Journal of Hydrology 519 (2014) 258–270

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Annual flow duration curves assessment in ephemeral small basins

D. Pumo *, F. Viola, G. La Loggia, L.V. Noto

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

ARTICLE INFO

Article history:
Received 6 November 2013
Received in revised form 18 June 2014
Accepted 12 July 2014
Available online 21 July 2014
This manuscript was handled by Laurent Charlet, Editor-in-Chief, with the assistance of Chong-Yu Xu, Associate Editor

Keywords:
Mediterranean hydrology
Ecohydrological models
FDC
Dry seasons
ModABa

SUMMARY

Flow duration curve (FDC) represents a comprehensive signature of temporal runoff variability often used to synthesize catchment rainfall–runoff responses. A new model, the ModABa (MODel for Annual flow duration curves assessment in ephemeral small BAsins), is here introduced. It can be thought as a wide mosaic whose *tesserae* are frameworks, models or conceptual schemes separately developed in different studies and harmoniously interconnected with the final aim of reproducing the annual FDC in intermittent small catchments. Two separated seasons within the hydrological year are distinguished: a dry season, characterized by absence of streamflow, and a non-zero season. Streamflow is disaggregated into a subsurface component and a surface component that, in turn, is considered formed by two different contributions: impervious runoff and surface runoff from permeable areas induced by heavy rains. The FDCs of the two streamflow components are first separately and differently computed, and then combined to obtain the non-zero FDC. This last, together with the estimated probability of null streamflow, allows the annual FDC assessment through the theory of total probability. The ModABa is here tested on a small Italian catchment and the results show how the model, once calibrated, is able to accurately reproduce the empirical FDC for the analyzed case, starting from easily derivable parameters and commonly available climatic data. In this sense, the model reveals itself as a valid tool, potentially suitable for predictions at ungauged basins in a regionalization framework.

1. Introduction

Flow duration curve (FDC) provides an important representation of the streamflow frequency distribution referred to a specific time period. Describing the basin attitude to provide flows of various magnitudes, it summarizes the streamflow regime, offering a simple, yet comprehensive, graphical view of the overall historical streamflow variability. The knowledge of the flow frequency regime is often necessary for a variety of hydrological and engineering applications, including water resource allocation and water quality problems, environmental flow management, hydropower feasibility analysis, flood damage assessment and design of hydraulic infrastructures. A valuable overview of the application and derivation of FDCs can be found in Vogel and Fennessey (1994, 1995).

FDC is usually computed using empirical observations, depending then upon the complete period of record, and the analyses on streamflow exceedances are often carried out following a steady state probabilistic approach. An alternative approach (LeBoutillier and Waylen, 1993; Vogel and Fennessey, 1994), particularly efficacious for distinguishing about wet and dry years, consists in the computation of the median, annual based, FDC (AFDC), representing the distribution of measured flow over a hypothetical median year.

The scarcity of measured streamflow data is a common problem that characterizes many geographical areas in the world. The frequent need for characterizing streamflow dynamics, thus, makes the derivation of FDC at ungauged basins an open and challenging question in modern hydrology. The various approaches recently investigated, range from regionalization procedures for FDC (e.g. Fennessey and Vogel, 1990; Franchini and Suppo, 1996; Singh et al., 2001; Viola et al., 2011) to various theoretical models (e.g. Holmes et al., 2002; Kavetsky et al., 2003; Castellarin et al., 2007; Ganora et al., 2009; Viola et al., 2013). Many of the hydrologists' efforts in recent past have focused, on the one side, on the development of stochastic models for reproducing the FDC by appropriate statistical distributions (Castellarin et al., 2004a; Iacobellis, 2008) and, on the other side, on the investigation on potential relationships between the parameters of such distributions and the catchment's climatic and physiographic characteristics (e.g., Sefton and Howarth, 1998; Castellarin et al., 2004b).

* Corresponding author. Tel.: +39 091 23896519.
E-mail addresses: dario.pumo@unipa.it (D. Pumo), francesco.viola77@unipa.it (F. Viola), goffredo.laloggia@unipa.it (G. La Loggia), leonardo.noto@unipa.it (L.V. Noto).

http://dx.doi.org/10.1016/j.jhydrol.2014.07.024
0022-1694/

The recent introduction of some ecohydrological principles in the FDCs modelling has quickly contributed to the accumulation of considerable empirical and theoretical knowledge on many of the above mentioned issues. Castellarin et al. (2004a) introduced a new stochastic approach to the FDCs reproduction, while, with regard to the only baseflow component, the mathematical formalism for the derivation of the daily FDC was presented by Botter et al. (2007a,b,c). In such works the authors introduced a new stochastic-dynamic lumped model, where a field capacity threshold and a characteristic residence time are the key parameters, respectively controlling the generation and the transport of streamflow. In Pumo et al. (2013), a slightly modified version of this model has been tested in a case study, demonstrating the importance of relating some model parameters, representative of the basin geomorphology and vegetation, to the climate forcings of the investigated reference period. The greatest limitation of the above mentioned approaches was that they explicitly neglect the contribution to total streamflow given by the surface runoff process, which, in several arid areas, may contribute substantially to the annual water budget. An attempt to include the surface runoff in the modelling was developed by Muneepeerakul et al. (2010), through an analytical approach tested in some US watersheds, which showed a good ability in capturing the streamflow probability density function and the corresponding autocorrelation function.

The time-scale separation between fast surface runoff and slow subsurface runoff continues to attract many hydrologists. Yokoo and Sivapalan (2011) introduced a new approach with the two streamflow components separately modelled: the slow component is studied by a numerically implemented version of the model by Botter et al. (2007a,b,c), that provides an FDC relative to the subsurface flow (SSFDC); while the FDC relative to the surface component (SFDC) is derived as a filtered version of the precipitation duration curve (PDC). This scheme derives from a conceptual interpretation of the shape of the FDC according to which the fast component, due to particularly intense precipitation events, strongly controls the upper tail of the FDC, while the middle section and the lower tail of the FDC are governed by the slow component.

The difficulties related to the FDCs modelling could be further exacerbated by the presence of discontinuities in the flow regime, characterizing ephemeral catchments in semiarid environments, where streamflow becomes null for significant periods during a year. This aspect was recently faced by two works. Croker et al. (2003) proposed an approach based on the theory of total probability, where the season characterized by absence of streamflow and the non-zero streamflow season are first modelled separately and then combined to predict the annual FDC. Viola et al. (2011) developed a similar empirical regional model for Sicily (Italy), combining a simple model for predicting the percentage of time with null streamflow with a model for predicting the FDC in the non-zero period. In particular, the FDC was described by a three parameters power law, whose parameters were related to the main morphological basins' characteristics through opportune regional regressive models.

Many of the studies above mentioned and related to particular aspects of FDC assessment could be thought as individual *tesserae* of a unique comprehensive mosaic. Under this prospective, the work presented here, could be imaged as an attempt to place at the right place all these *tesserae*, investigating on their compatibility and on the completeness of the resulting mosaic. Indeed, the mosaic structure of the model inspired the acronym of ModABa (MODel for Annual flow duration curves assessment in ephemeral small BAsins), derived from the name of an ancient floor mosaic, known as the *Madaba Mosaic Map* (Church of Saint George, Madaba, Jordan), which depicts a portion of the Jordan river.

The proposed model is aimed to the probabilistic characterization of the daily total streamflow (baseflow plus surface runoff) in ephemeral catchments with sub-daily time of concentration. The ModABa is essentially constituted by three interconnected modules. The first module (Module 1), aimed to the identification of the non-zero season, empirically provides the probability of zero-flow in a basin on the basis of the underlying precipitation regime. The second module (Module 2) analyzes the non-zero seasons; within it, the subsurface and the surface FDCs are first separately derived and then overlapped to derive the non-zero FDC relative to the total streamflow (FDC_{nz}). Finally, the last module (Module 3) combines the probability of null streamflow and the FDC_{nz} to obtain the annual FDC of the daily total streamflow.

The ModABa implementation has been driven by the principle of simplicity that, in hydrology, implies the use of few parameters that can be easily calibrated and/or derived. The result is a not computationally intensive model that opportunely assembles several principles and methods belonging to different existing models, also proposing some new approaches, such as that adopted to define and identify the non-zero season or that used to model the surface runoff component.

In this work the model description (Section 2) will be also supported by an application to a case study, providing some useful insights about the model calibration procedure. The case study, described in Section 3, represents an ideal test site, since it is a small ephemeral river basin where long and reliable series of observations, including daily precipitation, temperature and discharge measurements, are available. The entire time-span is divided into a first and longer subset, used to calibrate the model parameters through a procedure described in Section 4, and a subsequent shorter subset used for a site-specific model validation.

2. Model description

The ModABa structure, whose schematic representation is shown in Fig. 1, is rather simple and contemplates the separation of the hydrological year into a dry and a non-zero season and the distinction between the impervious (whose fraction is denoted as c_0) and the permeable (fraction equal to $1 - c_0$) portions of the basin. The model is lumped and adopts a daily time-scale. Rainfall occurring over the dry season is assumed to form no significant streamflow. Rainfall falling onto the permeable area of the basin during the non-zero season is assumed to drive the soil moisture dynamics; once the field capacity is reached, the water excess is transformed in subsurface streamflow. Heavy rainfall events, having intensity over a certain threshold, are partially refused by the permeable areas and the not-infiltrating water excess is assumed to form surface direct runoff. Another contribution to the surface runoff arises from the entire amount of rainfall falling onto the impervious portion of the basin during the non-zero season, forming the impervious runoff.

With regard to the transferring processes of the streamflow components toward the basin's outlet, the basin can be conceptualized as: a linear reservoir, acting on the subsurface contribution and characterized by the mean residence time of the basin; a linear channel, transferring instantaneously the fast surface contribution to the basin outlet. This last aspect limits the application of the ModABa, in the form here presented, to small basins with sub-daily or daily time of concentration. The ModABa structure is modular, with each module corresponding to a different model whose main objectives and key parameters are synthesized in Fig. 2 and discussed below. Among the parameters relative to each module, it is useful for what follows to distinguish between *basic model parameters*, which can be easily estimated from field observations and commonly available information regarding the basin, and *derived parameters*, which are derived starting from the *basic* ones