this surface for $B^*_r = B^*_T$. It is projected in the $(H, EVL)$ space according to the PER of total balance. The stochastic structures of rainfall in the same region have common characteristics, which allows regionalization. Indeed, for Lebanon, the regional analysis of the characteristics of the stochastic model of rainfall, shows:

- The seasonal modulation of the parameters of the rainfall alternation $T_1, T_2$ (characteristic times of a Markovian alternation of the 1st order) is identical for the different Lebanese stations.
- Daily intensities having the same non-dimensional statistical distribution, but with different averages dependent on the location.

In a homogeneous climatic region (for example Lebanon), local stochastic structures are different only by their mean daily intensity. By referencing the rainfall to the mean intensity $P_M$, we can define a non-dimensional rainfall which has an identical structure for all the stations in the area. The MEDOR model, forced by stochastically generated rainfall, becomes a stochastic runoff generator. The non-dimensional form of the MEDOR equations, complemented by the non-dimensional structure of rainfall, allows definition of the non-dimensional variables that characterize this generator, in particular the runoff coefficient of the catchment: $C_E$ (non-dimensional ratio of the streamflow volume and the precipitation volume). Thus, the MEDOR model generates a non-dimensional surface which characterizes the climatic region according to the production parameters $C_E = C_E(H/P_M, EVL/P_M)$. This allows regionalization of the PER, giving its variation across different basins.

6.2 Regionalization of iso-CE surfaces

The analysis of iso-$C_E$ surfaces is made using the projection of the cuts of the surface for defined values of $C_E$. The determination of iso-$C_E$ surfaces requires long rainfall series. We selected 36 pluviometric stations with long series distributed on the Mediterranean basin. The iso-$C_E$ surfaces of Beirut, Harkenaan and Telaviv show considerable
similarity, which allows them to be a reference for this region. Other stations, e.g., Nimes, have a different surface. The results of the 36 stations allows to define homogeneous zones for MEDOR, i.e. whose stochastic rainfall models generate similar iso-C$_E$ surfaces.

Figure 4. Location of the 36 rain gauge stations used for the regionalization and the iso-index cartography.

The Mediterranean basin can be divided in five homogenous zones (Figure 3): the Eastern Mediterranean zone; the zone of the Islands of the Eastern Mediterranean; the "Balkan" zone; the Southern Iberian zone; the Central Mediterranean zone which gathers a vast group starting from the North of Spain in Greece passing by France, Italy and Tunisia. A great similarity exists between iso-C$_E$ surfaces of the same zone. An average station defines a regional surface of reference. Figure 4 shows the regional surfaces iso-C$_E$ projections on ($\ln(H / P_M)$, $\ln(EVL / P_M)$) space of the five defined zones.

6.3 Interpretation

Beyond the general similarity, marked by seasonality, the most important difference between the climates of the various Mediterranean regions concerns the degree of severity and the duration of the summer aridity. The difference between the rainy season and the dry season can be characterized by an index of seasonal variation, which plays an essential role in the hydrological functioning by modulating an interannual carryforward of the hydrological balance.

This index is defined starting from the rainy moving average over 3 months.

$$I_s = 1 - \frac{\min(C)}{\max(C)} \text{ with } C(t) = \int_{t-3\text{months}}^{t} P(t) dt$$

(4)

Figure 5 shows the zones of equivalence of two Lebanese rivers. They are well centered on corresponding PER, and the Nash values are very close along these PER. These zones move on the PER depending of the length of the series. This result was verified on four French catchments in the Languedoc region. The reference station is Nimes, which is the closest rainfall station with the longest data series. The knowledge of this PER allows the number of degrees of freedom of the model to be decreased by one by creating a relation between the two production parameters. This relation is not an overparametrisation of the model because it is local
in relation with the location of the catchment in a defined climatic zone. The a priori estimation of this PER reduces to three the number of parameters to be calibrated.

8. _PREDICTIVE UNCERTAINTY_

An uncertainty on the value of C_E exists. This uncertainty is bound to the small number of annual data records. It can be estimated using generated rainfall and simulated streamflow data with variable length. Figure 6 shows the sensitivity of C_E to the length of the data series.

9. _CONCLUSIONS_

The search for optimal parameters in terms of representation of the time series of existing data using a criterion shows equifinality relations between parameters. This equifinality is demonstrated by the existence of a relation between the 2 parameters of production (PER). It is not, however, an over-parameterization of the model, but it is a specific property of the model, the catchment and the climate.

The stochastic structure of the rainfall has an important role in the calibration of MEDOR. In particular, production parameters can be determined using a stochastic regional rainfall generator and the annual balances or the total balance. A change of the stochastic rainfall model modifies the PER, which demonstrates that the production parameters are a function of the fine structure of the rainfall. Hence, parameters obtained by the calibration cannot be bound exclusively to the physical characteristics of the catchment.

The regional analysis of the statistical structure of the rainfall, associated with a non-dimensional representation of MEDOR, highlights the regional behaviour of the runoff coefficient of the catchment. This behaviour allows the Mediterranean basin to be classified into 5 distinct climatic regions. The knowledge of the runoff coefficient of a catchment allows the PER to be defined on the surface relative to its region, therefore reducing the number of parameters and simplifying its calibration. This knowledge can be obtained either by using catchment descriptors, or by using a short measured data series, with an uncertainty function of the length of the data record.

10. _REFERENCES_


