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EHSM: a conceptual ecohydrological model for daily streamflow simulation

F. Viola,* D. Pumo and L. V. Noto

Dipartimento di Ingegneria Civile, Ambientale, Aerospaziale, dei Materiali, Università degli Studi di Palermo, Viale delle Scienze, Edificio 8, 90128 Palermo, Italy

Abstract:

A parsimonious conceptual lumped model is here presented with the aim of simulating daily streamflow in semi-arid areas. The model, processing daily rainfall and reference evapotranspiration at basin scale, reproduces surface and subsurface runoff, soil moisture dynamics, and actual evapotranspiration fluxes. The key elements of this numerical model are the soil bucket, where rainfall, evapotranspiration, and leakage drive soil moisture dynamics, and two linear reservoirs working in parallel with different characteristic response times. The surface reservoir, able to simulate the fast response of the basin, is fed by rain falling on impervious area and by runoff generated with excess of saturation mechanism, whereas the deep reservoir, which simulates the slow response, is fed by instantaneous leakage pulses coming from the soil bucket. Seven model parameters, which summarize soil, vegetation, and hydrological catchment properties, are assessed on a Sicilian basin, first using simple basic ecohydrological knowledge and then Monte Carlo simulations as well.
The proposed model provides reliable estimate of daily runoff, accurate reproduction of flow duration curve, and physically consistent traces of soil moisture and evapotranspiration fluxes. Model performances are comparable in the two cases of calibrated and ecohydrologically driven parameters, emphasizing how basic descriptors are able to provide runoff estimation.

KEY WORDS ecohydrological model; rainfall–runoff model; flow duration curve

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INTRODUCTION

Runoff has been often considered as a side effect in ecohydrology, where the researcher interest has been more focused on soil moisture and related vegetation water stress dynamics. Using the terminology introduced by Rodriguez-Iturbe *et al*. (2011), green or biotic basin metabolism has attracted much more attention than blue metabolism under the ecohydrological framework.

From the beginning of the ecohydrology literature (Rodriguez-Iturbe *et al*., 1999), the key role in describing water-limited ecosystems has been recognized to soil moisture dynamics, which summarize climate forcing and vegetation uptake in soil water balance. Several analytic and numerical studies have been proposed in order to deepen the aforementioned interrelationships (Laio *et al*., 2001a,2001b; Porporato *et al*., 2001; Rodriguez-Iturbe *et al*., 2001). At the point spatial scale, runoff has been treated as missing infiltrated water (excess of saturation) or not retained in the soil (leakage). Botter *et al*. (2007) widened the spatial scale explicitly considering runoff within a basin and analytically describing the baseflow probability density function from rainfall pulses and climate forcings. Runoff is still generated by excess of saturation and/or leakage but is transferred to the basin outlet using a linear reservoir, whose residence times are described by an exponential distribution. Remarkably, the analytic model is able to reproduce a large part of flow duration curves (FDC), excluding the high quantiles, which in arid climates may represent a large amount of water volume. An interesting extension to Mediterranean ecosystems has been proposed by Pumo *et al*. (2013) where different operational approaches are proposed and explored, demonstrating the importance of relating some model parameters to the underlying climatic forcing.

Over the last few years, the relations between vegetational spatial pattern, runoff, and erosion have been deeply investigated and acknowledged (Wilcox *et al*., 2003; Noaman, 2005; Wilcox *et al*., 2005; Huang *et al*., 2006; Bautista *et al*., 2007; Turnbull *et al*., 2010; Jost *et al*., 2012) clarifying how vegetation cover and runoff are intimately linked in determining basin water balance (Guardiola-Clararnonte *et al*., 2011; Adams *et al*.,

*Correspondence to: Francesco Viola, Dipartimento di Ingegneria Civile, Ambientale, Aerospaziale, dei Materiali, Università degli Studi di Palermo, Viale delle Scienze, Edificio 8, 90128 Palermo, Italy.
E-mail: viola@idra.unipa.it

2012; Jost *et al*., 2012; Xu *et al*., 2012). The two aforementioned examples highlight the importance of the 'marriage' between hydrology and ecology (King and Caylor, 2011), notwithstanding the full integration between the two disciplines is still missing. From this point of view, runoff is not an exception, and it is worthy of an integrated approach for its assessment. Even if the ecohydrological framework seems to be the optimal context for modelling runoff as a function of climate, vegetation, and soil characteristics, only few rainfall–runoff (R–R) models have explicitly embedded ecohydrological insights, benefiting of such a multidisciplinary vision (Wigmosta *et al*., 1994; Botter *et al*., 2007).

Over the past years, a wide range of R–R models has been developed and used by researchers and engineers. Conceptual models are probably the most diffused because of their ability in describing catchments processes without including the specific features of process interactions, which would require more detailed catchment information (Sorooshian, 1991). Moreover, conceptual models are less complex than the physically based models, which require a higher amount of climatic input data and parameters. The most important advantage of conceptual R–R models consists in calibrating few parameters, which may retain some physical meaning. Conceptual R–R models have been widely and successfully used for simulating daily discharge at catchment scale. Some examples of conceptual R–R models are the Boughton Model (Boughton, 1965), the *Sacramento Soil Moisture Accounting Model*, developed by Burnash *et al*. (1973), the *Topography-Based Model* (Beven and Kirkby, 1979), the Zinanjiang Model (Zhao *et al*., 1980), the *Probability Distributed Model* (Moore, 1985; Moore and Bell, 2002; Moore, 2007), the *Variable Infiltration Capacity* hydrological model (Wood *et al*., 1992; Kalma *et al*., 1995; Sivapalan and Woods, 1995), the *Identification of Hydrographs and Components from Rainfall, Evapotranspiration and Streamflow Data* (IHACRES; Jakeman *et al*., 1990; Jakeman and Hornberger, 1993), and the *Large-Scale Catchment Model* (LASCAM) (Sivapalan *et al*., 1996).

Ye *et al*. (1997) evaluated how well conceptual models could perform on ephemeral catchments. They also investigated on the level of complexity required by conceptual models for predicting runoff. Namely, they compared performances of the Boughton, IHACRES, and LASCAM models in three Australian basins with different areas (from 0.82 to 517 km^2), showing the importance of including soil moisture dynamics and nonlinearity in runoff generation. The IHACRES model, because of its performances and parsimony, is often considered as a sort of benchmark model for runoff modelling in ephemeral catchments. The IHACRES, which is probably one of the most used conceptual R–R models for arid areas, undertakes identification of hydrographs and component flows purely from rainfall and evaporation. The R–R processes are represented by two modules: a nonlinear loss module transforms precipitation to effective rainfall and a linear module based on the classical convolution between effective rainfall and the unit hydrograph to derive the total streamflow.

The conceptual lumped hydrological model presented in this paper, the *Ecohydrological Streamflow Model* (EHSM), aims to estimate the daily runoff in small semiarid basins, linking soil and vegetational characteristics to model parameters providing, in this way, the basis for the runoff predictions in ungauged basins. The key concept that has guided the implementation of the model is the simplicity, which, in hydrology, means use of few parameters and few key points over which concentrate all the uncertainties arising from data and from the model structure. The model will be used in the Mediterranean area, which is characterized by an alternation of cold/rainy seasons and hot/dry seasons; this alternation affects the dynamics of Mediterranean ecosystems and is reflected in specific patterns of soil moisture dynamics and consequent plants water stress. The greatest difficulty in dealing with such a climatic system is modelling the ephemeral nature of runoff typical of many Mediterranean basins.

The model is described in the Model Description Section, where all the links between model parameters, soil, and vegetation characteristics are explained. The Case Study Section introduces a small ephemeral Sicilian catchment and describes the data used for the model calibration. In the Model Calibration Section, two different parameter sets are identified: one chosen using *a priori* knowledge of the underlying soil, climate, and vegetation conditions and one calibrated using a Monte Carlo procedure. Results are presented in the Results and Discussion Section, where model performances are compared with those relative to the IHACRES in reproducing daily streamflow and with the model of Botter *et al*. (2007) in reproducing FDCs. The model is validated in two time windows, assessing, at the same time, the predictive parametric uncertainty. Performances of the two sets of parameters are compared in order to demonstrate how embedding ecohydrological knowledge in model parameters can drive to satisfactory runoff estimation.

MODEL DESCRIPTION

The concepts behind the model are very simple and mainly related to soil permeability, which within a basin could be highly uneven, vegetation presence together with its role in water uptake, and groundwater hydrological response. Rain falling on impermeable surfaces is directly transferred towards the basin outlet through the river network in a time depending on the area, shape, and river connectivity of the basin. If the rain falls on permeable and vegetated areas, the runoff generation is driven by soil moisture content, which in turn is linked to evapotranspiration and leakage. On the one hand, the soil water content determines if rainfall produces a saturation excess or a leakage loss, and on the other hand, it constrains the evapotranspirative fluxes, so that, when it approaches to the saturation, the actual evapotranspiration tends to the potential one.

The hydrological scheme of the basin, depicted in Figure 1, follows these premises and consists of three interconnected elements: a soil bucket and two linear reservoirs. The surface soil bucket epitomizes in two distinct classes of different soils within a basin: the first class interprets the totally impermeable soil behaviours, whereas the second one describes permeable soils characteristics. The surface soil bucket is linked to the two linear reservoirs: one is responsible for the fast surface runoff component, whereas the other accounts for the slow subsurface runoff component. The surface reservoir is fed by the rain falling on impermeable areas and by the saturation excess generated over the permeable area. These two mechanisms are characterized by comparable times of response and together contribute to the fast component of runoff. The fast component is assumed to be instantaneously transferred to the surface reservoir, which is characterized by a mean residence time having the same order of magnitude of the basin concentration time. The subsurface reservoir, solely supplied by leakage pulses, is typically characterized by longer response times.

Soil water balance

A unit area of soil can be split into an impermeable fraction c_0 and a permeable fraction $(1 - c_0)$, where water infiltration and vegetation presence influence relative soil moisture s. The permeable fraction of soil is characterized by the soil porosity and by the root depth, termed respectively n and Z_r, whose product, known also as 'active soil depth', is considered as a parameter of the model.

Daily rainfall depth R (mm/day), considered as the main climatic forcing, is provided to the model as a time series spatially averaged over the catchment. Rainfall amount falling over the impervious area R_{imp}, equal to c_0R, is transferred to the *surface* linear reservoir, hereafter indicated with the subscript *sup*.

Rain falling on the pervious part of the soil, termed R_{perm} and equal to $(1 - c_0)R$, drives relative soil moisture dynamics. The determination of relative soil moisture

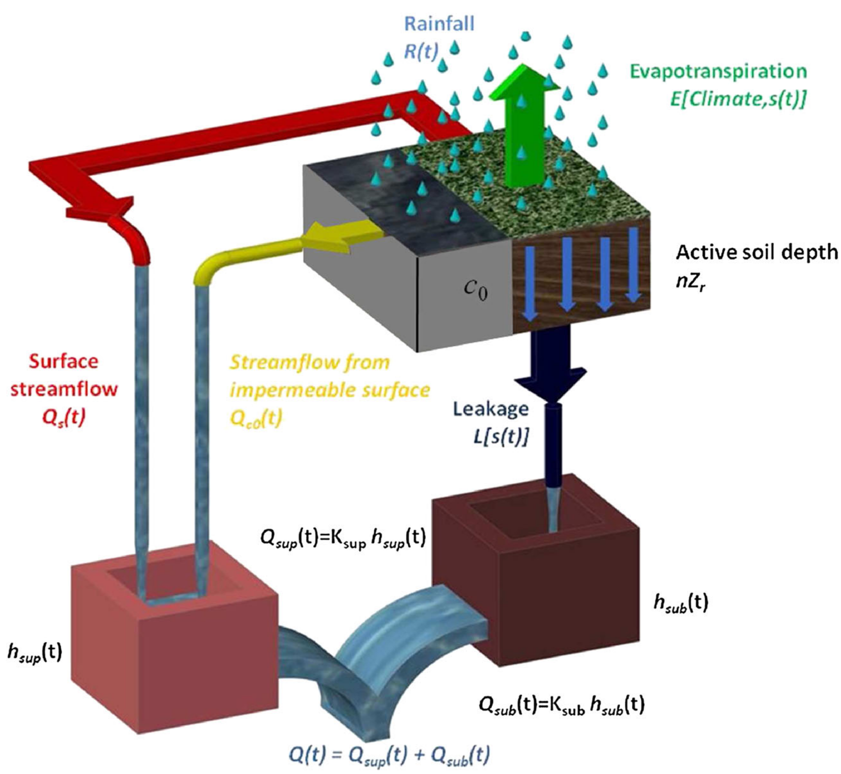

Figure 1. EHSM scheme. See text for details and explanations

variation Δs in the permeable part of the soil bucket during a daily temporal step is achieved with the numerical solution of the following water balance equation carried out through a forward finite differences method:

$$\frac{\Delta s}{\Delta t} = \frac{1}{nZ_r(1-c_0)}\left(R_{perm} - Q_s - ET - L\right) \quad (1)$$

where Q_s is the runoff over the permeable part of the basin, and ET and L represent the soil water losses due to evapotranspiration and leakage, which will be described in the next section. In particular, the runoff Q_s is produced when the rainfall exceeds the maximum storage capacity of the permeable soil equal to $W_{max} = (1-s)nZ_r(1-c_0)$, which is, of course, a function of relative soil moisture s. In this case, the water amount fluxing towards the surface reservoir reads as follows:

$$Q_s = R_{perm} - W_{max} \quad (2)$$

Evapotranspiration and leakage

The interrelation between water losses and soil moisture is a central topic in ecohydrology (Asbjornsen *et al.*, 2011). The relationship between the rate of plant water uptake and the soil moisture is often modelled as a stepwise function (Laio *et al.*, 2001b; Pumo *et al.*, 2008; Viola *et al.*, 2008). Following this approach, evapotranspiration is assumed to occur at a maximum rate E_{max} when soil moisture content is not limiting plant transpiration process, i.e. above the incipient stomata closure point. When soil moisture decreases, evapotranspiration is reduced linearly from E_{max} to a wilting rate (Schulze, 1986; Hale *et al.*, 1987), and below this characteristic point, only evaporation from soil persists, decreasing linearly to zero at the hygroscopic point.

Leakage losses are usually modelled in ecohydrology with the approach suggested by Clapp and Hornberger (1978), varying the hydraulic conductivity from zero, when the soil water content is at the field capacity, to the maximum, when the soil is saturated, according to a power law.

In the EHSM, the evapotranspiration–leakage–soil moisture relation, depicted in Figure 2, is simplified by assuming the presence of a soil moisture value, named s_t, over which evapotranspiration occurs at the maximum rate E_{max}. When water is accumulated between s_t and the saturation point ($s=1$), it is lost instantaneously as leakage, feeding the *subsurface* reservoir. Below s_t, evapotranspiration is reduced linearly to zero at a point named s_0, which can be defined as a hygroscopic point.

As compared with the classical approach used by Laio *et al.* (2001b), the number of parameters necessary to describe the stepwise curve relating soil moisture and

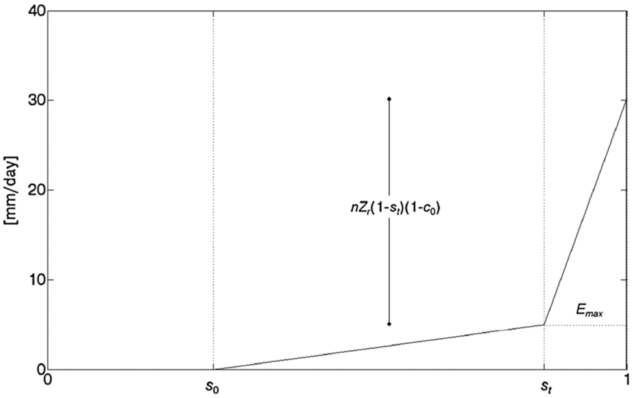

Figure 2. Daily evapotranspiration and leakage as a function of relative soil moisture

water losses is reduced from nine (four parameters characterizing the soil, two for the evapotranspiration, and three for hydraulic conductivity) to three (two parameters characterizing the soil and one for maximum evapotranspiration).

The relationship providing water losses from the permeable soil as a function of soil moisture thus reads as follows:

$$ET + L = \begin{cases} 0 & \text{if } s \le s_0 \\ E_{max}\left(\dfrac{s-s_0}{s_t-s_0}\right)(1-c_0) & \text{if } s_0 < s \le s_t \\ E_{max}(1-c_0) + (s-s_t)nZ_r(1-c_0) & \text{if } s_t < s \le 1 \end{cases} \quad (3)$$

In Equation (3), it is worthy of note that the only input to the subsurface reservoir is given by $(s-s_t)nZ_r(1-c_0)$ that is considered as an instantaneous pulse at the daily time scale. Consequently, the combination of s_t and nZ_r determines the maximum amount of leakage at the daily time scale, which in turn can be considered as a proxy of saturated hydraulic conductivity. Highly permeable soils can be described by lower values of s_t, which generates higher potential amount of daily leakage. Indeed, low permeable soils can be characterized by higher values of s_t, which produce small potential amount of daily leakage; it is important to point out that, in the model schematization (Figure 1), very low permeable soils are embedded into the impervious fraction where leakage is not allowed.

Furthermore, it is worth-mentioning that, even if the physical interpretation of the percolation dynamics can be considered approximated, the temporal leakage structure is irrelevant for the streamflow evaluation because the subsurface reservoir acts as an equalizer for this discontinuous input. Moreover, this kind of soil schematization is not able to interpret the presence of macro porosity and fractures, which may divert directly water to deep aquifers.

The daily evapotranspiration rate in well-watered conditions, E_{max}, is evaluated using the FAO-56 Penman–Monteith method (Allen *et al.*, 1998). The complete general procedure calculates the reference evapotranspiration, ET_0, as a function of solar radiation, air temperature, humidity, and wind speed, and then converts the reference evapotranspiration value into crop reference evapotranspiration using a crop coefficient, K_c, usually listed in agronomy literature [see for example Table 12 in the work of Allen *et al.* (1998)]. Different procedures can also be used to derive ET_0 in the absence of one or more climatic data; in the following, we will refer to a simplified procedure that uses only temperature data. The EHSM, instead of a specific crop coefficient, uses a vegetational coefficient, K_v, which is introduced to feature virtual vegetation, laying over the permeable part of the basin, in terms of mean potential evapotranspiration rate. Thus, E_{max} is calculated from reference evapotranspiration value according to a linear function $E_{max} = K_v ET_0$. The latter equation has been implemented in the model framework so that the reference evapotranspiration represents an external input, whereas the vegetational coefficient is a model parameter.

Quick and slow runoff

Soil water balance allows the calculation of the three components able to generate runoff volume at the basin outlet. These components are the runoff from impervious surface, $Q_{c0} \equiv R_{imp} = c_0 R$; the excess saturation surface runoff, Q_s; and the leakage L. These components are routed into two linear reservoirs (Chow, 1964). The choice of only two reservoirs is also supported by the work of Jakeman and Hornberger (1993), which speculated on the number of linear reservoirs needed to model streamflow.

Water contributions arising from the top layer of the soil, namely Q_{c0} and Q_s, are diverted into a surface linear reservoir, which is characterized by a residence time $1/K_{sup}$ and has outflow Q_{sup}, which is a linear function of water storage h_{sup} through the following relations:

$$\begin{cases} Q_{c0} + Q_s - Q_{sup} = \dfrac{\Delta h_{sup}}{\Delta t} \\ Q_{sup} = K_{sup} h_{sup} \end{cases} \quad (4)$$

The surface reservoir aims to describe the quick hydrological basin response; thus, the residence time $1/K_{sup}$ is expected to be of the same order of magnitude of the basin concentration time. If this time is lower than a day, Q_{c0} and Q_s will reach the basin outlet during the same day of the rainfall pulse, and thus K_{sup} should be equal to one.

The leakage contribution fed a *subsurface reservoir*, characterized by a residence time $1/K_{sub}$, and generates an outflow Q_{sub}, which reads as follows:

$$\begin{cases} L - Q_{sub} = \dfrac{\Delta h_{sub}}{\Delta t} \\ Q_{sub} = K_{sub} h_{sub} \end{cases} \quad (5)$$

where h_{sub} is the water stored in the subsurface reservoir. In the EHSM purposes, the subsurface reservoir is aimed to describe the slow hydrological basin response, and consequently, the residence time $1/K_{sub}$ is larger than $1/K_{sup}$ and, in general, equal to some days, weeks, or months. Again, the solution of Equations (4) and (5) is achieved by forward finite differences method at the daily time scale.

The effective rainfall, namely that part of precipitation that generates runoff, arises from surface and subsurface contributions. The first contribution is given by a fixed percentage of rainfall, plus an excess contribution that is a function of the amount of rainfall and soil moisture. The second contribution is a function of rainfall amount and soil moisture status. The ratio between the two contributions is thus not constant, which means a dynamic partitioning of effective rainfall between surface and subsurface reservoirs.

CASE STUDY

The case study (Figure 3) is a basin with an area of about 9.5 km^2 located in Sicily (Italy, 37.53°N, 13.18°E); its mean elevation is 792.2 m. a.s.l. (standard deviation of 194.6 m), and the basin surface response time is less than a day (Noto and La Loggia, 2007).

The basin has been already an object of several previous studies with different aims (Noto and La Loggia, 2007; Pumo *et al.*, 2008; Viola *et al.*, 2008; Pumo *et al.*, 2010). In particular, Pumo *et al.* (2008) identified three soil types within the basin (30% of sandy loam, 10% of loamy sand, and 60% of clay) and a dense vegetation covering the whole basin area with a surface woody layer and a bottom layer of shrubs and grasses. The vegetation is mainly of woody type, constituted by *Quercus pubescens*, *Acer campestre*, and *Fraxinus ornus*, even if vineyard, olive tree grove, pastureland with shrub vegetation, a low percentage of dry seminative land, and bare soils are also present in the downstream part of the basin.

The basin has been monitored for a long time with regard to temperatures, precipitations, and discharges at the basin outlet, and thus, consistently long data series are available. The entire dataset used here is constituted by 28 years of continuous observations, from 1977 to 2004. Simultaneous daily records of precipitations, temperatures,

Figure 3. Location of the Eleuterio at Lupo river basin (Sicily, Italy). In blue are the main river channels

and discharges are available except for the years 1997 and 2001. Most of the available records have been used for calibration purposes (from 1977 to 1996), whereas two time windows, namely from 1998 to 2000 and from 2002 to 2004, have been used for the model validation and the uncertainty estimation.

From the analysis of the historical data series recorded by Eleuterio at Lupo hydrometric station, different streamflow characteristics can be derived. The observed annual streamflow is rather variable, as it is typical in Mediterranean rainfall regimes, with values ranging from 49.9 to 659.6 mm/year and standard deviation equal to 142.2 mm. The mean daily discharge results equal to 0.82 mm/day with standard deviation of 2.52 mm, whereas the mean value computed by considering only the days with not null discharges is equal to 1.43 mm/day, with standard deviation of 3.36 mm. The percentage of days without discharge is rather high (about 41%), and these are mainly concentrated during the summer period. The analysis of climatic data recorded for the Eleuterio at Lupo river basin has highlighted a probable effect of climate changes. Specifically, a decreasing rainfall and a simultaneous increment of temperatures have been leading the basin towards drier conditions and lower discharges (Cannarozzo *et al*., 2006).

Figure 4 shows a synthesis of the statistical analysis on the daily streamflows recorded at the basin outlet. From the figure, it is possible to identify a season of the year typically characterized by daily streamflows close to zero. This condition identifies the basin behaviour as ephemeral and makes the task of any R–R model harder than for a perennial basin (Ye *et al*., 1997). In such a basin, also the overall evaluation of the average available water resources using FDCs fails because of the presence of dry periods with a strong interannual variability (Croker *et al*., 2003; Viola *et al*., 2011; Pumo *et al*., 2013).

MODEL CALIBRATION

The EHSM has seven lumped parameters: three describing soil characteristics, i.e. the active soil depth (nZ_r), the soil moisture values triggering the leakage (s_t), and the hygroscopic point (s_0); two describing the top layer, i.e.

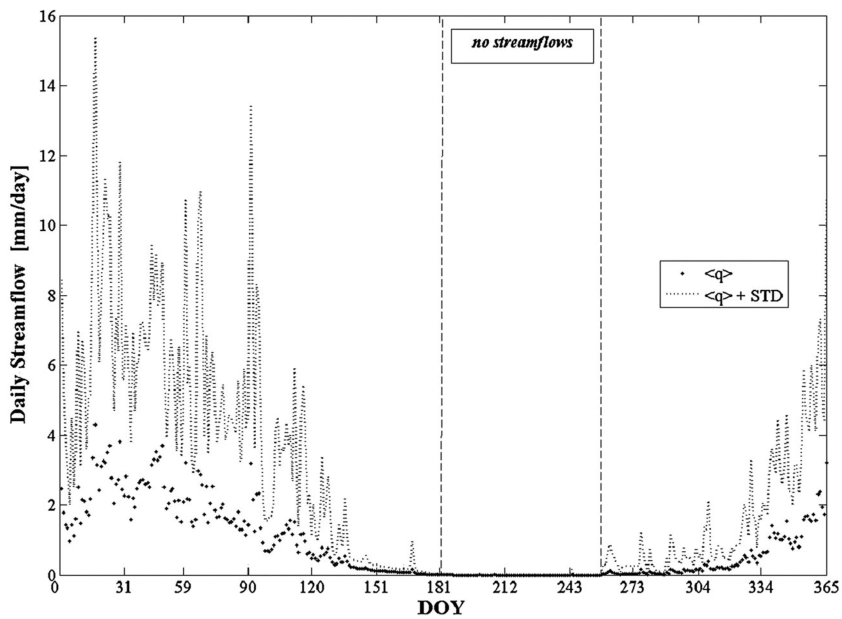

Figure 4. Mean behaviour of the observed daily streamflows at the Eleuterio at Lupo basin. Black points are the mean daily streamflow $<q>$ at each day of year (DOY). Black dashed line: sum of $<q>$ and the corresponding standard deviation (STD). After Pumo *et al*. (2013)

the fraction of impervious area (c_0) and the vegetational coefficient (K_v); finally, the two linear reservoir constants (i.e. K_{sup} and K_{sub}). A first set of parameters has been derived using some basic ecohydrological knowledge of the considered basin (θ_{KD}). Parameters have been derived from spatial average of different values, using spatial analysis techniques within a GIS software.

The active soil depth (nZ_r) has been derived from the product between soil porosity and the rooting depth of vegetation. Soil porosity ranges between 0.42 and 0.5 (respectively for loamy sand and clay), whereas trees are the most influent vegetation, leading nZ_r to a spatial averaged value of about 400 mm. The value triggering leakage, s_t, chosen equal to 0.85, is justified by the clayish nature of the basin (almost 60% of soils are clay). Conversely, the relative soil moisture value at which no evapotranspiration is allowed at basin scale, s_0, has been chosen equal to 0.3. The fraction of impervious area c_0 has been assessed from the land use map: Roads, country houses, and very low permeable soils sum to about 10% of the total area, providing a value of c_0 equal to 0.1.

The vegetational coefficient K_v has been derived comparing basin potential evapotranspiration estimated in Pumo *et al.* (2010) with the reference value estimated by the FAO-56 Penman–Monteith method, obtaining a value of K_v equal to 1.7. The surface linear reservoir constant, K_{sup}, has been set to 1 (per day), given that, as mentioned before, the surface concentration time of this basin is much smaller than a day. Finally, K_{sub} has been set to 0.11 (per day), using the value coming from the analysis of hydrograph recession curves.

Together with the ecohydrologically driven parameters set, an automatic parameter calibration procedure has been carried out using the Monte Carlo method (Metropolis and Ulam, 1949). The method consists in the random generation of several parameter vectors $\theta_i = (nZ_r,\ s_t,\ s_0,\ c_0,\ K_v,\ K_{sup},\ K_{sub})$ and then in the evaluation of the model performance with this set of parameters, using an appropriate likelihood measure, in reproducing historical streamflow series. The method provides the opportunity of exploring equifinality (Beven, 2006), i.e. the capability of several set of parameters to reproduce similar outputs. Model parameters have been chosen within ranges centred in the ecohydrologically driven values, according to a uniform distribution and fixing the extremes of these ranges (Table I). Model calibration has been carried out using rainfall and streamflow data from 1977 to 1996, whereas model validation has been performed in two periods, from 1998 to 2000 and from 2002 to 2004.

Concerning the choice of the goodness-of-fit measure, performance of individual parameter sets has been here assessed using the Nash and Sutcliffe (NS) efficiency criterion (Nash and Sutcliffe, 1970), based on the sum of squared errors:

Table I. Range of variation for the seven model parameters

Parameter	Knowledge driven θ_{KD}	Min value	Max value
nZ_r [mm]	400	100	1200
s_t [ ]	0.85	0.52	0.91
s_0 [ ]	0.30	0.11	s_t
c_0 [ ]	0.1	0	0.3
K_c [ ]	1.7	0.5	2.5
K_{sup} [1/day]	1	K_{sub}	1
K_{sub} [1/day]	0.11	0.01	0.5

s_0 is randomly generated from s_t in such a way that $0.11 < s_0 < s_t$; the same for K_{sup} that is generated between K_{sub} and 1.

$$NSE(\theta_i/Y) = \left(1 - \sigma_i^2/\sigma_{obs}^2\right) \quad \sigma_i^2 < \sigma_{obs}^2 \tag{6}$$

where $NSE(\theta_i/Y)$ is the likelihood measure for the ith model simulation for parameter vector θ_i conditioned on a set of observations Y, σ_i^2 is the associated error variance for the ith model, and σ_{obs}^2 is the observed variance for the given period. In this study, 50 000 sets of parameters whose efficiencies are positive were considered behavioural.

Furthermore, to evaluate the model capability in reproducing water resources amount, also the volumetric efficiency has been defined as follows:

$$VE(\theta_i/Y) = 1 - \left(\frac{V_{obs} - V_i}{V_{obs}}\right) \tag{7}$$

where V_{obs} (mm) is the total volume of water flowed in a considered period and V_i (mm) is the total volume obtained with the ith model for the same period.

RESULTS AND DISCUSSION

Basic ecohydrological knowledge has led to a parameter set $\theta_{KD} = (nZ_r,\ s_t,\ s_0,\ c_0,\ K_v,\ K_{sup},\ K_{sub}) = (400,\ 0.85,\ 0.30,\ 0.1,\ 1.7,\ 1,\ 0.11)$ whose performance has been evaluated in three time windows using the NS efficiency criterion. In the longest considered period (1977–1996), NSE is equal to 0.37, whereas in 1998–2000, it decreases to 0.28 and become even negative, equal to −0.48 for the 2002–2004 period.

By using this set of parameters, some considerations concerning water balance can be carried out with regard to the 1977–1996 period. The streamflow from impervious surface is equal to 10% of rainfall and arises from the c_0 parameter. This percentage also includes runoff from low permeable soils, which are embedded in the fraction c_0. The contribution from excess saturation over permeable soil is just 1%, because rainfall pulses rarely overpass the maximum storage capacity at a certain time W_{max}. The part of the soil that accumulates water available for the percolation is $nZ_r(1-s_t)(1-c_0)=54$ mm, whereas the leakage contribution is approximately 32% of rainfall. At the same time, 11% of rainfall is routed in the surface reservoir. Summing these two contributions, the total runoff is equal to 43%, and consequently, 57% of rainfall comes back into the atmosphere as evapotranspiration.

To understand if the model with basic ecohydrological knowledge performs in a satisfactory way, its performance must be compared with the best obtainable performance, namely with the one arising from Monte Carlo calibration.

The outcomes of the calibration process for the time window 1977–1996, obtained by means of the Monte Carlo method and the NS efficiency criterion, have been depicted in Figure 5, where the likelihood response surface is projected in the parameter space. In other words, the multidimensional space (θ_i, NSE_i) is projected on seven planes having as abscissa a single parameter and as ordinate the model efficiency. Each subplot contains 50 000 points, one for each behavioural simulation (Figure 5 shows only cases with $NSE>0.3$). The maximum likelihood is obtained for $\theta_{HE}=(nZ_r,\ s_t,\ s_0,\ c_0,\ K_v,\ K_{sup},\ K_{sub})=(424,\ 0.85,\ 0.4,\ 0.115,\ 1.79,\ 0.9,\ 0.15)$, and it is equal to 0.43, thus slightly higher than the one obtained, for the same period, fixing *a priori* parameter values. The IHACRES model, calibrated by the authors for the same time window, provided a likelihood measure equal to 0.39. This means that, although the model performance seems poor in absolute terms, the comparison with a benchmark model reveals acceptable performances, at least in relative terms. The reasons for these low performances, in both models, could be found in the quality of hydroclimatic data used as input. Furthermore, the use of a linear relation between storage and discharge could be a reason of discrepancy (Botter *et al*., 2009; Muneepeerakul *et al*., 2010).

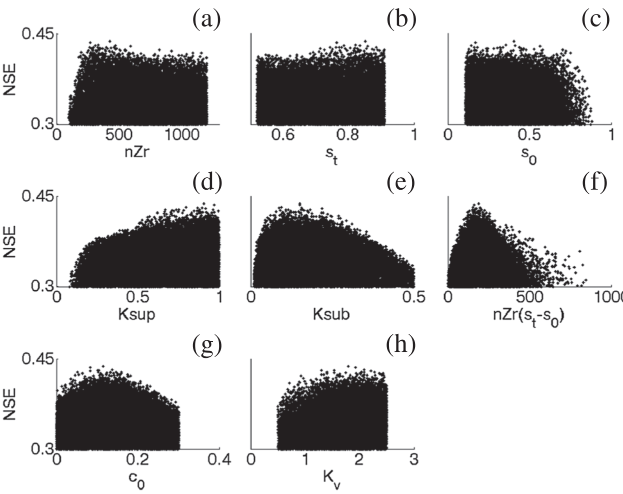

Figure 5. Calibration of the EHSM with Monte Carlo simulations in the time window 1977–1996: 50 000 behavioural set of parameters θ_i and the associated values of efficiency in reproducing historical streamflow data. The maximum likelihood ($NSE=0.43$) is obtained with a parameter combination $\theta=(nZ_r,\ s_t,\ s_0,\ c_0,\ K_v,\ K_{sup},\ K_{sub})=(424,\ 0.85,\ 0.4,\ 0.115,\ 1.79,\ 0.9,\ 0.15)$. (a) Rooting depth; (b) and (c) relative soil moisture triggering leakage and stopping evapotranspiration; (d) and (e) surface and subsurface reservoir constants; (f) combination of (a), (b) and (c); (g) impervious fraction; and (h) evapotranspiration scaling coefficient

The dot plots analysis shows that the model is affected by equifinality: several sets of parameters provide comparable performances. Model efficiency is very sensitive to the c_0 variation (Figure 5(g)), confirming the authors' expectations that the fraction of pervious area strongly affects the amount of water transformed in runoff. The higher efficiency has been obtained for $c_0=0.15$, thus very close to the value suggested by analysis of the land use map ($c_0=0.10$). The active soil depth variation makes the model efficiency increasing as long as nZ_r reaches 250 mm, whereas after this value, several active depths are equifinal (Figure 5(a)). Consequently, it is expected that the assumption of nZ_r equal to 400 mm, obtained from vegetation analysis, has low importance in determining the model performances. The two parameters describing soil properties (s_t and s_0) show different behaviours with respect to the model efficiency, which is more conditioned by s_t (Figure 5(b)). The model performs better when the latter parameter is close to 1, as the prevalent clayish nature of the soil would suggest, whereas the s_0 value seems to be irrelevant in determining *NSE* (Figure 5(c)).

The plot of a combination of the latter three parameters $[nZ_r(s_t-s_0)]$, which determines the maximum amount of water storable and available for vegetation uptake in the soil bucket, *versus* the model efficiency, points out the presence of a new relative maximum of *NSE* not evident in any of the shown parameters (Figure 5(f)). This aspect explains how different combinations of nZ_r, s_t, and s_0 may drive substantially model performances. This could be due to the different processes parameterized within the model structure using combinations of nZ_r, s_t, and s_0. Furthermore, $nZ_r(1-s_t)$ determines the maximum leakage contribution and affects the excess runoff generation. In general, shallow soils entail high excess runoff contributions and small leakages towards the subsurface reservoir, whereas deep soils behave inversely. Large differences between s_t and s_0 lead to larger amount of storable water, which involves low leakage and large excess runoff as in the case of clayish soils. On the contrary, if s_t and s_0 values are close, less water is storable in the soil, and consequently larger leakage is allowed, as it is for sandy soils. It is worth recalling that soil hydrological response depends also on the impermeable fraction c_0, which embeds low permeable conditions and allows the quick runoff formation even when high values of nZ_r do not permit runoff generation by saturation excess.

Also, the parameter for the scaling of the reference evapotranspiration, K_v, shows a local maximum, which highlights the model sensitivity to this parameter (Figure 5 (h)). It is interesting to observe how the calibrated value is more or less identical to that from the one calculated by Pumo *et al*. (2010), which used only climatic information, not directly related to streamflow (1.79 *vs* 1.7).

Finally, some considerations about K_{sup} and K_{sub} parameters are as follows: being the time of concentration of the basin less than a day, K_{sup} was expected to be close to one, as obtained in calibration. Coherent with the basin hydrological response, the model performances increase when K_{sup} approaches to one (Figure 5(d)). If the attention is focused on subsurface component, the historical analysis of runoff recession curves has given an average time lag of approximately 9 days ($K_{sub}=0.11$/day). Here, the optimal calibration provides a residence time equal to about 6 days ($K_{sub}=0.15$/day): this discrepancy can be due to the numerical scheme adopted to simulate the reservoirs' water balance, which slightly overestimates daily outflow. Remarkably, the model performances decrease as K_{sub} decreases, trying to model the subsurface basin response longer than that provided by recession analysis (Figure 5(e)).

Model ability in reproducing daily streamflows for the 1977–1996 period is represented in Figure 6(a). For a given historical rainfall input, the simulated streamflows obtained with the two sets of parameter, θ_{HE} and θ_{KD}, are shown together with the observed data. The acceptable ability in assessing key descriptors of water availability is also confirmed by the volumetric efficiency, *VE*, that is, 0.94 for the highest likelihood parameters set and 0.79 for ecohydrologically driven parameters.

Model output can be aggregated and presented in the form of an FDC. The comparison between the EHSM-derived FDC and the empirical one is presented in Figure 6(b). Model output captures the low frequencies streamflows and, at the same time, is able to evaluate the relative duration of null discharge periods. To evaluate the relative ability of EHSM to derive FDC, the model has been compared, using the same basin, with one of the few ecohydrological models able to directly derive FDCs: the model of Botter *et al*. (2007). This model summarizes climatic forcings in simple parameters, which describe rainfall (mean intensity and mean interarrival time), maximum evapotranspiration (with a unique fixed value), and soil and hydrological response (mean residence time of linear reservoirs). The considered basin, as most of Mediterranean areas, is characterized by marked seasonality in rainfall and temperature, and this entails the impossibility of representing the entire hydrologic year with few parameters, constant for the whole period. If average rainfall forcings and ET_{max} are provided to the Botter's model as input, the FDCs are very far from historical ones. For this reason, the Botter's model has been implemented numerically to allow seasonal inputs. The model has been forced with historical rainfall (same rainfall used for calibration, from 1977 to 1994) and with the same ET_{max} (same reference ET_0, scaled with $K_v=1.79$ as resulting from the EHSM calibration). If the reservoir constant of the Botter's model, K_B, is set equal to the value suggested by the recession analysis by Pumo *et al*. (2013), high flows and duration of the wet period are correctly estimated, but the relative duration of a given streamflow value is slightly overestimated, as shown in Figure 6(b). That demonstrates the necessity of distinguishing a slow and a fast component in the hydrologic basin response instead of a unique average response. In fact, the combination of the two linear reservoirs, interpreting fast and slow runoff components, improves the FDC reproduction with respect to a model scheme that averages these two hydrological behaviours.

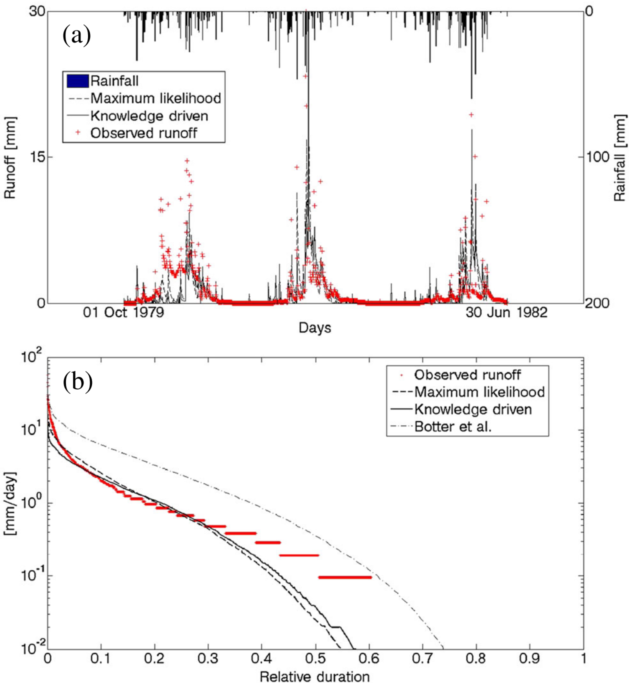

Figure 6. Calibration of the EHSM in the time window 1977–1996. (a) Daily streamflow reproduction from 01/10/1979 to 30/06/1982. Bars on the top represent rainfall inputs. The grey crosses stand for the recorded streamflow data, the dashed line is the maximum likelihood streamflow, and the continuous line represents streamflow derived considering ecohydrologic information. (b) Historical (grey crosses) and EHSM-derived flow duration curves (θ_{HE}, $NSE=0.43$, dashed and derived considering ecohydrologic information, continuous line, $NSE=0.369$). Also, theoretical FDC from the model of Botter *et al*. (2007) have been reported in dash-dot line

Model performances have been validated on other two time windows (from 1998 to 2000 and from 2002 to 2004) assessing the ability in reproducing historical streamflow of the behavioural sets obtained in calibration (1977–1996) and of the ecohydrologically driven model.

In the first validation period, an unexpected relation between calibration and validation efficiency has been observed. In fact, the parameters with low calibration efficiency perform in validation much better (*NSE* up to 0.65) than those characterized by high efficiency in calibration, as described in Figure 7. The performance obtained with the highest efficiency set θ_{HE} ($NSE=0.43$), decreases in validation down to 0.29, as well as the performance of the ecohydrologically driven set θ_{KD} decreases from 0.37 to 0.28. Figure 7 shows the comparison between the historical streamflow (crosses) and the synthetic streamflows obtained using θ_{HE} (dashed line) and θ_{KD} (continuous line). Analysing the figure, it is possible to notice how the two synthetic streamflows are similar, even if some underestimations are evident for different flood events that occurred in this period. Consequently, the *VE* is very low for both cases. At the same time, the envelope of all the behavioural streamflows (shaded area), which are computed using sets of parameters with positive efficiency, is presented. The envelope gives an idea of the parametric uncertainty associated with the use of the EHSM. As expected, the uncertainty increases with the streamflow values, but in correspondence of discharge peaks, this envelope is still not able to include the historical values.

In the second validation period, the model performances decrease in general. Notwithstanding the validation efficiency values increase when the calibration efficiency increases, the highest performance obtained in validation is less than the calibration value obtained for θ_{HE} (0.20 *vs* 0.42). Also the model running with θ_{KD} experiences a drop in performance, and the *NSE* falls to negative values (−0.48).

This drop in performance, shown in the inset of Figure 8, could be due to the specific climatic conditions of the analysed period, i.e. one of the most droughts of the last century. In such a context, even if the capability of reproducing daily streamflow is low, the model still interprets satisfactorily the FDC (Figure 8). Both the modelled FDCs, coming from θ_{HE} and θ_{KD} sets, give a first approximation of average water resources availability in the considered basin. The two FDCs interpret in an acceptable way the relative duration of dry period, as well. The volumetric efficiency supports and strengthens the aforementioned assertion: In fact, the highest likelihood parameter set θ_{HE} provides *VE* equal to 0.97, whereas the ecohydrologically driven parameter θ_{KD} reaches 0.79.

The differences in performances between calibration and validation are generally expected: Here, two of the many reasons explaining these performance changes have been investigated. Authors have analysed in the past the influence of the sampling size and the influence of the sampling position in R–R modelling and predictive uncertainty (Viola *et al.*, 2009). They showed that model performances and predictive uncertainty are dependent on streamflow variance, which in turn is strongly dependent from the period of sampling: When the streamflow variance is low, in general, a higher model performance is expected. This assertion is confirmed here: In fact, the streamflow standard deviation is equal to 2.4 m^3/s in the calibration period and increases to 5 and 4.5 m^3/s in the validation periods. Consequently, model performances were expected to decrease.

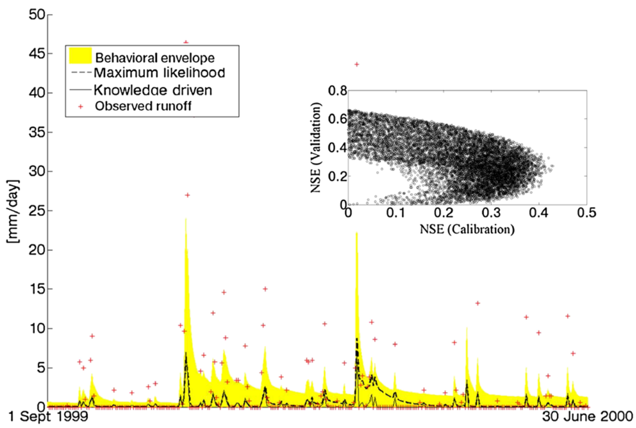

Figure 7. Validation 1998–2000. Historical series (grey crosses), runoff reproduction with the highest calibration efficiency (dashed line, $NSE=0.29$) together with the runoff-derived considering ecohydrologic information (continuous line, $NSE=0.28$). The shaded area represents the envelope of all the behavioural streamflow obtained with the parameter combinations depicted in Figure 5. The inset shows model efficiencies obtained in calibration *versus* the ones obtained in validation

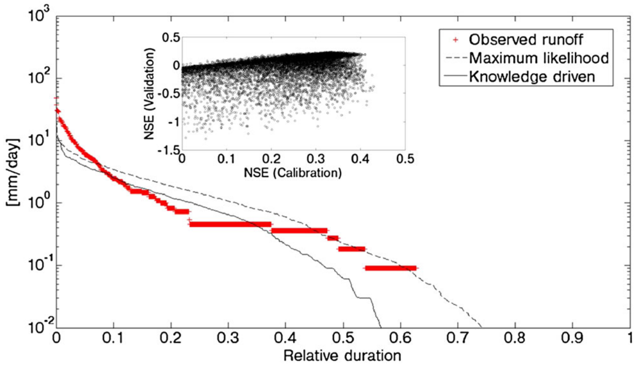

Figure 8. Validation 2002–2004. Comparison between empirical (grey crosses) and EHSM-derived flow duration curves (highest efficiency, dashed, $NSE=0.2$, and derived considering ecohydrologic information, continuous line, $NSE=-0.48$). The inset shows model efficiencies obtained in calibration *versus* the ones obtained in validation

Furthermore, climatic variability has been recognized as a key factor in determining model parameters value and performances. For instance, Pumo *et al.* (2013) demonstrated that, in the same basin, the mean residence time of the linear reservoir depends on the time-invariant geomorphologic features of the basin and on the mean climatic conditions. The model scheme used here considers time-invariant values of K_{sup} and K_{sub}, missing the capability of relating hydrological basin response to the climatic conditions. Thus, being the validation climatic conditions much different from the calibration ones, performances were expected to decrease.

CONCLUSIONS

The paper introduces the conceptual lumped ecohydrological model EHSM. The model has ecohydrological basis because it describes the basin hydrologic response by explicitly taking into account land use, soil moisture dynamics, and interrelations between these and water losses. Evapotranspiration and percolation are described in a simplified but effective way, functional to the desired output of the model, which is the daily runoff. With the aim of simulating the overall hydrologic response at the basin outlet, two classical linear reservoirs have been introduced for describing the fast and slow responses of the basin.

The model was designed to be parsimonious in the number of parameters; seven parameters in all describe 'average' soil, vegetation, and basin characteristics. Simple ecohydrological knowledge can be used to assess model parameters values.

The model has been calibrated on a Sicilian small basin using the Monte Carlo approach. The maximum efficiency obtained is higher than that obtainable with similar model (i.e. IHACRES model) specially developed to work on ephemeral basins. Furthermore, the highest performance set of parameters is very similar to the knowledge driven set. That gives reliability to the knowledge driven set in reproducing streamflow, confirming *a posteriori* the parameters physical meaning.

The efficiency in validation showed a behaviour strongly dependent on the underlying climatic conditions for the two considered periods. In one of the two cases here presented, the efficiency increased, whereas in the second case, characterized by a severe drought, the model performances decreased, as compared with those obtained in calibration. The opportunity of linking model parameters to the underlying climatic conditions deserves future investigations.

The results presented here appear very encouraging. The model meets all the requirements sought at design: simplicity, ability to represent ephemeral and seasonal runoff, and physical meaning of parameters.

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