Advances in Water Resources 109 (2017) 320–332

Contents lists available at ScienceDirect

Advances in Water Resources

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

Analytical estimation of annual runoff distribution in ungauged seasonally dry basins based on a first order Taylor expansion of the Fu's equation

D. Caracciolo*, R. Deidda, F. Viola

Dipartimento di Ingegneria Civile, Ambientale e Architettura (DICAAR), Università di Cagliari, Via Marengo 2, Cagliari, Italy

ARTICLE INFO

Keywords:
Annual runoff distribution
Bootstrap technique
Budyko's curve
GLUE method
Ungauged basins
Water resources management tool

ABSTRACT

The assessment of the mean annual runoff and its interannual variability in a basin is the first and fundamental task for several activities related to water resources management and water quality analysis. The scarcity of observed runoff data is a common problem worldwide so that the runoff estimation in ungauged basins is still an open question. In this context, the main aim of this work is to propose and test a simple tool able to estimate the probability distribution of the annual surface runoff in ungauged river basins in arid and semi-arid areas using a simplified Fu's parameterization of the Budyko's curve at regional scale. Starting from a method recently developed to derive the distribution of annual runoff, under the assumption of negligible inter-annual change in basin water storage, we here generalize the application to any catchment where the parameter of the Fu's curve is known. Specifically, we provide a closed-form expression of the annual runoff distribution as a function of the mean and standard deviation of annual rainfall and potential evapotranspiration, and the Fu's parameter. The proposed method is based on a first order Taylor expansion of the Fu's equation and allows calculating the probability density function of annual runoff in seasonally dry arid and semi-arid geographic context around the world by taking advantage of simple easy-to-find climatic data and the many studies with estimates of the Fu's parameter worldwide. The computational simplicity of the proposed tool makes it a valuable supporting tool in the field of water resources assessment for practitioners, regional agencies and authorities.

1. Introduction

Accurate estimates and predictions of stream runoff are needed for numerous practical purposes of societal relevance such as water resources management and planning of water allocation for irrigation, industry and human use, hydropower operation and environmental flow releases. The most accurate way of estimating water fluxes at any location is to measure them for an extended period. However, in most catchments of interest no runoff data are available for logistic or financial reasons, so a commonly adopted alternative is to estimate them from measurements at other locations in the region and to transfer them, in some way, by modeling methods (Blöschl, 2016; Parajka et al., 2013).

In the field of hydrological science, how to predict hydrological variables in ungauged basins is one of the greatest challenges. Indeed, the predictions in ungauged basins (PUB) problem has been the focus of the Hydrological Decade 2003–2012 (Hrachowitz et al., 2013; Sivapalan et al., 2003) of the International Association of Hydrological Sciences (IAHS), which has resulted in several relevant publications related to this topic (see e.g., Beven, 2007; Beven and Kirkby, 1979; Blöschl, 2005, 2013; Boegh et al., 2007; Boughton and Chiew, 2007; Bulygina et al., 2011; Caracciolo et al., 2014; Castellarin et al., 2007; McIntyre et al., 2005; Parajka et al., 2013; Salinas et al., 2013; Sivapalan et al., 2003; Viglione et al., 2013; Wagener and Montanari, 2011; Winsemius et al., 2009; Yadav et al., 2007, among the others). The main focus of this initiative was to advance the knowledge and the understanding of climatic and landscape controls on hydrologic processes occurring at all scales and to improve the ability to predict the fluxes of water in ungauged basins, along with their uncertainties (Sivapalan et al., 2003).

The PUB has been tackled with different approaches, depending on the investigated hydrological variable: hydrological modeling, that is the more common approach, has been mostly used for runoff hydrograph estimation, while statistical methods (i.e., regression and geostatistical methods) have been mostly used for runoff quantiles estimation. For a comprehensive review of these approaches, the reader is referred to Parajka et al. (2013) and Salinas et al. (2013), respectively. Parajka et al. (2013) compared about thirty studies, involving about four thousand catchments, dealing with prediction of runoff hydrographs in ungauged basins provided by hydrological models. The

* Corresponding author.
E-mail address: caracciolo@unica.it (D. Caracciolo).

http://dx.doi.org/10.1016/j.advwatres.2017.09.019
Received 7 June 2017; Received in revised form 18 August 2017; Accepted 23 September 2017
Available online 25 September 2017
0309-1708/

predictive accuracy of the daily runoff was described by the Nash-–Sutcliffe efficiency. The aim was to learn from the similarities and differences between river basins in different areas worldwide and to interpret the differences in the performances in terms of climate and landscape controls. On the basis of a literature review of thousands of case studies around the world, Salinas et al. (2013) analyzed the predicting performance of statistical methods (i.e., regression and geostatistical approaches) in term of coefficient of determination for extreme runoff and low flow estimation, and concluded that regression methods had lower performance than geostatistical approaches. In particular, Parajka et al. (2013) and Salinas et al. (2013) found that flood, low flow, and runoff-hydrograph predictions in ungauged basins tend to be less accurate in arid than in humid climates and more accurate in large than in small basins. Therefore, a clear pattern of decreasing performance of predicting runoff with increasing aridity has been found. Runoff processes in arid climates tend to be more heterogeneous than in humid or cold climates. Similarly, the temporal dynamics of runoff tend to be more episodic and spiky in arid climates. Therefore, the relatively larger space-time variability results in lower predictability of runoff in arid ungauged basins around the world.

Some studies used both the statistical and hydrological methods (see e.g., Boughton and Chiew, 2007; Viglione et al., 2013) to deal with the PUB problem. Boughton and Chiew (2007) used multiple linear regressions to relate mean annual runoff to mean annual rainfall and potential evapotranspiration using data from two hundred catchments of Australia. The relative errors in the estimation of the mean annual runoff values obtained by the linear regressions were within ± 25% of the observed values in more than 70% of the catchments. Subsequently, a hydrological model at daily time scale, which self-calibrates its surface storage parameters to the mean annual runoff values obtained by the linear regressions, was forced by daily rainfall to estimate daily runoff. The monthly and annual runoff time series were simulated satisfactorily by the hydrological model in many river basins, with only slightly poorer performances than those obtained by calibrating the hydrological model with recorded runoff. Viglione et al. (2013) assessed prediction performance of daily runoff time series considering almost two hundred river basins in Austria by a regionalized rainfall-runoff hydrological model and a geostatistical approach. They focused their analysis on different runoff signatures, i.e. annual runoff, seasonal runoff, flow duration curves, high flows, low flows, and runoff hydrographs. Results of the comparative assessment showed that the predictive performance increases with basin area for both methods and for most signatures, and it tends to increase with elevation for the rainfall-runoff model. Annual and seasonal runoffs have been predicted more accurately than all the other signatures.

Among the hydrological methods which could be exploitable in PUB, the Budyko's model (Budyko, 1961, 1974) appears to be particularly interesting because of its simplicity, elegance and wide diffusion. Budyko empirically derived the homonymous curve which relates evapotranspiration losses to the aridity index, defined as the ratio of potential evapotranspiration to precipitation. The curve shows the partitioning of precipitation into runoff and evapotranspiration, assuming steady-state conditions and that hydrological processes are driven by the macro-climate for large catchments and temporal long-term averages. McMahon et al. (2013) carried out a literature review focusing on prediction of annual runoff in ungauged catchments and compared the skills of very different methods (i.e., regional and global regressions, Budyko's method, geostatistical approach and process-based method) when applied in different climatic conditions. They found that the Budyko's model outperforms the other considered methods in arid and semi-arid regions, as it is built around the principle of water versus energy competition, while in humid catchments the Budyko's approach and regression methods perform similarly (although the Budyko's framework slightly underestimates mean annual runoff). The authors concluded that Budyko's method has several advantages with respect to the other considered approaches when characterizing the hydrological behavior of large numbers of catchments, since it accounts, in a holistic and very simple framework, for the interrelation among climate, catchment properties and runoff.

After the equation proposed by Budyko (1974), Fu (1981) developed a mono-parametric formulation where the ratio between actual evapotranspiration and rainfall is shaped with only one parameter, ω, that should be calibrated using measured data. Starting from the nineties, many researchers fitted the Fu's equation in different catchments around the world and provided estimates of the ω parameter. Zhang et al. (2001) reproduced the behavior of 250 catchments worldwide (ranging from humid to arid climate) fitting the observed data with the Fu's equation and, depending on land-cover type, obtained ω equal to 2 for forested basins, 1 for mixed vegetation (i.e., herbaceous mixed with forest) basins and 0.5 for pastured and grassland basins. Subsequently, Zhang et al. (2004) using a different rational function approach and considering a different database of 470 basins worldwide with long-term records of precipitation, potential evapotranspiration, and runoff, obtained the best fit value of ω value equal to 2.63. They also split their results for forested and grassland basins, and obtained ω equal to 2.84 and 2.55, respectively. Yang et al. (2007) analyzed several catchments in central China and estimated ω to be equal to 3.22 in 54 arid catchments in the Loess Plateau, ω equal to 2.95 in 38 arid catchments in the Haihe River basin, ω equal to 2.27 for 9 non-humid basins in the Tibetan Plateau, and ω equal to 1.60 for 7 basins in the Inland River basin. Potter and Zhang (2009) found ω equal to 2.96 for 331 basins around Australia, while Donohue et al. (2011) obtained ω equal to 2.05 for 97 basins within Murray Darling basin in Australia. Li et al. (2013) using data from 26 major global river basins that are larger than 300,000 km^2 found ω equal to 2. Xu et al. (2013) developed a neural network model to estimate the ω parameter using 224 small United States basins (100–10,000 km^2) and 32 large global basins (230,000–600,000 km^2), and found values of ω close to 3 and to 2, respectively, for the two ensembles of basins. The authors applied the developed neural network model also to an independent global dataset of 36,600 basins to obtain a global map of ω. Results show that ω decreases from the equatorial zone to high latitudes ranging from 1 to 5 (with mean 2.2 and median 1.9). Greve et al. (2015) developed a new probabilistic Budyko's framework based on the Fu's equation to derive the distribution estimates of water availability and quantify deviations from the mean curve in a probabilistic sense, obtaining a median of ω equal to 2.56 for 438 catchments in the United States. More recently, Viola et al. (2017) analyzed 47 basins in Sicily (Italy) and estimated ω value equal to 2.65.

The above premises depict the wide diffusion and the worldwide interest in the Budyko's framework, ranging from humid to arid climatic context, aiming at the estimation of long-term hydrological components. As an extension, with reference to seasonally dry basins, Viola et al. (2017) proposed a method to analytically derive also the annual runoff distribution assuming a linear behavior for the Budyko's curve. Although the method provides an easy estimation of annual runoff distribution, it could produce misestimation of the latter in areas where the linear regression fails in interpreting the rainfall partitioning rules. Furthermore, in order to be directly applicable, the method needs the full availability of data to perform the linear interpolation, namely simultaneous time series of rainfall, potential evaporation and runoff in a significative number of catchments in the area of interest.

In this context, the aim of this work is to provide and test a simple tool to estimate annual surface runoff distribution that is suitable for ungauged basins and adopts the Budyko's curve framework. We propose a practical tool that can be easily used in the field of water resources assessment by practitioners and engineers in order to estimate the probability density function (pdf) and consequently the cumulative density function (cdf) of the annual runoff, even in ungauged arid and semi-arid basins, at regional scale. Using a first order Taylor expansion of the Fu's equation we obtained the annual runoff distribution as a function of annual rainfall and potential evapotranspiration mean and