Signatures of large-scale soil moisture dynamics on streamflow statistics across U.S. climate regimes

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[1] In this paper we address an observational validation of recent theoretical results on the structure of the probability density function (pdf) of daily streamflows through the analysis of data pertaining to several catchments covering various sizes, climatic regimes, and topographic features across the United States. Seasonal streamflow pdfs obtained from recorded time series are directly compared with the theoretical distribution derived by Botter et al. (2007a) by coupling a suitable transport model with a stochastic description of runoff production through soil moisture dynamics. The ecohydrological and morphological parameters defining the theoretical streamflow pdf are inferred for each watershed on the basis of easily gathered land use information and incorporate directly measured hydrologic and climatic data. An excellent agreement is shown with the corresponding observed distribution in variably sized and widely heterogeneous catchments across different climate regimes. In particular, our data confirm that the shape of the daily streamflow pdf shows different regimes well described by a Gamma distribution. Such regimes, roughly termed wet and dry, are controlled by the ratio between the runoff frequency and the inverse of the mean residence time of subsurface flow, which in turn controls the behavior of the basins for low-stage streamflows.

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1. Introduction

[2] The derivation of a complete probabilistic characterization of streamflows in river basins from first principles represents a major task in hydrology because of the noteworthy implications on water resources availability for human needs and ecological services (related, e.g., to riparian plant nutrition, irrigation, or storage management of any kind). Streamflows at the closure of whole river basins are the byproduct of many intertwined ecohydrological and climatic processes, such as infiltration from rainfall, evapotranspiration, runoff production and transport dynamics occurring in channeled and unchanneled regions of the basin. The intrinsic temporal variability of runoff series hence reflects the stochastic nature of the underlying rainfall and climate forcings, which is reflected by many other relevant hydrologic fluxes.

[3] Stochastic fluctuations of runoff, recognized for a long time, have been frequently studied through the generation of streamflow series, resulting as the output of rainfall-runoff models forced by stochastic inputs. In that context, effective rainfall series have been assumed as trajectories of stochastic processes with prescribed statistical features [e.g., *Weiss*, 1977; *Yue and Hashino*, 1999; *Aksoy and Bayazit*, 2000; *Xu et al.*, 2002; *Claps et al.*, 2005; *Szilagyi et al.*, 2006] or derived from continuous soil-water balances driven by stochastic climate forcings [e.g., *Milly*, 1993, 1994; *Hamlet and Lettenmaier*, 1999; *Botter et al.*, 2006; *Son and Sivapalan*, 2007]. Furthermore, the impact of possible climate changes on streamflow characteristics and hydrologic extremes have been analyzed by theoretical and observational studies [e.g., *Kottegoda and Horder*, 1980; *Murrone et al.*, 1997; *Hamlet and Lettenmaier*, 1999; *Katz et al.*, 2002; *Niemann and Eltahir*, 2005; *Kingston et al.*, 2006; *Novotny and Stefan*, 2007]. Relevant statistical features of observed streamflows series have been studied also to analyze drought characteristics in arid and semiarid environments [e.g., *Kroll and Vogel*, 2002; *Fleig et al.*, 2006].

[4] Recently, *Botter et al.* [2007a] provided an analytical characterization of the probability distribution function (pdf) of the slow, subsurface contribution to runoff (i.e., the base flow) on the basis of a stochastic description of soil moisture dynamics. Therein, rainfall was thought of as a point Poisson process and travel time in subsurface states was approximated by an exponentially distributed random variable. Although aware of the many timescales possibly occurring in the hillslope response to precipitation [e.g., *McGlynn et al.*, 2002; *Troch et al.*, 2003, 2004; *McGuire et al.*, 2005], *Botter et al.* [2007a] focused on the slow, subsurface contribution to runoff, which may be reasonably portrayed by a single timescale. The ensuing simplified approach proved able to couple ecohydrological processes traditionally treated independently, yielding exact analytical solutions [for a detailed discussion see *Botter et al.*, 2007a, 2007b]. In that framework, the steady state pdf of the

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subsurface contribution to streamflows was obtained as a Gamma distribution, whose parameters may be linked to macroscopic rainfall properties, soil-vegetation parameters, and key geomorphological features. The approach was initially structured in a spatially lumped framework by assuming average properties, as in the related literature on soil moisture dynamics [see, e.g., *Rodriguez-Iturbe et al.*, 1999; *Rodriguez-Iturbe and Porporato*, 2004; *Settin et al.*, 2007], but has been more recently extended to tackle the effects of spatially distributed soils, vegetation and morphological features [*Botter et al.*, 2007b]. Even though the dynamics of surface runoff triggered by intense storms is neglected by the analytical model [*Botter et al.*, 2007a], the exact base flow pdf derived therein is argued to be reasonably interpreted as a proxy of the overall (catchment scale), daily streamflow pdfs in many cases of practical interest. This holds, of course, as subsurface contributions to streamflows in many circumstances represent the major runoff component in terms of discharged volumes [e.g., *Botter et al.*, 2007a; *Rinaldo et al.*, 2006], particularly when considering daily streamflows in relatively flat, vegetated catchments. On this specific point the paper presents a number of relevant computational applications that illuminate and extend the framework of analysis.

[5] The main goal of this paper is comparing daily streamflow pdfs obtained from continuous measurements in several catchments across various climate regimes of the United States with the theoretical gamma distribution derived by *Botter et al.* [2007a]. Data are openly accessible through the Web and pertain, in particular, the time series of daily streamflows collected and made available by the U.S. Geological Survey (e.g., http://waterdata.usgs.gov). As one of the major implications of this study is to provide a linkage between the main features of the observed streamflow pdfs and the underlying climatic and ecohydrological processes, the ready accessibility of the data seems indeed noteworthy.

[6] The paper is organized as follows: Section 2 briefly reviews the modeling scheme adopted by *Botter et al.* [2007a] to derive exact probability distribution functions of streamflows; a comparison of the above model against daily streamflow pdfs obtained from continuous measurements in several catchments throughout the United States is presented in section 3, where both the cases of homogeneous and heterogeneous basins are considered. A set of conclusions closes then the paper.

2. Exact Probabilistic Characterization of Daily Streamflows

[7] In this section we briefly review (and adapt to the case at hand) the modeling scheme presented by *Botter et al.* [2007a, 2007b], which allows a linkage between the probabilistic structure of streamflows and underlying ecohydrological, climate and transport processes in relatively flat, vegetated catchments.

[8] Following *Rodriguez-Iturbe et al.* [1999], *Rodriguez-Iturbe and Porporato* [2004] and *Botter et al.* [2007a], rainfall is assumed as a zero-dimensional point process with frequency λ_P [T^{-1}]. The latter assumption implicitly postulates catchment sizes, say A, smaller than the correlation scale of rainfall events and timescales of the process of interest greater than the characteristic duration of single rainfall events (e.g., daily timescales). Furthermore, daily rainfall depths are assumed as exponentially distributed with parameter γ_P [L^{-1}]. Meanwhile, constant (i.e., spatially and temporally averaged) soil and vegetation parameters are employed to characterize the relevant ecohydrological processes occurring in the active soil layer. These parameters are: effective soil depth, Z_r, porosity, n, and maximum evapotranspiration rate, ET, which are assumed as representative of a prescribed season either pointwise [see, e.g., *Rodriguez-Iturbe et al.*, 1999; *Porporato et al.*, 2004; *Rodriguez-Iturbe and Porporato*, 2004] or upscaled to heterogeneous catchment scales [*Settin et al.*, 2007]. The temporal evolution of spatially averaged relative soil moisture, $s(t)$, is seen as the result of three independent processes (for a review see *Rodriguez-Iturbe and Porporato* [2004]): linear losses due to evapotranspiration (in the range of soil moisture between the wilting point, s_w, and a suitable soil moisture threshold s_1); instantaneous leakage due to deep percolation (above s_1); and stochastic increments due to infiltration from rainfall. The thresholds s_w and s_1 are, again, assumed to be representative for the ecohydrological process occurring in the considered region. In this framework, subsurface runoff events are assumed to be triggered by the exceedence of the soil moisture threshold s_1 (which is typically between field capacity and soil saturation). Water pulses infiltrating into soil beyond the root zone are assumed to be released toward the stream network as subsurface or groundwater flow with a rate proportional to the instantaneous water storage [e.g., *Eng and Milly*, 2007]. Thus, consistently with the spatial and temporal scales considered, the fluxes at the absorbing barrier of the transport volume (i.e., the gauging station of catchments where streamflows are measured) are described by exponential residence time distributions [*Botter et al.*, 2007a, 2007b]. Under the above assumptions the steady state pdf of the base flow Q (here identified by the subsurface contribution to runoff), $p(Q)$, is expressed by a Gamma distribution of the type [*Botter et al.*, 2007a]

$$p(Q) \sim p(Q, t \to \infty) = c^* \, Q^{\left(\frac{\lambda}{k}-1\right)} \exp\left(-\gamma_Q Q\right), \qquad (1)$$

where c^* is the normalizing constant, $\gamma_Q = \gamma_P/(k A)$ represents the mean runoff increment due to incoming rainfall events and k [T^{-1}] is the inverse of the mean residence time in subsurface. Moreover, the parameter λ [T^{-1}] in equation (1) represents the runoff frequency (i.e., the frequency of episodic events determining runoff production because of infiltrating precipitation), which can be expressed in terms of the underlying rainfall, soil and vegetation properties as follows [*Porporato et al.*, 2004; *Botter et al.*, 2007a]:

$$\lambda = \eta \frac{\exp(-\gamma)\gamma^{\frac{\lambda_P}{\eta}}}{\Gamma(\lambda_P/\eta, \gamma)}, \qquad (2)$$

where $\Gamma(a, b)$ is the incomplete gamma function of parameters a and b, $\eta = ET/(nZ_r(s_1 - s_w))$ and $\gamma = \gamma_P \, nZ_r(s_1 - s_w)$. The probability distribution of Q is thus related to the underlying soil and vegetation properties (through the parameter λ) and to key rainfall properties (through both the parameters γ_Q and λ), but it also depends on important geomorphic factors such as the mean residence time of subsurface flow ($1/k$) and the size

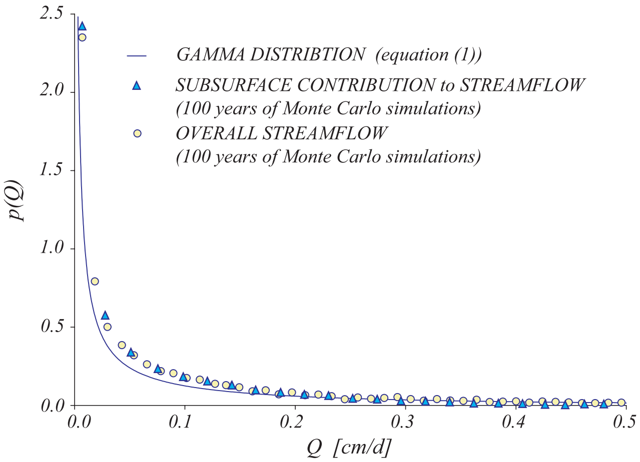

Figure 1. Comparison between the spring runoff pdf derived from the Monte Carlo application of a continuous geomorphically based rainfall-runoff model coupled with a stochastic rainfall generator and the corresponding analytical daily streamflow pdf in the Dese catchment (equation (1), solid line). Both the overall, numerical streamflow pdf (circles) and the pdf of the subsurface contribution to streamflow (triangles) are shown. The parameters used in the analytical model are congruent with the parameters employed in the numerical Monte Carlo rainfall-runoff model. The complete set of soil, vegetation, and transport parameters used by the continuous numerical rainfall-runoff model can be found in work by *Rinaldo et al.* [2006] and *Botter et al.* [2006, 2007a]. The corresponding parameters used in the analytical model are $n = 0.55$ (porosity), $Z_r =$ 30 cm (soil depth), $s_w = 0.18$ (wilting point), $s_1 = 0.6$ (deep percolation threshold), $ET = 0.25$ cm/d (maximum evapotranspiration), $k = 0.6$ d^{-1} (inverse of the mean residence time in subsurface), $\lambda_P = 0.33$ d^{-1} (rainfall frequency), and $\gamma_P = 1.1$ cm^{-1} (parameter controlling the distribution of the rainfall depths).

of the basin (A). In particular, according to equation (1), the behavior of $p(Q)$ is chiefly controlled by the ratio between the runoff frequency, λ, and the inverse of the mean residence time in subsurface, k. When $\lambda/k > 1$ ('wet conditions') the pdf of the runoff is bell shaped with $p(Q \to 0) \to 0$ (i.e., the probability density of the smallest streamflows is zero), while for $\lambda/k < 1$ ('dry conditions') $p(Q)$ goes to infinity for $Q \to 0$, and it monotonically decreases for $Q > 0$ [*Botter et al.*, 2007a].

[9] In deriving equation (1), *Botter et al.* [2007a] focused only on the subsurface contribution to streamflows, thus neglecting fast surface runoff possibly triggered by intense storms or accessing either macropores or preferential flow paths. In many cases, however, the overall daily subsurface contribution to streamflows may approximate quite well the daily discharge, particularly in flat, vegetated catchments. In fact, surface flows frequently involve only small portions of the drainage basin, usually characterized by convergent topography [e.g., *Woods and Sivapalan*, 1997; *D'Odorico and Rigon*, 2003]. In absence of pronounced topographic effects and/or impermeable surfaces, the surface contribution to runoff is often overshadowed by the subsurface contribution, particularly at large timescales [e.g., *Rinaldo et al.*, 2006].

[10] To further analyze typical effects of fast surface runoff on the catchment-scale streamflow pdf, we have performed a numerical Monte Carlo test for a relatively flat, well instrumented basin discharging into the Venice Lagoon, namely the Dese River basin at Villa Volpi (see *Rinaldo et al.* [2006] for a detailed description that includes information on soil types and the pertinent hydrology). Therein, the analytical base flow pdf given by equation (1) has been compared with the numerical result derived from the application of a continuous, hydrologic model forced by stochastic rainfall and climate generators [*Botter et al.*, 2006, 2007a]. Needless to say, the numerical runoff production module suffers no limitations apart from accuracy of the numerical code, and allows one to single out both surface (fast) and subsurface (slow) contributions to runoff. Note that in this case physical constraints prohibit a significant involvement of deep groundwater in base flow dynamics [*Rinaldo et al.*, 2006]. The numerical test performed allowed us to quantify the impact of surface contributions to the overall discharge pdf in a real-world setting. Figure 1 shows the analytical pdf (equation (1), solid line) compared both with the overall discharge pdf derived by the 200 a Monte Carlo simulation of the numerical model (circles), and with the numerical pdf corresponding to the sole subsurface contribution to streamflows (triangles). The comparison suggests that the difference between the overall streamflow pdf and the pdf of the subsurface contribution to runoff is in this case negligible. Obviously, this may not be true in general as in other circumstances our model could underestimate peak flows probabilities related to intense storms mobilizing surface runoff. As we shall see, however, the analytical base flow pdf provided by equation (1) appears to reasonably capture the overall behavior of the streamflow pdf in many cases of practical interest.

3. Ecohydrological Signatures of Streamflow Statistics Across U.S. Climate Regimes

[11] The climatic regions in the United States vary from the tropical rain forests to the arctic expanse of Alaska. Thus investigating streamflow variability within different catchments across various U.S. regions permits the analysis of how climatic, rainfall, ecologic and transport features may impact the probabilistic structure of streamflow series.

[12] In this section, the analytical streamflow pdf given by equation (1) is compared with streamflow pdfs observed in seven catchments belonging to different climate regions of the U.S. (see Figure 2): Rock Creek (Washington), Molalla River (Oregon), Bear Butte Creek (South Dakota), Redgate Creek (Texas), West Swan River (Minnesota), White River (Arkansas) and Jacob Fork (North Carolina). Variability of the underlying climate regimes is depicted in Figure 2 through the spatial distribution of mean annual precipitation, which allows a relatively simple and objective representation of the climatic gradients existing across United States. Streamflow statistics for the above catchments have been derived by continuous daily streamflow measurements collected by the U.S. Geological Survey (http://waterdata.usgs.gov). According to the basic assumptions of the analytical model of *Botter et al.* [2007a], we

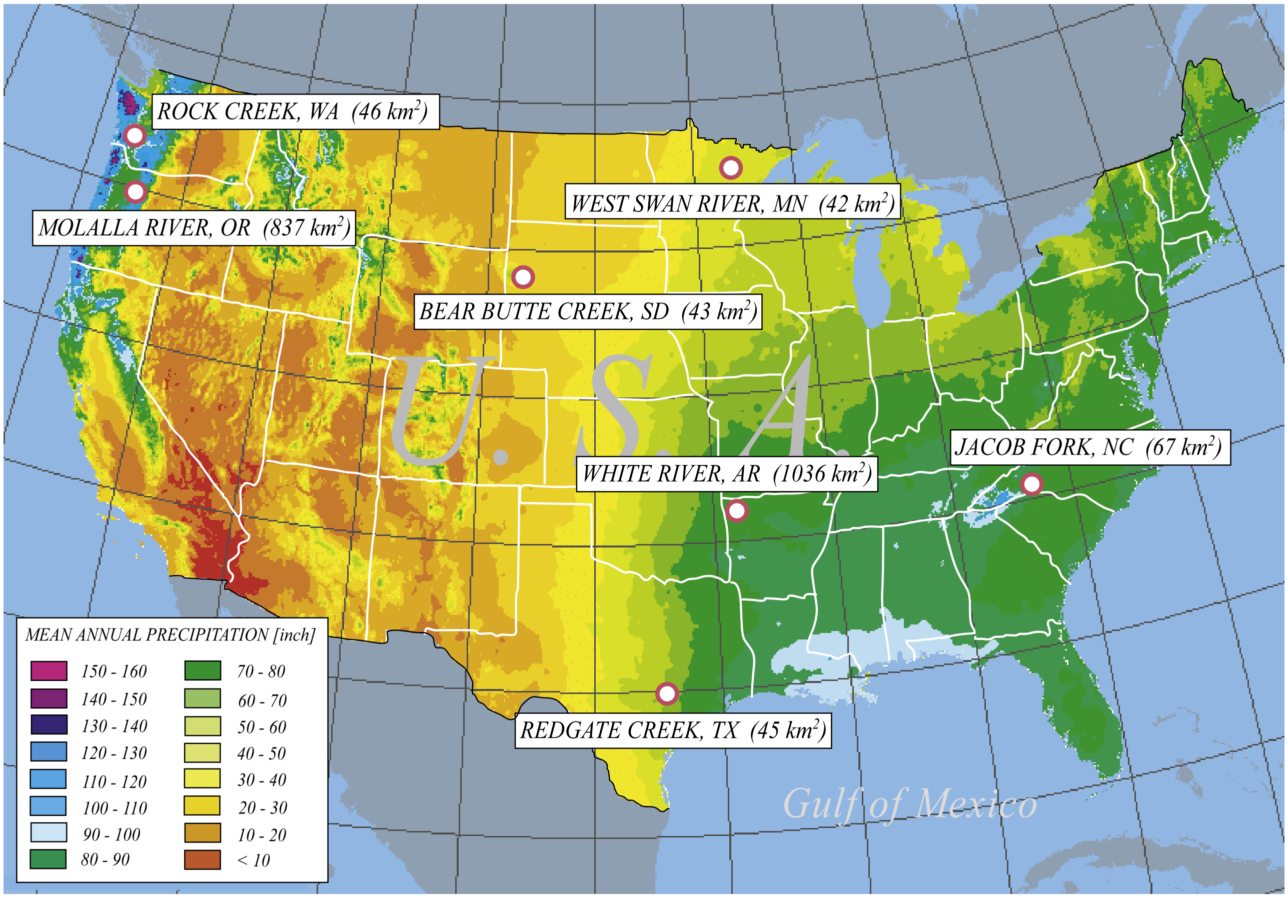

Figure 2. Location and extent of the seven study catchments investigated in this paper (from west to east): Rock Creek (46 km^2, Washington), Molalla River (837 km^2, Oregon), Bear Butte Creek (46 km^2, South Dakota), Redgate Creek (45 km^2, Texas), West Swan River (42 km^2, Minnesota), White River (1036 km^2, Arkansas), and Jacob Fork (67 km^2, North Carolina). The spatial variability of the underlying climate regimes is schematically represented through the mean annual precipitation: blue/purple, wet regime; orange/red, arid regime (taken from The National Atlas of the United States of America, 2005, http://nationalatlas.gov/).

shall first focus on daily streamflow statistics of relatively small, vegetated catchments where uniform soil vegetation and rainfall properties may be reasonably assumed (section 3.1). Then we will extend our analysis to larger basins ($O(10^3)$ km^2), to asses the robustness of the approach in predicting streamflow statistics in presence of heterogeneity of rainfall, soil and vegetation properties (section 3.2). Note that in the selection of the basins (and of the seasons investigated) we have deliberately avoided cases in which the accumulation of snow may be important.

3.1. Homogeneous Basins

[13] The West Swan River catchment closed near Silica (St. Louis County, Minnesota) is a relatively flat vegetated basin, which has an overall drainage area of 42.2 km^2 (Table 1), an average elevation of 414 m above the see level, a maximum elevation of 460 m and is mainly covered by deciduous forests. The climate regime of this region is humid-continental of the subtype "warm summer," which is marked by large seasonal temperature variance (30–40°C), relatively hot summers and snowy winters. Daily streamflows in West Swan River have been continuously measured from 1963 to 1979 by means of an old gauging station dismissed since 1979 (47°14′40″, 93°02′30″). During the same period, rainfall has been recorded at a nearby meteorologic station (Hibbing, 47°23′, 92°50′). The summer pdf of daily runoff has been derived from the available streamflow record by means of usual sample analysis techniques.

[14] The goal of the paper is to compare observed and predicted probability distribution functions of daily streamflows. To this aim, the parameters of the theoretical pdf given by equation (1) should be properly estimated. The estimate of the rainfall, soil, vegetation and transport parameters introduced by the analytical model has been carried out as follows: the mean rainfall frequency λ_P, and the inverse of the mean daily rainfall depths, γ_P, are derived directly from the daily rainfall records. The runoff frequency, λ, is then estimated by means of equation (2) assuming reasonable values for the underlying soil and vegetation parameters (active soil depth nZ_r, wilting point s_w, soil moisture thresholds s_1 and maximum evapotranspiration ET), which are chosen in a narrow range physically meaningful on the basis of land use, soil and climate information. In the West Swan catchment, for example, we expect maximum evapotranspiration rates to be relatively high because of the large mean

Table 1. Geometrical, Soil, Climate, and Vegetation Parameters for the Seven Test Catchments Explored in This Paper[a]

Catchment	A, km^2	Period	γ_P, mm^{-1}	$\overline{T}$, deg C	λ_P, d^{-1}	ET, cm/d	γ	λ, d^{-1}	k, d^{-1}	λ/k
Bear Butte Creek	43.0	1988–2006	0.11	5.3	0.30	0.25	13.3	0.08	0.16	0.50
Molalla River	836.6	1963–1978	0.12 (*F*)	11.9 (*F*)	0.44 (*F*)	0.30	6.2	0.16	0.32	0.50
			0.12 (*W*)	5.4 (*W*)	0.68 (*W*)	0.08	6.3	0.59	0.27	2.21
Jacob Fork	66.6	1975–1994	0.09	14.9	0.33	0.18	11.7	0.18	0.07	2.60
Redgate Creek	44.8	1987–2006	0.08	15.6	0.32	0.55	10.6	0.03	0.80	0.04
Rock Creek	64.2	1945–1971	0.20 (*Su*)	16.6 (*Su*)	0.29 (*Su*)	0.15	17.3	0.05	0.08	0.61
			0.08 (*W*)	4.8 (*W*)	0.65 (*W*)	0.12	10.5	0.56	0.27	2.08
West Swan River	42.2	1963–1979	0.12	17.1	0.34	0.32	14.6	0.05	0.48	0.11
White River	1036.0	1975–1994	0.09	14.0	0.35	0.25	11.1	0.15	0.15	1.02

[a]For each catchment we have provided the following information: drainage area, A; period of observation of streamflows; inverse of the mean daily rainfall depths, γ_P; mean daily temperature in the considered season, $\overline{T}$; mean rainfall frequency, λ_P; estimated maximum evapotranspiration, ET; $\gamma = \gamma_P n Z_r (s_1 - s_w)$; mean runoff frequency, λ (see equation (2)); and inverse of the mean residence time in subsurface, k. Also provided (last column) is the ratio λ/k which controls the shape of the streamflow pdf. The parameters γ_P, $\overline{T}$, and λ_P have been derived from rainfall and climate data collected by the National Climatic Data Center (http://cdo.ncdc.noaa.gov/). ET and γ have been estimated on the basis of land use and climate information. The inverse of the mean residence time in subsurface has been estimated by suitably fitting recorded recession curves with an exponential function.

temperatures observed during the considered period (Table 1). To ensure the reliability of the estimated runoff frequency we have also checked a posteriori the consistency of the estimated value of λ with the directly measured relative frequency of positive jumps observed in the recorded streamflow series. Finally, the inverse of the mean residence time in subsurface states, k, has been estimated by suitably fitting recorded recession curves with an exponential function—a rather old and reliable hydrological practice indeed. In this context, it should be stressed that the model of *Botter et al.* [2007a] includes a single subsurface component of runoff, embedding both subsurface and deep groundwater flow. Therefore the mean residence time in subsurface may be considered as an average value between the timescales characteristic of the above processes, depending on the specific case considered. For the above reason, we may observe a temporal variability of k across the seasons even within the same catchment, depending on the relative importance of the above mechanisms in determining the soil drainage. Under wet climate conditions (that is, when the interarrival between subsequent runoff events is relatively short), in fact, the recession limb of the hydrograph is controlled by subsurface flow determined by soil moisture dynamics. Conversely, during dry periods (i.e., when the interarrival between subsequent runoff events is relatively large), the tail of the recession curve is usually controlled by deeper groundwater flows which are usually much slower than the subsurface contribution to streamflows. Clearly, the mean residence time directly estimated from seasonal data embeds all that in a simplified manner. Note that, owing to the physical nature of the parameters involved and the relatively small amount of data required for their estimate, the method described above is deemed quite promising also for ungauged basins, where a proper estimate of relevant base flow statistics may be indeed important [e.g., *Potter*, 2001].

[15] The complete set of soil, vegetation, transport and morphological parameters for the West Swan catchment, as well as for all other basins studied herein, is reported in Table 1. Figure 3a shows the graphical comparison of observed (circles) and theoretical (solid line, equation (1)) daily streamflow pdfs during the summer period (May–July) for the West Swan River. Also shown (inset) is a sketch of the underlying river network and of the soil use distribution, suitably derived from high-resolution satellite images (http://nationalmap.gov). The theoretical gamma distribution is found to fit well the observed streamflow pdf; in particular the limiting behavior of $p(Q)$ for $Q \to 0^+$, which is determined by the ratio λ/k, seems to be properly captured by the analytical model.

[16] In Figure 3b the same comparison shown in Figure 3a is reported for the Bear Butte creek near Deadwood (western South Dakota). The above watershed is a mountain basin of 43 km^2 mainly covered by evergreen forest ($\sim$90%) at an average elevation of $\sim$1500 m a.s.l. South

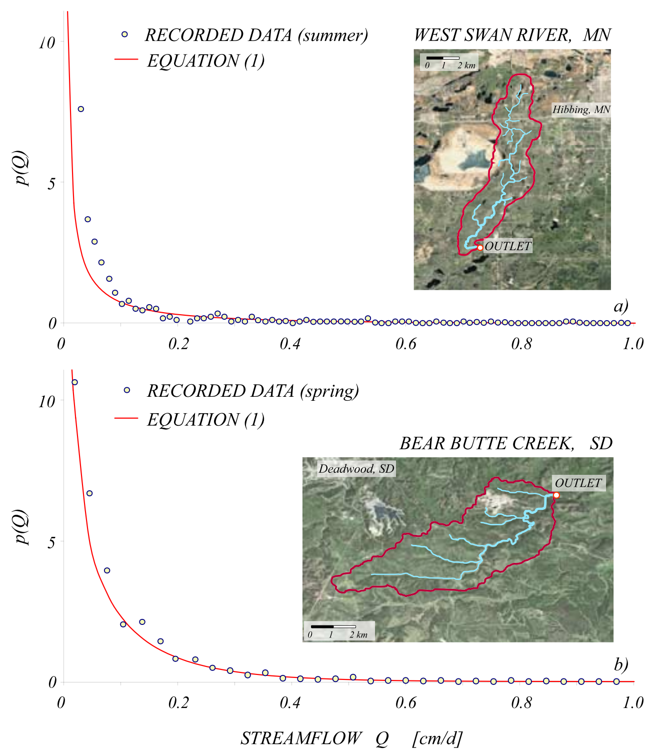

Figure 3. Comparison between the analytical streamflow pdf (solid line, equation (1)) and the streamflow pdf derived from field data (circles) in two different catchments: (a) West Swan River (Minnesota), summer season and (b) Bear Butte Creek (South Dakota), spring season.

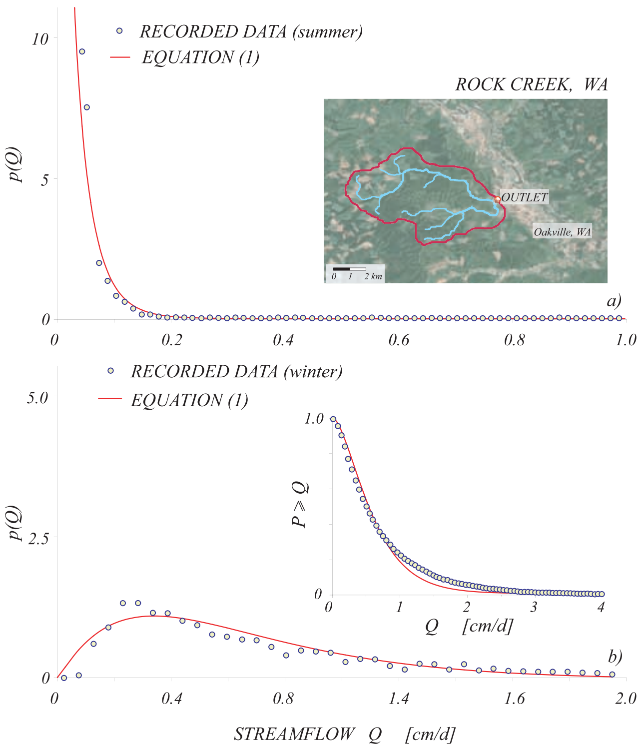

Figure 4. Comparison between the analytical streamflow pdf (solid line, equation (1)) and the streamflow pdf derived from field data (circles) in the Rock Creek catchment (Washington): (a) summer and (b) winter.

Dakota has an interior continental climate, with hot summers, extremely cold winters, high winds, and periodic droughts, especially in the western part of the region. Normal annual precipitation (1971–2000) averages at about 650 mm/a in the southeast, decreasing to less than 330 mm/a in the northwest. western South Dakota is generally characterized by semiarid climate conditions. The Bear Butte catchment, however, is located in the Black Hills, an isolated wet spot where the recorded average annual precipitation is relatively high compared to the surrounding areas. Accordingly, the rainfall frequency estimated from field measurements collected at the meteorologic station of Deadwood (44°22′, 103°44′) during the period 1992–2001 is relatively large (Table 1). In this case, the comparison between the theoretical and the observed daily streamflow pdf is carried out for the spring season (Figure 3b). Soil, vegetation and transport parameters of the analytical model are estimated as discussed above. Note that the maximum evapotranspiration rate is assumed to be smaller with respect to that estimated in the West Swan River ($ET = 0.25$ cm/d, Table 1), owing to the lower temperatures observed in this area. Conversely, the analysis of the recession limb of measured hydrographs, evidences an increase of the mean residence time in subsurface states which can be related to geomorphological and hydrological reasons (e.g., a low drainage density and/or the nature of the soils involved). Even though equation (1) has been derived by neglecting spatial gradients of soil moisture (thus implicitly assuming relatively flat catchments), the agreement between observed (circles) and theoretical (solid line, equation (1)) streamflow statistics in this mountainous basin is intriguing. The relative error on the estimate of the mean streamflow is well below 15%. Because of a large mean residence time in subsurface (~6 days), the Bear Butte creek basin yields a larger ratio λ/k with respect to that estimated for the West Swan River (Table 1), with increased probabilities for medium streamflows (i.e., in the range 0.1 ÷ 0.3 cm/d).

[17] Figure 4 shows the seasonality of the daily streamflow pdf in the Rock Creek catchment at Cedarville (46°52′05″, 123°18′,25″, Grays Harbor County, Washington), where streamflow statistics are investigated both during summer (Figure 4a) and winter (Figure 4b). The climate of Washington is predominantly of the marine type, with mild summers and winters and, as a result, a limited annual temperature ranges. Frequent cyclonic storms bring prolonged periods of rain, drizzle and fog to these west coast locations. In some locations it is not uncommon to receive as much as 2500 mm/a of precipitation, an amount that rivals the rainy tropics. During summers the climate is windy, particularly along the coast, and precipitation decreases with respect to winter and fall. The Rock Creek catchment is located west of the Olympic Mountains, where heavy precipitation and winds of gale force occur frequently, especially in winter. The gauged catchment has an area of 64 km^2, and it is mainly covered by evergreen and deciduous forests (~90%). The average elevation is about 200 m a.s.l., and the relief is of the order of 300 m. Precipitation has been measured from 1950 to 1963 at the meteorologic station of Elma (47°00′, 123°24′): the rainfall frequency λ_P ranges from 0.3 d^{-1} in summer up to 0.66 d^{-1} in winter. The average rainfall depth in rainy days is about 1.1 cm in winter, and decreases to less than 0.5 cm in summer (Table 1). The seasonal pdfs of daily streamflows are derived from data covering about 25 a. Soil and vegetation parameters for winter and summer seasons are listed in Table 1. Note that in this case estimated maximum evapotranspiration rates are 0.15 cm/d (summer), and 0.08 cm/d (winter). In winter, in fact, high rainfall rates and humidity, jointly with relatively low temperatures, partially limit the exchange between vegetation, soil and atmosphere. In summer, instead, increased temperature and insolation promote the increase of the maximum evapotranspiration rate despite the common persistence of fog and low clouds early in the day. As usual, the mean residence time has been estimated by fitting the recession curves of observed hydrographs with exponential functions. We observe a pronounced variability of k during the year (Table 1) because in winter the groundwater contribution to the streamflow is beclouded by sizable volumes of faster runoff components. Note also that in the highest locations of the Rock Creek catchment we may observe snowfall during the cold season. The accumulation of winter snowfall, however, is usually limited both in space and time and may be thus neglected for our purposes.

[18] The summer streamflow pdf of the Rock Creek catchment (Figure 4a) shows an excellent agreement with the theoretical pdf, with a relative error on the estimate of the first two moments of the streamflow pdf of about 10% and 15%, respectively. In this case relatively large probabilities are associated with extremely low streamflows (e.g., smaller than 0.05 cm/d). Conversely, owing to the increase of the rainfall frequency λ_P (that determines a marked increase of the runoff frequency λ), the shape of the

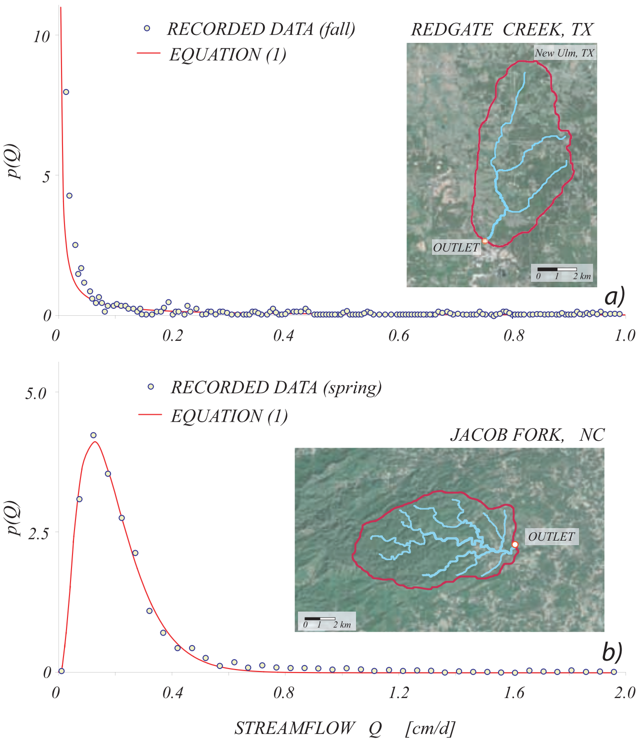

Figure 5. Comparison between the analytical streamflow pdf (solid line, equation (1)) and the corresponding streamflow pdf derived from field data (circles): (a) Redgate Creek catchment (Texas), fall and (b) Jacob Fork (North Carolina), spring.

streamflow pdf drastically shifts from a dry to a wet mode during winter. This is an interesting confirmation of the theoretical prediction implied by equation (1). During winter we observe small probabilities for low discharges (i.e., smaller than 0.1 cm/d), with the highest probabilities (the mode) around 0.3 cm/d and an average daily streamflow exceeding 0.4 cm/d. Even though the pdf derived from recorded streamflow data is closely reproduced by the analytical model, equation (1) tend to slightly overestimate the probability associated to relatively large streamflows (>1.4 cm/d). This fact is clearly evidenced also by the comparison between the modeled and observed cumulative exceeding probabilities, which is reported in the inset of Figure 4b.

[19] Figure 5a shows the comparison between the predicted and the observed streamflow pdf in a warm and relatively dry catchment, the Redgate Creek closed near Columbus (29°47′57″, 96°31′55″, Colorado County, Texas). The climate regime in eastern Texas is eminently humid subtropical, with warm weather year round and slight temperature differences between seasons. Precipitation is generally plentiful in the humid subtropical climate zone, and total annual precipitation decreases from east to west. Although most areas tend to have precipitation spread evenly throughout the year, areas in Texas that are slightly inland from the Gulf of Mexico generally observe a peak of precipitation in the spring, with a deep, drought-like pattern in summer. The Redgate Creek is a flat vegetated catchment with an overall area of 45 km^2 located in the "Gulf Coastal Plains," which embeds prairies and marshes. Soil uses exhibit a predominance of pasture/hays. The annual average precipitation is about 1500 mm/a, with rainfall events which are mostly concentrated during late fall and spring. Rainfall was measured at the meteorologic station of Columbus (29°42′, 96°32′) in the period 1990–2000, whereas streamflow series were collected at the outlet during the last 20 a. The recorded rainfall frequency during the late fall (October–December) is about 0.3 d^{-1}, with an average daily temperature of 16°C. The soil vegetation and transport parameters are reported in Table 1. Note that in this catchment we have a high maximum evapotranspiration rate ($\sim$0.5 cm/d) because of the high temperatures and small relative humidities that characterize the winter climate in this area. As a result, the ratio between the runoff frequency and the inverse of mean residence time in subsurface, λ/k, is the smallest among the considered catchments (0.04). The agreement between observed and predicted streamflow pdfs at Redgate Creek during the considered period is quite good. The resulting pdfs indicate enhanced drought risks, with a cumulated probability for streamflows smaller than 0.05 cm/d, which exceeds 0.95.

[20] Figure 5b, instead, shows the spring daily streamflow pdf for the Jacob Fork catchment at Ramsey (35°35′26″, 81°34′01″, Burke County, North Carolina). North Carolina belongs to the humid subtropical climate region, which characterizes most part of the southeastern United States. While there are no distinct wet and dry seasons, average rainfall does fluctuate around the year, with relative maxima during the spring and the early summer. In the region where the Jacob Fork catchment is located, in particular, we have an average precipitation of about 2300 mm/a, one of the highest in the eastern United States. Rainfall was measured at the meteorologic station of Casar (35°29′, 81°36′) in the period 1980–1990, whereas streamflows were collected from 1975 to 1994. The recorded rainfall frequency during the spring is about 0.35 d^{-1}, with an average daily temperature of 15°C. The estimated values of the underlying soil, vegetation and transport parameters are reported, as usual, in Table 1. Despite high temperatures characterizing this area, we do not expect exceedingly large evapotranspiration rates because of the persistence of high humidities and cloudiness during the spring and the early summer (minimum daily humidity sometimes exceeds 70%). The mean residence time in subsurface states is quite large because the recession curve of the hydrographs is dominated by deep groundwater contributions. The general agreement between observed and predicted streamflow statistics is reasonably satisfactory, even though in this case the model slightly underestimates peak flow probabilities.

3.2. Heterogeneous Basins

[21] Coping with the basic assumptions of the theoretical model (equation (1)), in section 3.1 we have considered small vegetated catchments (i.e., $A < 10^2$ m^2) where uniform rainfall, soil and vegetation properties could be reasonably assumed. In what follows, we shall explore the applicability of equation (1) in predicting streamflow statistics of relatively large catchments (typically $A = O(10^3)$ km^2), where rainfall and soil properties may exhibit a pronounced spatial variability. It should be stressed that *Botter et al.* [2007b] have provided a framework for handling the case of

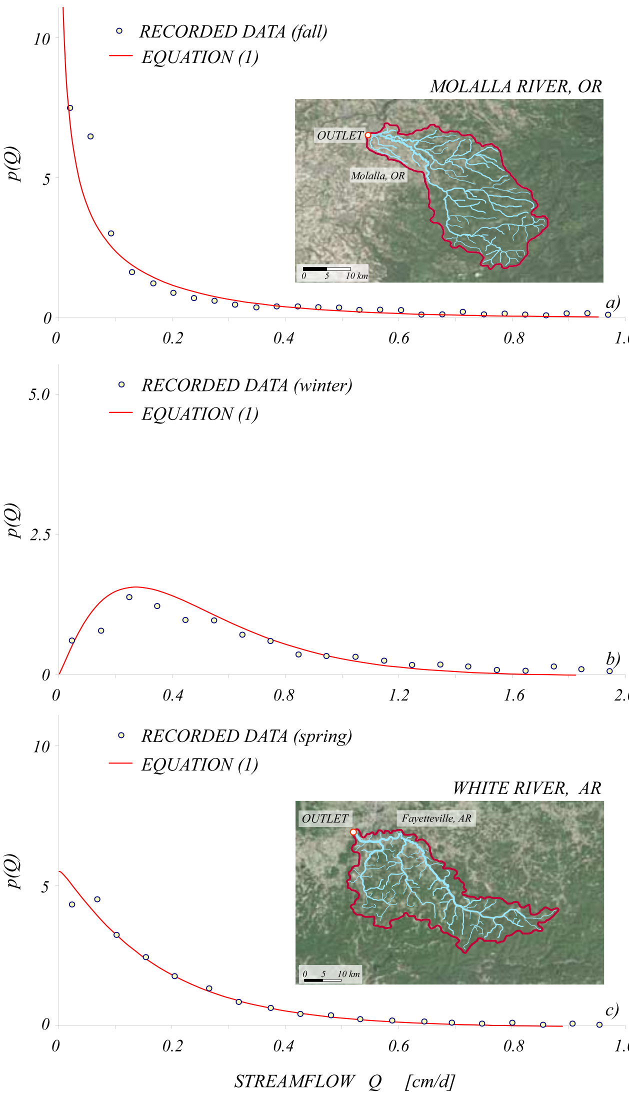

Figure 6. Comparison between the analytical streamflow pdf (solid line, equation (1)) and the streamflow pdf derived from field data (circles) in large catchments in Molalla River (Oregon) during (a) fall and (b) winter and in White River, Arkansas during (c) spring.

spatially variable soil vegetation and transport characteristics, which could be useful in treating large basins. The spatially distributed model, however, inevitably implies an increase in the number of parameters. Hence we have tried to test the model described in section 2 also in the case of heterogeneous basins, via the possible identification of basin-scale effective parameters. Note that this proved possible for the stationary distribution of soil moisture [*Settin et al.*, 2007].

[22] The first catchment investigated in this section is the Molalla River near Canby (45°14′40″, 122°41′10″, Clackamas County, Oregon). The Molalla catchment belongs to a transition zone between the West Coast marine and the Mediterranean climate regions, which is characterized by relatively sunny summers and mild fall. Precipitation is relatively heavy year round, but is particularly high during the winter, which is cold and foggy. The Molalla catchment has an overall area of 840 km^2, with a southeastern mountainous part mainly covered by evergreen forests. The western part of the basin, instead, is flat and mostly covered by pastures, hays and row crops. Rainfall data collected from different meteorologic stations located within and nearby the considered catchment (e.g., Estacada, Molalla, Silverton) suggest that rainfall occurrences are quite homogeneous in the whole catchment area, whereas daily depths exhibit a general decrease from east to west, particularly during winter. Aware of the difficulties existing in the full analytical treatment of spatially distributed rainfall forcings, we have treated rainfall as a zero-dimensional Poisson process where the parameter controlling the distribution of the rainfall depths, γ_P, has been derived as a spatial average of the different parameters characterizing different stations located within the catchment. Spatially averaged soil and vegetation properties have been reasonably estimated from available information on soil coverage and types. Note that spatial variability of soil and vegetation properties (whose detailed distribution can hardly be provided) may lead to uncertain estimates of the underlying runoff frequency, λ. In the cases presented in this paper, however, the accuracy of the estimate has been checked by comparing a posteriori the estimated values of λ with the observed frequencies of positive streamflow jumps in the recorded runoff series. Finally, the mean residence time has been derived, as usual, by fitting the recession curve of measured hydrographs with an exponential function. The complete set of parameters for the Molalla catchment is shown in Table 1.

[23] Observed and predicted streamflow statistics of the Molalla catchment are investigated during both the fall and the winter seasons. The fall pdf (Figure 6a) is of a dry type, slowly decreasing toward zero thus ensuring nonnegligible probabilities for relatively large discharges (e.g., $Q = 0.2 \div 0.3$ cm/d). The observed streamflow pdf (dots) shows a good agreement with the theoretical gamma pdf (solid line), except than for the smallest streamflows. Owing to the observed increasing of the rainfall frequency, the shape of the distribution shifts mode from dry to wet in winter (Figure 6b). Under the above circumstances, the highest probabilities are found around 0.3 cm/d, with an average streamflow of about 0.4 cm/d. Even though the general shape of the distribution derived from recorded data is closely reproduced by the analytical model, the analytical pdf significantly underestimates the probability associated to large streamflows (>1.6 cm/d), whose values are strongly influenced by surface runoff triggered by intense storms that are neglected by the theoretical model.

[24] The comparison presented in Figure 6c refers to the spring streamflow pdf in the White River catchment near Fayetteville (36°04′23″, 94°04′52″, Washington County, Arkansas). The considered catchment belongs to the humid subtropical climate region, and is thus marked by climate conditions which are rather similar to those characterizing the Jacob Fork catchment (see Table 1). The White River basin closed near Fayetteville has an overall drainage area of about 1040 km^2 and shows highly heterogeneous soil uses, with a predominance of deciduous forests, pastures and hays. Topographic slopes are gentle, with an overall unevenness which does not exceed 300 m. Recorded rainfall data in different meteorologic stations located within and nearby the

considered catchment (e.g., St. Paul, Fayetteville) suggest that rainfall occurrences are quite homogeneous in the whole catchment area, whereas daily depths exhibit a smoothed spatial variability. Following the considerations developed above, rainfall has been simplified as a zero-dimensional Poisson process where the mean rainfall depth is assumed as a spatially averaged parameter. Spatially averaged soil and vegetation properties have been reasonably estimated from available information on soil uses and types. Estimated maximum evapotranspiration rates are in this case larger than those obtained for the Jacob fork catchment because of the different soil uses and the smaller humidity. The complete set of parameters for the white River catchment is shown in Table 1. In this case the estimated ratio between the runoff frequency and the inverse of the mean residence time in subsurface, λ/k, is around 1. As a consequence, the theoretical daily streamflow pdf is exponential, with $\lim_{Q \to 0^+} p(Q) = a$ $(0 < a < \infty)$, a feature closely reproduced by the observed streamflow pdf (Figure 6c).

[25] Further work on detailed comparison of streamflow statistics in nested watersheds is ongoing, in particular aimed at seeing under what conditions controlling parameters of the model can be kept constant. Indeed the same database allows to probe watersheds that come in various sizes from small to large ones (in absolute and relative terms), so as to test the fit within (or very well outside) the correlation range of the precipitation.

4. Conclusions

[26] The following conclusions are worth emphasizing.

[27] 1. Seasonal probability distribution functions of daily streamflows, computed from data gathered in different catchments throughout the United States, have been compared to the theoretical distribution derived by *Botter et al.* [2007a]. The necessary parameters have been estimated from rainfall, hydrologic, climate and land use information easily available through the Web. This suggests the possible relevance of the theoretical approach developed, which allows the prediction of streamflow statistics on the basis of a few parameters with a clear physical meaning. This, of course, is more appealing than fitting parameters of arbitrary distributions to match observed pdfs.

[28] 2. The agreement between predicted and observed daily streamflow pdfs is reasonably satisfactory in all the cases investigated. This is deemed to be a somewhat surprising result given the purported limitations of the theory that, e.g., ignores fast responses to intense rainfall events and spatial patterns of rainfall. Our study cases include small flat catchments, steep mountain basins and large complex catchments characterized by heterogeneity of rainfall, soil, vegetation and morphological features. The range of conditions tested is interesting per se.

[29] 3. Theory and this study evidence that two quite distinct regimes exist as predicted, labeled respectively as the wet and the dry runoff regimes. Seasonal transitions between such regimes do occur within the same basin. In particular, the overall behavior of the streamflow pdf is theoretically predicted, and empirically shown to depend on the ratio between the runoff frequency and the inverse of the mean residence time of subsurface runoff contributions.

[30] 4. The theoretical distribution reproduces particularly well the data from relatively small and flat vegetated catchments, and this conforms with the assumptions of the model. Somewhat unexpected, however, is the good performance of the model in the important cases of (1) large basins (that is, characterized by spatial scales larger than the correlation scales of rainfall events) for which effective parameters are needed through sensible spatial averaging or (2) particularly wet basins where heavy rainfall may compensate the effect of higher interception rates related to thick vegetation (commonly associated with wet climate conditions), leading to nonnegligible surface runoff volumes during intense storms.

[31] We thus conclude that the robustness of the probabilistic structure of base flows (where the term is somewhat generally addressing the runoff responding to precipitation infiltrated at the command of stochastic soil moisture dynamics) to a wide range of conditions supports its applicability to many cases of practical interest. In particular, an important application of the model proposed may be the derivation of exact expressions for the flow duration curves in gauged and ungauged catchments, a tool that may serve important activities related to water resources management.

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References

Aksoy, H., and M. Bayazit (2000), A model for daily flows of intermittent strams, *Hydrol. Processes*, *14*, 1725–1744.

Botter, G., T. Settin, M. Marani, and A. Rinaldo (2006), A stochastic model of nitrate transport and cycling at basin scale, *Water Resour. Res.*, *42*, W04415, doi:10.1029/2005WR004599.

Botter, G., A. Porporato, I. Rodriguez-Iturbe, and A. Rinaldo (2007a), Basin-scale soil moisture dynamics and the probabilistic characterization of carrier hydrologic flows: Slow, leaching-prone components of the hydrologic response, *Water Resour. Res.*, *43*, W02417, doi:10.1029/2006WR005043.

Botter, G., A. Porporato, E. Daly, I. Rodriguez-Iturbe, and A. Rinaldo (2007b), Probabilistic characterization of base flows in river basins: Roles of soil, vegetation, and geomorphology, *Water Resour. Res.*, *43*, W06404, doi:10.1029/2006WR005397.

Claps, P., A. Giordano, and F. Laio (2005), Advances in shot noise modeling of daily streamflows, *Adv. Water Res.*, *28*(9), 992–1000.

D'Odorico, P., and R. Rigon (2003), Hillslope and channel contributions to the hydrologic response, *Water Resour. Res.*, *39*(5), 1113, doi:10.1029/2002WR001708.

Eng, K., and P. C. D. Milly (2007), Relating low-flow characteristics to the base flow recession time constant at partial record stream gauges, *Water Resour. Res.*, *43*, W01201, doi:10.1029/2006WR005293.

Fleig, A. K., L. M. Tallaksen, H. Hisdal, and S. Demuth (2006), A global evaluation of streamflow drought characteristics, *Hydrol. Earth Syst. Sci.*, *10*(4), 535–552.

Hamlet, A. F., and D. P. Lettenmaier (1999), Effects of climate change on hydrology and water resources in the Columbia River basin, *J. Am. Water Res. Assoc.*, *35*(6), 1597–1623.

Katz, R. W., M. B. Parlange, and P. Naveau (2002), Statistics of extremes in hydrology, *Adv. Water Res.*, *25*(8–12), 1287–1304.

Kottegoda, N. T., and M. A. Horder (1980), Daily flow model based on rainfall occurences using pulses and a transfer function, *J. Hydrol.*, *47*, 215–234.

Kingston, D. G., D. M. Lawler, and G. R. McGregor (2006), Linkages between atmospheric circulation, climate and streamflow in northern North Atlantic: Research prospects, *Prog. Phys. Geogr.*, *30*(2), 143–174.
Kroll, C. N., and R. M. Vogel (2002), Probability distribution of low streamflow series in the United States, *J. Hydrol. Eng.*, *7*, 137–146.
McGlynn, B. L., J. J. Mc Donnel, and D. D. Brammer (2002), A review of the evolving perceptual model of hillslope flowpaths at the Maimai catchments, New Zealand, *J. Hydrol.*, *257*, 1–26.
McGuire, K. J., J. J. McDonnell, M. Weiler, C. Kendall, B. L. McGlynn, J. M. Welker, and J. Seibert (2005), The role of topography on catchment-scale water residence time, *Water Resour. Res.*, *41*, W05002, doi:10.1029/2004WR003657.
Milly, P. C. D. (1993), An analytical solution of the stochastic storage problem applicable to soil-water, *Water Resour. Res.*, *29*(11), 3755–3758.
Milly, P. C. D. (1994), Climate, soil-water storage, and the average annual water balance, *Water Resour. Res.*, *30*(7), 2143–2156.
Murrone, F., F. Rossi, and P. Claps (1997), Conceptually-based shot noise modelling of streamflows at short time interval, *J. Stochastic Hydrol. Hydraul.*, *11*(6), 483–510.
Niemann, J. D., and E. A. B. Eltahir (2005), Sensitivity of regional hydrology to climate changes, with application to the Illinois River basin, *Water Resour. Res.*, *41*, W07014, doi:10.1029/2004WR003893.
Novotny, E. V., and H. G. Stefan (2007), Stream flow in Minnesota: Indicator of climate change, *J. Hydrol.*, *334*, 319–333.
Porporato, A., E. Daly, and I. Rodriguez-Iturbe (2004), Soil water balance and ecosystem response to climate change, *Am. Nat.*, *164*(5), 625–632.
Potter, K. W. (2001), A simple method for estimating baseflow at ungauged locations, *J. Am. Water Res. Assoc.*, *37*(1), 177–184.
Rinaldo, A., G. Botter, E. Bertuzzo, A. Uccelli, T. Settin, and M. Marani (2006), Transport at basin scales: 1. Theoretical framework, *Hydrol. Earth Syst. Sci.*, *10*, 19–30.
Rodriguez-Iturbe, I., and A. Porporato (2004), *Ecohydrology of Water Controlled Ecosystems: Soil Moisture and Plant Dynamics*, Cambridge Univ. Press, New York.
Rodriguez-Iturbe, I., A. Porporato, L. Ridolfi, V. Isham, and D. Cox (1999), Probabilistic modelling of water balance at a point: The role of climate soil and vegetation, *Proc. R. Soc. London, Ser. A*, *455*, 3789–3805.
Settin, T., G. Botter, I. Rodriguez-Iturbe, and A. Rinaldo (2007), Numerical studies on soil moisture distributions in heterogeneous catchments, *Water Resour. Res.*, *43*, W05425, doi:10.1029/2006WR005737.
Son, K., and M. Sivapalan (2007), Improving model structure and reducing parameter uncertainty in conceptual water balance models through the use of auxiliary data, *Water Resour. Res.*, *43*, W01415, doi:10.1029/2006WR005032.
Szilagyi, J., G. Balint, and A. Csik (2006), Hybrid, Markov chain-based model for daily streamflow generation at multiple catchment sites, *J. Hydrol. Eng.*, *11*, 245–256.
Troch, P. A., C. Paniconi, and E. Emiel van Loon (2003), Hillslope-storage Boussinesq model for subsurface flow and variable source areas along complex hillslopes: 1. Formulation and characteristic response, *Water Resour. Res.*, *39*(11), 1316, doi:10.1029/2002WR001728.
Troch, P. A., A. H. van Loon, and A. G. J. Hilberts (2004), Analytical solution of the linearized hillslope-storage Boussinesq equation for exponential hillslope width functions, *Water Resour. Res.*, *40*, W08601, doi:10.1029/2003WR002850.
Weiss, G. (1977), Shot noise models for generation of synthetic streamflow data, *Water Resour. Res.*, *13*(1), 101–108.
Woods, R. A., and M. Sivapalan (1997), A connection between topographically driven runoff generation and channel network structure, *Water Resour. Res.*, *33*(12), 2939–2950.
Xu, Z. X., G. A. Schultz, and A. Schumann (2002), A conceptually-based stochastic point process model for daily stream-flow generation, *Hydrol. Processes*, *16*, 3003–3017.
Yue, S., and M. Hashino (1999), A stochastic model for deriving the basic statistics of *J*-day averaged streamflown of streamflow, *Water Resour. Res.*, *35*(10), 3127–3138.

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