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Ecohydrological modelling of flow duration curve in Mediterranean river basins

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A B S T R A C T

Flow duration curve provides an important synthesis of the relevant hydrological processes occurring at the basin scale, and, although it is typically obtained from field observations, different theoretical approaches finalized to its indirect reconstruction have been developed in recent years. In this study a recent ecohydrological model for the probabilistic characterization of base flows is tested through its application to a study catchment located in southern Italy, where long historical series of daily streamflow are available. The model, coupling soil moisture balance with a simplified scheme of the hydrological response of the basin, provides the daily flow duration curve. The original model is here modified in order to account for rainfall reduction due to canopy interception and stress its potential applicability to most of the ephemeral Mediterranean basins, where measurements of air temperature and rainfall often represent the only meteorological data available. The model shows a high sensitivity to two parameters related to the transport and evapotranspiration processes. Two different operational approaches for the identification of such parameters are explored and compared: by the first approach, these parameters are considered as time invariant quantities, while, in the second approach, empirical relationships between such parameters and the underlying climatic forcings are first derived and then adopted in the parameters calibration procedure. The model ability in reproducing the empirical flow duration curves and the model sensitivity to climate forcings, here referred as elasticity of the model, are investigated and it is shown how the adoption of the second approach leads to a general improvement of the model elasticity.

1. Introduction

The understanding of the terrestrial hydrological cycle and its impact on river basins is a very relevant issue, with important implications for water resource availability, flood occurrence, biogeochemistry, and plant conditions [1–3]; an appropriate description of all the hydrological processes involved requires a synergistic use of empirical observations, simple and detailed models, and theoretical and numerical analyses. One of the most important components of the water cycle is the runoff at the basin outlet that is the product of complex hydrometeorological and ecological processes. The stochastic nature of rainfall process and, in general, the random characteristics of key hydrological fluxes, together with the heterogeneity of the transport dynamics in channeled and unchanneled regions of a basin, imply a pronounced temporal variability of runoff.

Flow duration curves (FDCs) are simple and powerful tools, commonly used in hydrology to describe the runoff regime in a river basin. These tools, typically obtained from field observations, represent the relationship between magnitude and frequency of streamflows, providing thus an important synthesis of the relevant hydrological processes occurring at the basin scale. Streamflow duration curves have a long history in the field of water-resource engineering and have been widely used in hydrologic studies including flood control, hydropower engineering, water-quality management, river sedimentation, water-use engineering, etc. Vogel and Fennessey [4] presented a comprehensive review of some FDC applications in water resources planning and management. In the traditional approach [5], FDC consists of the complement of the cumulative distribution function of the daily streamflows over the whole available period of records, and for this reason it is also referred as *period-of-record* FDC. Following a different approach [6], referred as annual interpretation of FDC (AFDC), a median annual FDC, which represents the distribution of streamflows in a median hypothetical year, can be easily derived from gauged river flow data.

The lack of stream gauges and the limited amount of streamflow observations characterize several geographical areas around the world. Thus, the estimation of FDC at ungauged river basins is certainly an open and important issue in the hydrological literature. Different approaches have been experimented in recent years, from the formulation and proposal of numerous regionalization procedures for FDC to the development and implementation of several theoretical models, e.g. [7–12].

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Here, we focus on a novel ecohydrological framework developed by Botter et al. [13–16] and, in particular, on a probabilistic model that has provided considerable results in term of theoretical reproduction of FDC in river basins and could potentially be an important tool for the reconstruction of streamflow regime in ungauged, or partially gauged, catchments.

The model, described in Section 2, aims to a probabilistic characterization of base flows in river basins, represented by the slow subsurface contribution to runoff. This contribution, in many circumstances, such as in the case of relatively flat, vegetated catchments, may represent the major runoff component in terms of discharged volumes. Starting from few macroscopic climatic, ecohydrologic and geomorphologic parameters, the model derives the temporal dynamics of spatially averaged soil water content as the result of deterministic, state dependent loss processes (e.g. evapotranspiration, leakage) and stochastic increments driven by intermittent rainfall forcings. The episodical exceedance of a certain threshold for the catchment-averaged soil moisture (i.e., critical soil moisture level) is considered as the triggering mechanism for water release from soil toward the catchment outlet. Coupling soil moisture balance with a simplified scheme of the hydrological response of the basin, the model provides the probability distribution function of the daily streamflows, allowing, at the same time, the derivation of the FDC. The original model by Botter et al. [13] is here slightly modified in order to account for rainfall reduction due to canopy interception, which in many Mediterranean regions cannot be neglected. Since this paper focuses on semiarid Mediterranean environments, which are typically characterized by an ephemeral regime of streamflow, the model is then applied in order to return a FDC only relative to the part of the year with significant streamflows. Moreover, a temperature-based procedure to estimate the potential evapotranspiration, which requires the introduction of a new model parameter, is adopted in order to stress the model potential applicability to most of the Mediterranean basins, where measurements of air temperature and rainfall represent the only meteorological data available.

In this work the ability of the considered model in reproducing the long term empirical FDC and, at the same time, the "model elasticity" to different reference periods are tested through an application to a study catchment. The concept of climate elasticity has been introduced by Schaake [17] for evaluating the sensitivity of streamflow to changes in climate and it is typically defined by the ratio between the proportional change in streamflow and the proportional change in a climate variable. There have been several efforts to develop a robust estimator of the sensitivity of streamflow to climate which can produce unbiased estimates under different model assumptions [18,19]. In this paper, the concept of elasticity will be used in a broader sense, adopting the term "model elasticity" to indicate the model ability in reproducing, for the same basin, the empirical FDCs derived from historical data relative to different reference time periods characterized by a certain climatic variability.

The case study, described in Section 3, is a typical Mediterranean basin with ephemeral streamflows and it represents one of the few Sicilian basins where long series of reliable daily discharge measurements is available. The model performances are here evaluated on the basis of a (dis)similarity index between the empirical and theoretical FDC, computed according to a simple distance-based procedure. The comparison between empirical and theoretical FDCs will be performed at the level of the entire time span of available data (Long Period – LP) and through the consideration of several sub-periods having fixed size (Shorter Periods – SP).

Two different operational model approaches are explored and compared in Section 4: *Fixed Parameters Approach* (*FPA*) and *Generalized Approach* (*GA*). In particular, the model sensitivity to three model parameters is investigated using a Monte Carlo method: the first parameter is the mean residence time of the basin that is mainly related to the geomorphologic characteristics of the basin, the second is the soil moisture threshold critical for streamflow production, which is then related to the soil, while the third is the parameter introduced in the adopted procedure for evapotranspiration estimate, and it is mainly related to the vegetation. In the *FPA*, these parameters are considered as time invariant parameters. The results arising from this kind of approach will confirm the relevant model ability in reproducing the empirical FDC for any considered time periods but, at the same time, they will highlight weak model elasticity to different climatic scenarios. The application of the model on a certain basin under different climatic conditions with fixed parameters, even if these lasts are derived by a long calibration period, could be then inappropriate for many practical applications, such as the reconstruction of the FDC to summarize the potential impacts of predicted climate changes. The paper will show how significant improvements of the model performances in terms of elasticity can be obtained by following a different approach, the *GA*, according to which only the soil critical parameter is assumed as a constant, while the other two investigated parameters are derived from the climatic parameters by mean of empirical relationships.

2. Model description

The original model by Botter et al. [13–15] is based on the well known ecohydrological procedure used by Rodriguez-Iturbe et al. [20] to derive the steady state probability distribution function (*pdf*) of soil moisture at a point. It focuses on the evaluation of the water losses from the soil, and, more specifically, of that part contributing to the base flow of the basin, through a stochastic soil moisture balance equation that accounts for the major hydrologic processes involved within the hydrologically active topsoil layer.

Although the model has been recently extended to tackle the effects of spatially distributed soils, vegetation and morphological features [14], here, the original approach, structured in a spatially lumped framework [13], is considered by assuming average soil–vegetation parameters. Thus, the topsoil layer can be well described by few constant, spatially averaged properties such as rooting depth, Z_r, porosity, n, and saturated hydraulic conductivity, k_s.

Rainfall, at the daily level, represents the main stochastic forcing of the dynamic system. As in previous analytical model for soil moisture dynamics, e.g. [20,21], the rainfall interarrival process is assumed to be well represented by a stationary marked Poisson process with rate λ_p. The marks correspond to independent and exponentially distributed daily rainfall depths with mean $1/\gamma'_p$. Differently from the original approach by Botter et al. [13], in this study a procedure of rainfall reduction due to the process of interception by plant canopy is also introduced, since in some areas characterized by a relevant fraction of woody vegetation, water losses by interception are not negligible. For this purpose, the approach proposed by Robriguez-Iturbe et al. [20] is adopted by considering a censoring process on the overall rainfall series and fixing a canopy interception threshold, Δ_{veg}, for rainfall depth below which no water effectively reaches the ground.

Under this assumption the apparent rainfall process occurs with a rate $\lambda'_p = \lambda_p \exp(-\Delta_{veg}/\gamma'_p)$.

The water balance equation can be written as:

$$\frac{ds(t)}{dt} = \xi_t - \rho[s(t)] \tag{1}$$

where the term $s(t)$ is the relative soil moisture, spatially averaged within the active topsoil layer, ξ_t represents stochastic instantaneous inputs due to infiltration from rainfall, while $\rho[s(t)]$ is the normalized soil loss function. The terms ξ_t and $\rho[s(t)]$ of Eq. (1)