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Exploring the effects of hillslope-channel link dynamics and excess rainfall properties on the scaling structure of peak-discharge

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ABSTRACT

Several studies revealed that peak discharges (Q) observed in a nested drainage network following a runoff-generating rainfall event exhibit power law scaling with respect to drainage area (A) as $Q(A) = \alpha A^{\theta}$. However, multiple aspects of how rainfall-runoff process controls the value of the intercept (α) and the scaling exponent (θ) are not fully understood. We use the rainfall-runoff model CUENCAS and apply it to three different river basins in Iowa to investigate how the interplay among rainfall intensity, duration, hillslope overland flow velocity, channel flow velocity, and the drainage network structure affects these parameters. We show that, for a given catchment: (1) rainfall duration and hillslope overland flow velocity play a dominant role in controlling θ, followed by channel flow velocity and rainfall intensity; (2) α is systematically controlled by the interplay among rainfall intensity, duration, hillslope overland flow velocity, and channel flow velocity, which highlights that it is the combined effect of these factors that controls the exact values of α and θ; and (3) a scale break occurs when runoff generated on hillslopes runs off into the drainage network very rapidly and the scale at which the break happens is determined by the interplay among rainfall duration, hillslope overland flow velocity, and channel flow velocity.

1. Introduction

An emerging approach to peak discharge estimation across scales is based on the statistical dependence of peak flow on watershed area. While the statistical self-similarity of peak flow (flood) statistics has been well-established (e.g. regionalization studies), recent research has shown that, in a nested watershed, peak discharge scale as a power law of drainage area for individual events, given by the form $Q(A) = \alpha A^{\theta}$, where $Q(A)$ is peak discharge, A is the drainage area, α is the intercept, and θ is the exponent. Empirical results by Goodrich et al. [1]; Ogden and Dawdy [2], Smith et al. [3], Gupta et al. [4], and Lima and Lall [5] offer clear evidence in support of the theory (e.g. Gupta [6]; Gupta et al. [7]) that the aggregated runoff response in a watershed, which is a result of complex interactions of catchment physical processes that are highly variable in space and time, exhibit scale invariance. Mandapaka et al. [8] showed that, by assuming the runoff generating mechanism to be uniform in space, the spatial variability of rainfall leads to significant variability of peak discharge at smaller watershed scales ($\sim$10 km^2). However, the variability of peak discharge becomes insignificant at increasingly larger scales ($\sim$>150 km^2), which demonstrates that the aggregated catchment runoff response resulting from spatially variable rainfall-runoff processes in a nested watershed preserves scale invariance. This interesting insight offers an avenue for peak discharge estimation across scales without going through the rigors of calibration to estimate the spatially variable parameters that are required in complex rainfall-runoff models. For other implications of peak-flow scaling, refer to Gupta [6] and Gupta et al. [7].

Earlier efforts were devoted to understanding the role of the drainage network (e.g. Gupta and Waymire [9]; Menabde et al. [10]) and the spatial structure of rainfall (e.g. Gupta et al. [11]; Menabde and Sivapalan [12]; Mandapaka et al. [8]) in controlling θ. Recent research is geared towards understanding which aspects of the rainfall-runoff processes control α and θ (e.g. Furey and Gupta [13,14]; Di Lazzaro and Volpi [15]). We continue on this trajectory and devote the present study to further understanding the role of the drainage network and the interplay among rainfall intensity (I), duration (T), channel flow velocity (v_c), and hillslope overland flow velocity (v_h) in determining the scaling structure of peak discharges. Our approach involves simulation using the drainage network based hydrologic model CUENCAS [16]. We systematically altered catchment process variables to gain insight into their effects on the scaling structure of peak discharges. To this end, we carried out systematic simulation experiments across multiple watersheds to determine whether our findings hold for watersheds that have different shapes, sizes, and width functions.

The paper is organized as follows. In the next section we provide a literature review of reported results on catchment runoff

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response and scaling of peak flows. We then discuss the study area and our methodology in greater detail in the following section. This section outlines the drainage network based hydrologic model called CUENCAS and the three different watersheds we studied. We also discuss the physical assumptions we have made, the associated limitation of the study, and the systematic setup of our simulation experiments. We follow this by presenting our results and discussing their implications on peak discharge estimation across scales. We conclude the paper with a summary of our findings and recommendations for future research.

2. Literature review

Drainage area was first recognized as a peak discharge scaling parameter in the classical Rational Method [17]. In this method, for a given soil type (topography), rainfall intensity I and rainfall duration T, that is equal to the longest travel time in the watershed ("time of concentration," t_c), peak discharge scales linearly with drainage area at internal locations in the catchment and can be estimated using the formula $Q(A) = c_r \cdot I \cdot A$, where c_r is the runoff coefficient. Under this method, α corresponds to I_e ($I_e = c_r \cdot I$) and $\theta = 1$. The method is still being used in engineering practice for the design of small drainage structures and is applicable to small catchments with drainage areas as large as 15 km^2 [18]. Around the same time the Rational Method was outlined, O'Connell [19] proposed the power law formula $Q(A) = \alpha A^{0.5}$ that linked peak discharge to drainage area, where α is a coefficient related to the region.

In the early 1960s, the United States Geological Survey (USGS) adopted and popularized an empirical quantile regression method for regional flood frequency estimation that is used throughout the world (see Dawdy et al. [20] for a comprehensive review). These quantile regressions often use drainage area as the only predictor variable and follow the form $Q_p(A) = \alpha(p)A^{\varphi(p)}$, where both the intercept α and the exponent φ are functions of the probability of exceedance p. The flow quantile $Q_p(A)$ exhibits a log–log linear relationship with drainage areas located in a homogeneous region. This means that streams that belong to different drainage networks, and are therefore not nested but are located in a homogeneous region, exhibit similar peak flow scaling structure. It is important to note here that the delineation of homogeneous regions is based on the residuals from regression analysis and on physiographic characteristics of river basins [21].

Goodrich et al. [1] reported the first empirical evidence that showed peak discharges in nested watersheds exhibit self-similarity. They used empirical data from the semi-arid Walnut Gulch experimental watershed in Arizona, whose nested watersheds have drainage areas that range from 0.0018 to 149 km^2. Their quantile-based empirical analysis revealed φ values of 0.85 and 0.90 for the 2-yr and 100-yr return periods and drainage areas up to 1 km^2, whereas φ equals 0.55 and 0.58 for the 2-yr and 100-yr return periods and drainage areas greater than 1 km^2, which suggests multiscaling. The fact that φ assumes different values for drainage areas above and below a certain critical drainage area, in this case 1 km^2, also suggests the existence of a scale break. They attributed the observed scale break to partial area storm coverage and ephemeral channel losses through infiltration as the stream flow propagates downstream.

The quantile-based estimates of φ discussed thus far offer little that would enhance the understanding of which aspects of the rainfall-runoff processes control θ during a single event. This is because peak flows used in the quantile regression approach likely correspond to different rainfall events which, in the case of USGS's regional regression equations, may also come from different watersheds that are not nested and, hence, belong to different drainage networks. The first event-based empirical study of peak discharge comes from Ogden and Dawdy [2], who studied the scaling structure of peak discharges in a nested watershed where the spatial rainfall pattern is fairly uniform. They analyzed peak discharge data from the 21.2 km^2 Goodwin Creek experimental watershed (GCEW) located in Mississippi in the South-Central United States. They examined 16 yr of continuous rainfall and runoff data from subcatchments with drainage areas ranging from 0.172 to 21.2 km^2 at the outlet. Their estimate of φ with the value of 0.77 was independent of the return period, which suggests simple scaling. They also reported an event-based analysis of θ in which they studied basin-wide peak discharge data from 226 runoff events. Their results showed that the estimated θ values were different for different events and generally varied between 0.6 and 1. The event-to-event variability of θ was also shown to decrease as the magnitude of peak discharge at the outlet increases. This is because, they argued, more intense rainfall events that are responsible for larger peak discharge events have less spatial variability when compared with less intense rainfall events.

Motivated by the findings of Ogden and Dawdy [2], Furey and Gupta [13] undertook an event-based analysis of peak discharge scaling structure in the GCEW with the main objective of understanding which physical processes are responsible for the event-to-event variability of both α and θ. Their study, which was based on 148 rainfall-runoff events, showed that θ depends on T, whereas α depends on excess rainfall depth (P_e). They found that the significant event-to-event variability of θ observed at smaller peak discharge values is due to the variability in the antecedent soil moisture state and the increased spatial rainfall variability associated with less intense rainfall events. In their follow up paper, Furey and Gupta [14] further investigated the role of P_e and T in determining α and θ. They devised, based on the theory of a geomorphic instantaneous unit hydrograph (GIUH) [22,23], an analytical formula that relates the expected value of peak discharge to P_e, T, and A. Their results further confirmed the systematic dependence of α and θ on P_e and T. Drawing from results of their preliminary analysis of the effect of v_c and v_h on α and θ, they concluded that both α and θ can be affected by v_c and v_h. Their theoretical estimates of the peak discharge are comparable with empirical data from GCEW only when realistic v_h values were used. This confirms the importance of the hillslope residence time in determining the scaling structure of peak discharges. It is also independently confirmed by Saco and Kumar [24], and Botter and Rinaldo [25], that the runoff response at all scales is not only shaped by the drainage network and v_c but also by v_h.

Although our work is closely connected to that of Furey and Gupta [14], we use a drainage network-based hydrologic model simulation to provide in-depth insight into the role of the interplay among, T, v_h, and v_c in controlling α and θ, which Furey and Gupta [14] did not fully address in their work, and which to our knowledge, has yet to be reported. A further understanding of this problem is important because, in reality, these catchment processes are interdependent, and understanding their relative roles in determining the scaling structure provides further insight into our quest to estimate α and θ from catchment variables that can be either directly measured or estimated.

3. Methodology

3.1. Study watersheds

We considered three different watersheds in Iowa: Clear Creek, Old Mans Creek, and Boone River, which have drainage areas of 254, 520, and 1082 km^2, respectively. We extracted their respective drainage networks and hillslopes from a one arc-second