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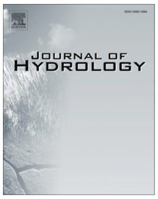

Research papers

Impact of climate seasonality on catchment yield: A parameterization for commonly-used water balance formulas

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ABSTRACT

This paper examines the hydrological impact of the seasonality of precipitation and maximum evaporation: seasonality is, after aridity, a second-order determinant of catchment water yield. Based on a data set of 171 French catchments (where aridity ranged between 0.2 and 1.2), we present a parameterization of three commonly-used water balance formulas (namely, Turc-Mezentsev, Tixeront-Fu and Oldekop formulas) to account for seasonality effects. We quantify the improvement of seasonality-based parameterization in terms of the reconstitution of both catchment streamflow and water yield. The significant improvement obtained (reduction of RMSE between 9 and 14% depending on the formula) demonstrates the importance of climate seasonality in the determination of long-term catchment water balance.

1. Introduction

1.1. Notations

In this paper, we discuss the catchment-scale water balance and its three main components: precipitation (P), streamflow (Q) and maximum evaporation (E_x). Here maximum evaporation is understood in the sense of Budyko (1963/1948), as the water equivalent of the energy available to evaporation. The three fluxes are computed at catchment scale, expressed in millimetres per year, and represent long-term averages (long-term being at least a decade and preferentially three decades). When working on long-term values, catchment storage changes (both soil moisture and groundwater) become negligible compared to the three fluxes over these time scales. Then, by assuming that exchanges between surface and deep groundwater are limited compared to the other fluxes, we may estimate long-term catchment-scale actual evaporation (E_a) as the residual value between P and Q ($E_a = P - Q$). Last, in what follows, the E_x/P ratio is called the aridity ratio, its inverse (i.e. the P/E_x ratio) is called the humidity ratio, and the Q/P ratio is called catchment water yield.

1.2. On the hydrological impact of the relative seasonality of precipitation and maximum evaporation

Estimating catchment water yield is crucial for water resources assessment. In many cases, where ground-based hydrological measurements are not available, gross estimations of mean flow based on climate characteristics can be extremely useful. Simple water balance formulas can provide such assessments, and they have been used for over a century to this end for various water resources applications. In 1911 Oldekop first proposed to compute catchment water yield as a function of the aridity ratio (Andréassian et al., 2016). This idea was later popularized by Budyko (1963/1948), Turc (1954) and others. Today, many hydrologists agree on describing catchment water yield as a first-order function of aridity, and several formulations based on this principle are widely used (see among others the studies of Arora, 2002; Asokan et al., 2010; Choudhury, 1999; Donohue et al., 2011; Dooge, 1992; Greve and Seneviratne, 2015; Le Moine et al., 2007; Moussa and Lhomme, 2016; Oudin et al., 2008; Potter and Zhang, 2009). The three formulations retained for our study (detailed in Table 2) are the formulations proposed by Oldekop (1911), Turc and Mezentsev (Mezentsev, 1955; Turc, 1954) and Tixeront and Fu (Fu, 1981; Tixeront, 1964).

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Beyond aridity, it has long been acknowledged that climate seasonality also has an impact on water yield (Thornthwaite, 1948; Turc, 1954; Wang et al., 2016). Depending on the catchment, the regime curves of climate variables can show more or less variable patterns in terms of amplitude; besides, the dynamics of different climate variables can be more or less synchronized or out of phase (Thornthwaite, 1948). In his classic paper dedicated to the average flow of rivers, Pardé (1933) underlines that 'for identical values of precipitation and temperature, everything else being equal, the runoff coefficient Q/P will be smaller where the larger part of precipitation falls during the warm season.' As an example, Pardé (p. 508) brings the 'miserable' runoff coefficient of the Missouri River (2 L/s/km2), which he explains by the fact that 68% of its precipitation occurs between the months of March and August, when evaporative demand is high. Thornthwaite (1948) proposed to classify climates initially with two indices (one characterizing the periods of water surplus and the other the periods of water deficiency), which he subsequently combined into a single index. Lucien Turc, at the very end of his 1954 paper, writes (p. 539) that 'the most urgent improvement [to his actual evaporation formula] should be the introduction of the distribution of precipitations and of the temperature changes within the year.' But Turc did not propose any solution at the interannual time step and subsequently preferred to work at the monthly and 10-day time steps. Budyko (1974), who had proposed a consensus actual evaporation formula based on the work of Oldekop (1911), also underlined that this formula was likely to underestimate values derived from the catchment water balance in those catchments where rainfall and maximum evaporation were in phase.

A few recent studies have discussed the impact of climate seasonality on water balance (see for example the review of Wang et al. (2016)). We present below the main studies, which we have divided into two groups: those based on theoretical considerations (i.e. model computations) and those based on the analysis of actual water balance data.

1.2.1. Theoretical studies

Dooge (1992) presented theoretical curves relating the energetic yield E_a/E_x to the humidity ratio P/E_x, where he introduced as a parameter the length of the dry season. Milly (1994) proposed a theoretical computation of actual evaporation based on the aridity ratio, the seasonality of the difference $P - E_x$ and plant-available water-holding capacity. Yokoo et al. (2008, p. 262) made theoretical computations to show that 'climate seasonality has a tendency to decrease annual evapotranspiration and increase total runoff if precipitation and potential evapotranspiration are out of phase, compared to the case when they are in phase or they have no seasonality.' Roderick and Farquhar (2011) summarized the major factors that should lead to a change in runoff yield in the Murray Darling Basin, and mentioned the impact that these factors would have on the parameter n of the Turc-Mezentsev formula: an increase of P in summer and a complementary decrease in winter would increase n (and decrease Q); an increase of E_x in summer and a complementary decrease in winter should decrease n (and increase Q). Feng et al. (2012) developed a framework for evaluating the role of seasonal climatic variability on soil moisture and mean annual evaporation; they concluded that stronger seasonality results in more runoff and lower actual evaporation. Donohue et al. (2012) used this framework and proposed a parameterization of the parameter n of the Turc-Mezentsev formula for the Murray-Darling basin, based on plant-available soil water-holding capacity, mean storm depth and effective rooting depth.

1.2.2. Data-based studies

Potter et al. (2005) studied the impact of rainfall seasonality on mean annual water balance in Australia, and obtained contradictory results: first using the stochastic model proposed by Milly (1994), they showed that catchments where the precipitation and evaporation regimes are out of phase should produce more runoff (or less actual evaporation); but then, analyzing data measured in 262 Australian catchments, they were surprised to find the opposite. They concluded that this was probably due to the significant role of two other factors: soil storage capacity and average rainfall intensity, in a context where infiltration-excess runoff was substantial. Using an extended data set of 326 Australian catchments, Hickel and Zhang (2006) went one step further and attempted to distinguish climate-controlled and storage-controlled evaporation; they described climate seasonality with the two indices proposed by Thornthwaite (1948) (water surplus and water deficiency) and assumed that catchment-scale evaporation could be modelled as the sum of two components, one controlled by climate and the other controlled by soil moisture storage. They concluded that it was difficult to assess the impact of climate seasonality because the two components were reacting in opposite directions. Yang et al. (2012) used a dataset of 108 Chinese catchments to develop two empirical relationships linking parameter n of the Turc-Mezentsev formula with (i) Milly's parametric climate seasonality index and (ii) the soil saturated hydraulic conductivity, the mean precipitation intensity and the plant extractable water capacity.

To assist the interpretation of this review of the scientific literature, Figure 1 presents the monthly series of two catchments from our own data set: both have an identical humidity ratio (P/Ex = 1.05) and only differ in more pronounced seasonality (in catchment b). Both catchments have a similar seasonal evaporation regime and differ in the seasonality of precipitation. In this example, one observes a behaviour coherent with the predictions of the theoretical studies: seasonality enhances runoff yield. Clearly, this is only a single example, which we will attempt to generalize in this paper.

1.3. Objectives of this paper

This paper deals with three classical water balance formulas, which have been designed to account for the effect of aridity (the first-order effect of climate on catchment yield), but which do not account for the second-order seasonality effect. Our objectives in this paper are threefold: (i) to present a quantitative index able to describe the relative seasonality of P and E_x; (ii) to use this index in a relevant parameterization of the above mentioned water balance formulas; and (iii) to show how the seasonality information improves the performance of each water balance formula. These objectives provide the structural sub-headings used in the Methods and Results sections.

2. A set of catchments without significant intercatchment groundwater flows

If we are to use the long-term water balance of natural catchments as a measure to assess long-term actual evaporation losses, we need to be able to assume that the catchments in question are *conservative* (see e.g. Eakin, 1966; Goswami and O'Connor, 2010), in the sense that there are no significant *intercatchment groundwater flows* (IGF). Small catchments which form most catchment data sets have (at least in the geological conditions present in France) a tendency to be net contributors to regional groundwater systems (see the discussion in section 7 of the paper by Mouelhi et al., 2006). Where IGFs are substantial, we will not be able to close the catchment water balance with any of the formulas presented in Table 2.