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Modeling seasonal surface runoff and base flow based on the generalized proportionality hypothesis

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SUMMARY

The proportionality hypothesis, originating from the curve number method at the event scale, is extended for modeling runoff in the water-limited and energy-limited seasons, respectively. The proposed seasonal runoff model includes three parameters for two separate seasons, which are wetting capacity, initial wetting and initial evaporation. The parameters for 203 watersheds from the United States are estimated, and the empirical relationships between the parameters and watershed properties, which include duration of the season, duration, intensity and frequency of rainfall events, Normalized Difference Vegetation Index (NDVI) and soil saturated hydraulic properties, are obtained for applications in ungauged watersheds. These empirical equations present physical controls on runoff at the seasonal scale besides climate seasonality. The Nash–Sutcliffe Efficiency coefficient of the seasonal runoff simulation for total runoff is higher than 0.5 in 86% (77%) of the study watersheds; while the surface runoff is 38% (46%) and the base flow is 92% (78%) in the energy-limited seasons (water-limited seasons). This paper shows the potential application of the proportionality hypothesis for estimating seasonal runoff, which is valuable for water resources planning and management.

1. Introduction

Reliable seasonal runoff prediction under a changing environment provides key information for water resources management, particularly reservoir operations. The dominant controlling factors on rainfall partitioning vary with time scale, from long-term to seasonal scales. For mean annual water balance, runoff (Q) and evaporation (E) are dominantly controlled by the long-term climate (Budyko, 1958, 1974). The climate indicator is defined as the ratio between atmospheric water demand and water supply, which is represented by the ratio between potential evaporation (E_p) and precipitation (P), and called climate aridity index (E_p/P). Various functions have been developed to quantify the dependence of the evaporation ratio (E/P) or the runoff coefficient (Q/P) on E_p/P (Turc, 1954; Pike, 1964; Fu, 1981; Choudhury, 1999; Zhang et al., 2001; Yang et al., 2008; Wang and Tang, 2014; Wang et al., 2015). Besides climate, the impacts of vegetation (Zhang et al., 2001; Gentine et al., 2012), soil storage (Milly, 1994a, 1994b; Potter et al., 2005) and seasonality (Hickel and Zhang, 2006; Yokoo et al., 2008; Gerrits et al., 2009) on mean annual water balance have been studied as well.

When the time scale is shortened to inter-annual and seasonal periods, climate seasonality and storminess, vegetation, and soil properties become increasingly important in rainfall partitioning (Sankarasubramanian and Vogel, 2002; Zhang et al., 2008; Donohue et al., 2012; Istanbulluoglu et al., 2012; Wang, 2012; Xu et al., 2013; Guo et al., 2014). Troch et al. (2009) found that vegetation rain-use efficiency across different ecosystem types is related with the inter-annual water balance in the catchment. Wang and Alimohammadi (2012) found that the impact of soil water storage change became non-negligible at the annual scale, particularly in water-limited regions. Feng et al. (2012) found that soil water storage can compensate for the seasonality effects, especially in dry regions. Xu et al. (2012) investigated the relationship between inter-annual rainfall partitioning and catchment vegetation types, and concluded that catchments dominated by woody vegetation have a higher annual runoff ratio.

A number of studies have been focused on simulating inter-annual variability of water balance. Jothityangkoon and Sivapalan (2009) explored the inter-annual rainfall-runoff relationship with a focus on seasonality and storminess. Chen et al. (2013) introduced storage change (ΔS) into *Budyko*'s framework to model seasonal evaporation. In their study, the available water, which is precipitation in the original *Budyko* framework, is replaced by the difference between precipitation and storage change, i.e., $P - \Delta S$.

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As an analog to E_p/P, the quantity $E_p/(P-\Delta S)$ is defined as the aridity index at the seasonal or monthly scale. Water-limited seasons and energy-limited seasons are identified based on the monthly values of $E_p/(P-\Delta S)$.

As the time scale is further shortened to the event scale, runoff generation is predominantly controlled by rainfall intensity (Horton, 1933), soil infiltration (Green and Ampt, 1911), soil storage capacity (Dunne and Black, 1970), land use and land cover (USDA SCS, 1985), topography (Beven and Kirkby, 1979), and the corresponding spatial heterogeneity (Li and Sivapalan, 2011; Chen and Wang, 2013). As a conceptual hydrologic model, the SCS curve number method (USDA SCS, 1985) is based on the proportionality hypothesis and developed for estimating direct runoff at the event scale. The generalized proportionality hypothesis has been successfully applied to model inter-annual runoff variability (Ponce and Shetty, 1995; Sivapalan et al., 2011) and mean annual water balance (Wang and Tang, 2014; Wang et al., 2015). In those studies, surface runoff and base flow are simulated based on the concept of two-stage partitioning (L'vovich, 1979). At the first stage, rainfall is partitioned into surface runoff and soil wetting; at the second stage, soil wetting is partitioned into base flow and evaporation.

The purpose of this paper is to develop a conceptual model for surface runoff and base flow at the seasonal scale based on the generalized proportionality hypothesis. As mentioned before, when the proportionality hypothesis is applied to the seasonal scale, water storage change needs to be considered in the functional form. The seasonal runoff model in this study combines the proportionality hypothesis and the seasonality framework (Chen et al., 2013) described previously. The model is applied to 203 watersheds representing a range of climatic regions across the United States. In Sections 2 and 3, the development of the model is described in detail, as well as the data sources. In Section 4, the performance of the seasonal runoff model is evaluated, and the physical controls on the model parameters are investigated.

2. Methodology

2.1. Proportionality hypothesis

The SCS curve number method was developed for estimating surface runoff at the event scale (USDA SCS, 1985). At the early stage of a rainfall event, rainfall losses by interception and surface retention are defined as initial abstraction (I_a). The remaining rainfall ($P-I_a$) is partitioned into continuing abstraction (F_a) and surface runoff (Q_s). Based on the observed data from a large number of watersheds, this partitioning follows the proportionality formula (USDA SCS, 1985):

$$\frac{F_a}{S}=\frac{Q_s}{P-I_a} \tag{1}$$

where S is the potential value of F_a and dependent on the soil wetting capacity; whereas the potential value of Q_s is $P-I_a$ when F_a approaches to zero. Substituting $F_a=P-I_a-Q_s$ into Eq. (1) and assuming that I_a is a certain percentage of S (i.e., $I_a=\lambda S$), the SCS equation for computing surface runoff is obtained:

$$Q_s=\frac{(P-\lambda S)^2}{P+(1-\lambda)S} \tag{2}$$

The basis of the SCS model is the proportionality relationship in Eq. (1), which can be generalized as follows (Ponce and Shetty, 1995). The amount of available water is Z, which is partitioned into X and Y over a specified time interval. X has an upper bound denoted as X_p; whereas Y increases with Z unboundedly. Before the competition between X and Y, X_0 is allocated to X. The partitioning is determined by the following generalized proportionality equation:

$$\frac{X-X_0}{X_p-X_0}=\frac{Y}{Z-X_0} \tag{3}$$

which has been successfully applied to the partitioning of annual rainfall (Ponce and Shetty, 1995; Sivapalan et al., 2011). The generalization of proportionality to other time scales is also possible, such as long-term and monthly scales (Wang and Tang, 2014). In this study, the proportionality hypothesis is extended to the seasonal scale for simulating surface runoff and base flow by including water storage change.

2.2. Two-stage annual rainfall partitioning

At the annual scale, precipitation is partitioned into runoff and evaporation when soil water storage change is negligible compared with other fluxes:

$$P=Q+E \tag{4}$$

This partitioning can be decomposed into two stages (L'vovich, 1979). At the first stage of the partitioning, precipitation is partitioned into surface runoff and soil wetting (W), which includes all abstractions:

$$P=Q_s+W \tag{5}$$

At the second stage of the partitioning, the soil wetting is partitioned into base flow (Q_b) and evaporation (E):

$$W=Q_b+E \tag{6}$$

where Q_s and Q_b sum to the total runoff (Q). By applying this concept to many watersheds across the world, L'vovich (1979) observed the following patterns: (1) surface runoff and base flow will not occur until the available water reaches a certain level; and (2) the magnitude of W and E have upper limits while Q_s and Q_b do not.

Based on the two-stage rainfall partitioning concept, Ponce and Shetty (1995) applied the SCS formula (Eq. (2)) to the annual scale by generalizing the proportionality relationship. Initial wetting is represented as a percentage (λ_s) of soil wetting capacity (W_p). $\lambda_s W_p$ is the minimum threshold of rainfall required to generate surface runoff. When $P>\lambda_s W_p$,

$$Q_s=\frac{(P-\lambda_s W_p)^2}{P+(1-2\lambda_s)W_p} \tag{7}$$

It should be noted that the functional difference between $(1-\lambda)$ in Eq. (2) and $(1-2\lambda_s)$ in Eq. (7) is due to the definitions of S and W_p. S is the maximum value of continuing wetting; while W_p is the maximum value of total wetting. As an analog to surface flow, wetting threshold for base flow generation is defined as $\lambda_b V_p$. When $W>\lambda_b V_p$, base flow is computed by:

$$Q_b=\frac{(W-\lambda_b V_p)^2}{W+(1-2\lambda_b)V_p} \tag{8}$$

2.3. Two-stage seasonal runoff modeling

Storage carry-over between years is a source of uncertainty in the two-stage annual runoff model. Storage change (ΔS) is even more important for the seasonal rainfall partitioning, and has to be included in seasonal runoff models. The water balance over a season is represented as:

$$P=Q+E+\Delta S \tag{9}$$