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On the use of mean monthly runoff to predict the flow–duration curve in ungauged catchments

Wafa Chouaib^a, Younes Alila^a and Peter V. Caldwell^b

^aForest Sciences Centre, Vancouver, British Columbia, Canada; ^bUS Department of Agriculture Forest Service, Center for Integrated Forest Science, Southern Research Station, Franklin, North Carolina, USA

ABSTRACT

We examine the applicability of predicting the daily flow–duration curve (FDC) using mean monthly runoff represented in its stochastic form (MM_FDC) to aid in predictions in ungauged basins, using long-term hydroclimatic data at 73 catchments of humid climate, in the eastern USA. The analysis uses soil hydrological properties, soil moisture storage capacity and the predominant runoff generation mechanism. The results show that MM_FDC did not distinguish the shapes of the upper and lower thirds of the FDC. The upper third is where the precipitation pattern and the antecedent moisture conditions are dominant, while the lower third is where drought-induced low flows and the evapotranspiration effect are prevalent. It is possible to use the MM_FDC to predict the middle third of the FDC (exceedence probabilities between 33% and 66%). The method is constrained by the catchment flow variability (slope of FDC), which changes in accordance with landscape properties and the predominant runoff generation mechanism.

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1 Introduction

The prediction and characterization of the flow regime are critical for management of water resources and aquatic ecosystems (Poff *et al.* 1997). They are also relevant for public safety as they help in protecting against floods, and allow the quantification of water supplies during droughts (Muneepeerakul *et al.* 2010). A central problem of hydrology is understanding the processes that affect streamflow and making predictions in river basins (Botter *et al.* 2009, Booker and Snelder 2012, Ameli *et al.* 2015), a process made particularly difficult in basins where measured hydroclimatic data are not available.

The flow–duration curve (FDC) characterizes the flow regime within a stochastic framework. The FDC is a graphical representation of the frequency, or the fraction of time during which a specified magnitude of runoff is equalled or exceeded (Vogel and Fennessey 1994, Castellarin *et al.* 2013). The FDC is relevant for many hydrological applications, including the management of aquatic systems, flooding and drought, in addition to lake sedimentation studies, water quality management and water resources allocation (Vogel and Fennessey 1995, Atieh *et al.* 2017).

The FDC prediction in ungauged catchments traditionally consists of two steps. First, the FDC distribution parameters are determined for gauged catchments using streamflow observations and curve fitting (Booker and Snelder 2012). In the second step, a regional regression model is developed by (i) predicting the statistical distribution parameters for ungauged catchments from the physiographic and climatic characteristics of the catchments (LeBoutillier and Waylen

1993, Smakhtin *et al.* 1997, Singh *et al.* 2001, Holmes *et al.* 2002, Sauquet and Catalogne 2011, Pugliese *et al.* 2016), (ii) deriving a regional non-dimensional distribution using daily flows of gauged catchments of a homogeneous region, which is subsequently multiplied by the index flow at the ungauged catchments, determined by mapping and interpolations (Vandewiele and Elias 1995, Razavi and Coulibaly 2012, Blöschl *et al.* 2013), or (iii) through correlation with the basin characteristics (Claps and Fiorentino 1997, Castellarin *et al.* 2004, Razavi and Coulibaly 2012, Requena *et al.* 2018). The FDC at an ungauged site can also be obtained from FDC at a gauged site by using a dissimilarity method (Ganora *et al.* 2009). The method of Ganora *et al.* (2009) is based on the value of a dissimilarity index between pairs of catchments. The dissimilarity index is calculated using values of the basin descriptors (e.g. area, mean elevation, mean slope and drainage path length). The difference in dissimilarity indices for each pair of catchments helps to cluster “similar” catchments; the smaller the value of the dissimilarity index the more “similar” are the catchments (Ganora *et al.* 2009). Recently, another technique that employed the kriging interpolation (Castellarin 2014, Castellarin *et al.* 2018) has shown to be particularly accurate and easily applicable over large geographical areas.

Despite their utility, process-based studies that predict the FDC for ungauged catchments are rare (e.g. Botter *et al.* 2007a, 2007b, 2009, Muneepeerakul *et al.* 2010, Yokoo and Sivapalan 2011). Process-based stochastic models that predict the FDC have been tested; however, they have not been

validated in actual catchments across a range of topographic and hydroclimatic settings (Botter *et al.* 2007a, 2007b, 2009, Muneeppeerakul *et al.* 2010, Yokoo and Sivapalan 2011). Botter *et al.* (2007a) developed a stochastic model of the subsurface flow to predict the overall streamflow response. The stochastic dynamic model was used to analytically derive FDCs in a few catchments in both the USA and Europe (Botter *et al.* 2007b, 2010, Ceola *et al.* 2010). The stochastic model used physical parameters that can be easily determined for ungauged catchments, including soil, vegetation and geomorphic attributes (mean residence time of subsurface flow and the size of the basin). The model could only be applied seasonally with constant parameter values for each season. Muneeppeerakul *et al.* (2010) complemented the work of Botter *et al.* (2007a, 2007b) adding the surface flow component (fast flow) using a stochastic model of rainfall–streamflow generation. Testing the model in a few catchments showed that complex streamflow processes can be captured by separately simulating the surface and subsurface flows. However, this stochastic modelling framework has not been validated in watersheds of different sizes, geological settings and climate.

The theoretical study by Yokoo and Sivapalan (2011) tested the effect of several combinations of climate and landscape properties, using a hypothetical catchment, on the shape of the FDC in relation to the mean monthly runoff represented in its stochastic form (MM_FDC). The study used three years of synthetic rainfall time series to run a water balance model that makes use of climate, geographical parameters (e.g. depth of soil layer, average thickness of saturated zone) and soil parameters (e.g. hydraulic conductivity, porosity). The investigation invoked the simulated flow components of the FDC (surface flow FDC and subsurface flow FDC). The study tested the effect of climate (humid *vs* dry), soil type (silt *vs* sand) and soil depth (shallow *vs* deep) in conditions of different climate seasonality (precipitation in phase/out of phase with potential evapotranspiration). Yokoo and Sivapalan (2011) conjectured that the upper third of the FDC is determined by a non-linear transformation of the precipitation. In catchments with perennial flow and humid climate, Yokoo and Sivapalan (2011) hypothesized that the middle and the lower third are represented by the mean monthly runoff data that might need corrections to account for the effect of evapotranspiration (ET) on low flows in order to predict the FDC lower third. In catchments with ephemeral flows, the conjectures about the use of the mean monthly runoff data are not applicable. The conceptual model of Yokoo and Sivapalan (2011) is intended to facilitate predictions for ungauged catchments – at least in a humid climate – through extrapolation from gauged catchments of daily precipitation, monthly flow, climate dryness and storage capacity (needed for the effect of ET). Precipitation data are often available at ungauged catchments (e.g. weighted average from raingauges, global or regional climate reanalysis (Feser *et al.* 2011)) and by extrapolation from gauged catchments via a hydro-climatic classification system (Coopesmith *et al.* 2014).

The mean monthly runoff is relatively easy to obtain for ungauged catchments from predictions of global hydrological models (GHMs) (e.g. Xie and Arkin 1996, Nijssen *et al.* 2001). We acknowledge that more detailed information than mean

monthly runoff can be obtained from GHMs, such as one-day time resolution data (Sood and Smakhtin 2015). However, the use of this information requires further investigation. The meteorological data used to run GHMs can be obtained from global climate models (GCMs), or from spatial interpolation and observation networks (e.g. the DAYMET database). The former is considered unreliable at time scales shorter than 1 month and does not provide reliable estimates of rainfall variance, making it difficult to develop appropriate downscaling methodologies (Prudhomme *et al.* 2002), while the latter have climate time series that extend only into the 1980s or so (Sood and Smakhtin 2015). Therefore, global models would be more efficient at a monthly than a daily time step. Further investigation is needed to validate the use of GHMs at the daily time step.

The use of mean monthly data would also be valuable when flow data at the daily time scale are not available in the neighbouring “similar” gauged catchments. The findings and hypotheses of Yokoo and Sivapalan (2011) were based on a conceptual investigation using one theoretical catchment and hypothetical combinations of climate and landscape characteristics. Therefore, there is a need to develop and test hypotheses on actual catchments that will advance the process understanding and prediction of FDCs for ungauged catchments using monthly flow data.

Our objective was to extend the work of Yokoo and Sivapalan (2011) to real catchments with varying characteristics and flow regimes. We investigated the use of mean monthly flow when represented in its stochastic form (MM_FDC) to make estimates of the FDC across many catchments at the regional scale. In this study, our line of reasoning is: (a) to do a meta-analysis using different sites (73 catchments) of heterogeneous hydroclimate characteristics and learn from the data to find out patterns of change in FDC and MM_FDC; and (b) to understand the patterns, providing technical and physical explanations and set hypotheses that will be subject to testing in future studies. Testing the hypotheses will help in designing the prediction model of the FDC using the MM_FDC. This model is more widely applicable because it is developed from a large spectrum of heterogeneity in characteristics and process mechanisms offered by the multiple sites (Sivapalan *et al.* 2003).

By definition, a meta-analysis is the approach of combining qualitative and quantitative data from several sites/studies to develop conclusions that have greater statistical power (Barthold and Woods 2015, Evaristo and McDonnell 2017). The meta-analysis provides an objective measure and is a useful platform for generating large-scale conclusions (Evaristo and McDonnell 2017). Meta-analysis studies are of great value in hydrology and have recently been used to identify key characteristics of the hydrological responses of Mediterranean catchments at different time scales (Merheb *et al.* 2016). The meta-analysis has applications not only in hydrology but also in other disciplines, such as epidemiology (Greenland *et al.* 2008).

The line of reasoning we propose here is a top-down approach (Sivapalan *et al.* 2003), which provides a systematic framework to learn from the data, including setting the hypotheses and testing them in following stages. This approach is in contrast to a bottom-up approach in catchment hydrology (Ye *et al.* 2012),

which predicts the catchment response from smaller-scale understanding of the processes (starting with setting the hypotheses, collecting and analysing the data and developing the conceptual predictive model). From this perspective, the predictive models require up-scaling to conduct analyses at larger scales (catchment or regional) (Klemeš 1983, Sivapalan *et al.* 2003). However, extrapolation and prediction of catchment responses across different places and a range of scales is a challenging problem in hydrology (Beven 1989, 2000, Grayson *et al.* 2002).

The results of our regional study, namely, the observed patterns, the physical explanations and the hypotheses, will advance our understanding and contribute to the wider objective of developing an FDC predictive model – on a physical basis – to enable prediction in ungauged catchments. Barthold and Woods (2015), using a meta-analysis of several sites and studies, concluded that progress in hydrology requires knowledge to be synthesized in order to develop prediction models that are applicable to a wide range of environmental conditions and that facilitate prediction in ungauged catchments.

We conduct our analysis in the eastern USA using outcomes of the environmental controls of the FDC in Chouaib *et al.* (2018) (e.g. soil moisture storage capacity, topography and predominant runoff generation mechanisms). The outcomes described in Chouaib *et al.* (2018) support the results of the meta-analysis. The results of the current study will further our understanding about the conditions that limit the use of the MM_FDC in prediction of the FDC. The meta-analysis takes advantage of the diversity in hydroclimate conditions and properties of the flow variability (steep vs flatter slopes of the FDC) across the study catchments.

In this study, we use observed mean monthly flows to construct the MM_FDCs and daily flows to construct the FDCs. To test/verify the use of predicted mean monthly flows from a regionalization approach compared to those from GHMs was beyond the scope of our study. It is assumed that an exact prediction of the mean monthly flow will be available at the ungauged catchment and we admit the attributed uncertainty resulting from the use of a GHM or a regionalization approach. The uncertainty of the mean monthly predictions using GHMs is amenable to improvements (Sood and Smakhtin 2015).

2 Dataset and study area

In this study, we use the Model Parameter Estimation Experiment (MOPEX) catchments of Chouaib *et al.* (2018) that are located in the eastern USA. The MOPEX dataset provides the data in each catchment (Duan *et al.* 2006). In MOPEX, the hydro-meteorological records (i.e. air temperature, precipitation, potential evapotranspiration and flow) have a daily time step and 50 years length on average (1948–2000). More details about the MOPEX dataset are provided in Chouaib *et al.* (2018, Section 2). The MOPEX dataset provides flow and meteorological data in addition to physiographic characteristics for many catchments in the USA and other countries (Duan *et al.* 2006). Several hydrologists and modellers have collaborated to develop the MOPEX dataset and share expertise in modelling and parameter estimation. These collaborations put the MOPEX dataset in the forefront for use in studies of prediction in ungauged

catchments (Hrachowitz *et al.* 2013). In the eastern USA, precipitation has a limited seasonal fluctuation (Sawicz *et al.* 2011, Coopersmith *et al.* 2012, Chouaib *et al.* 2018). The catchments are medium to large (67–8052 km²), as shown in Table 1. These catchments are mainly forested, with some agricultural lands and a limited influence of urban areas (Table 1). The Appalachian Mountains, which characterize the topography of the study area (see the digital elevation model, DEM in Fig. 1) have a northeast to southwest orientation. In terms of the soil characteristics, the proportion of soil with medium infiltration rate (HGB soils; Wood and Blackburn 1984) decreases from south to north, while the proportion of soil with slow infiltration rate (HGC soils; Wood and Blackburn 1984) declines from north to south (Fig. 1).

3 Methods

3.1 Sacramento model (SAC-SMA) calibration

We use the Sacramento soil moisture accounting (SAC-SMA) model to assess the surface and subsurface flow FDCs that will support our investigation of the MM_FDC in relation to the FDC. Details of the hydrological model can be found in Chouaib *et al.* (2018). The SAC-SMA model is calibrated in each of the study catchments that have limited snow effect. We designate the study catchment as having limited snow effect because the perennial snow cover is absent for most catchments and does not exceed 3% of the surface area in individual catchments (Berghuijs *et al.* 2014). We used a sample of 100 catchments of limited snow effect for calibration, and those with a Nash-Sutcliffe coefficient (NS; Nash and Sutcliffe 1970) of less than 0.50 were disregarded; we retained 73 catchments after the calibration. Model performance, in particular for surface and subsurface flow predictions that are used in the analysis, was not used to check the results of this study, because the efficiency of the SAC-SMA calibration was satisfactory (Chouaib *et al.* 2018). As seen in Fig. 2, we found that 90% of the catchments have NS > 0.6.

3.2 Analysis of the MM_FDC in relation to the FDC

The MM_FDC is constructed from the average of all flows that fall in each month over the entire period of flow records (50 years on average) following the theoretical study by Yokoo and Sivapalan (2011). The MM_FDC in each study catchment has 12 readings (one for each month). The FDC is constructed from the daily flows of the entire period of record.

We normalized the empirical FDCs and MM_FDCs by the value of the mean flows, as in Yokoo and Sivapalan (2011) and

Table 1. Statistics of the catchments used in this study. MAP: mean annual precipitation.

Catchment descriptor	Maximum	Minimum	Median
Slope (%)	34	0.6	12.7
Mean elevation (m a.s.l.)	1212	16.2	442.6
Land cover – Crops (%)	59	0	15.8
Land cover – Forest (%)	98	28.64	65.68
Land cover – Urban (%)	18.67	0	6.3
Catchment size (km ²)	8052	67	1170.70
MAP (mm)	2072	982	1199

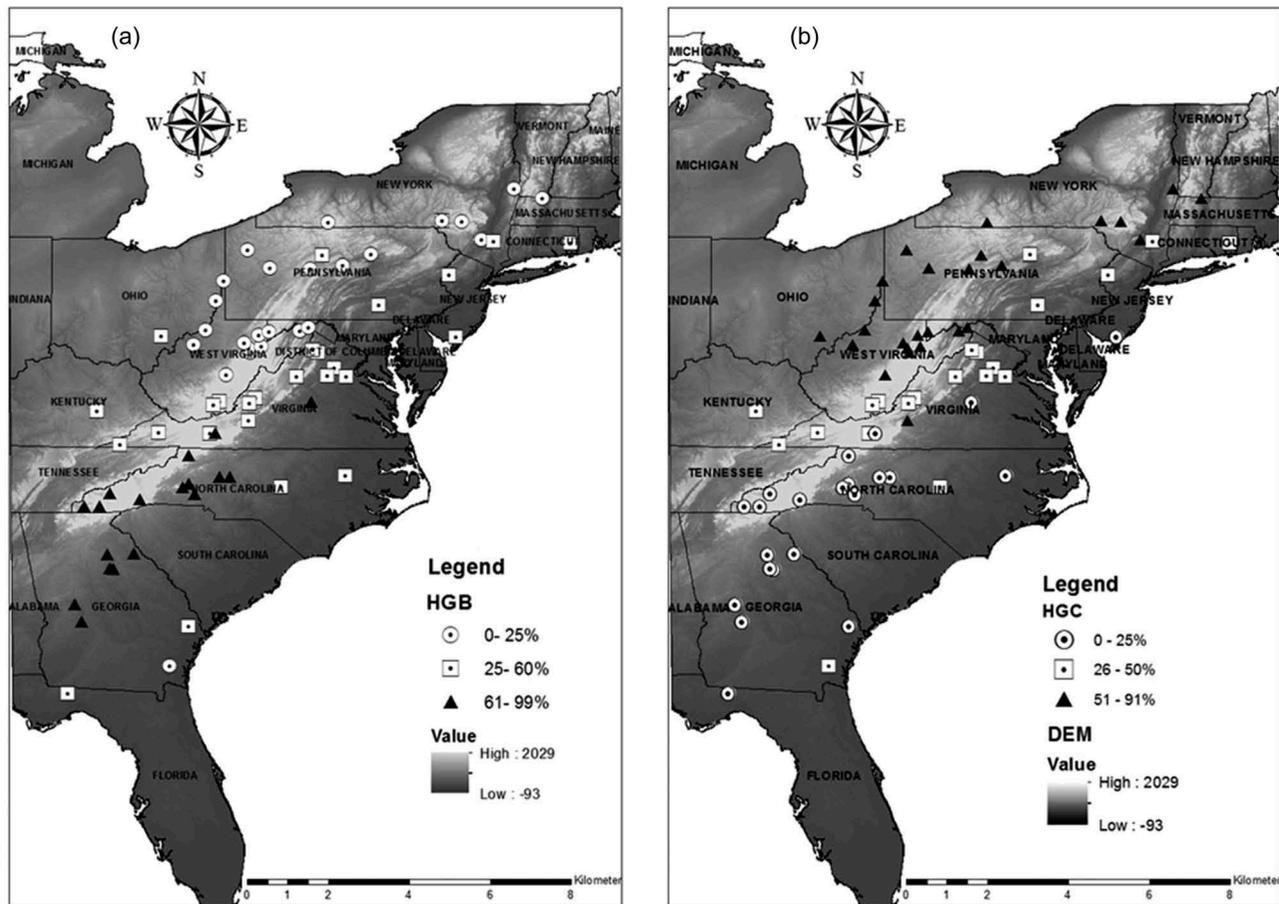


Figure 1. Map of the study site showing the spatial distribution of the soil hydrologic groups: (a) HGB and (b) HGC.

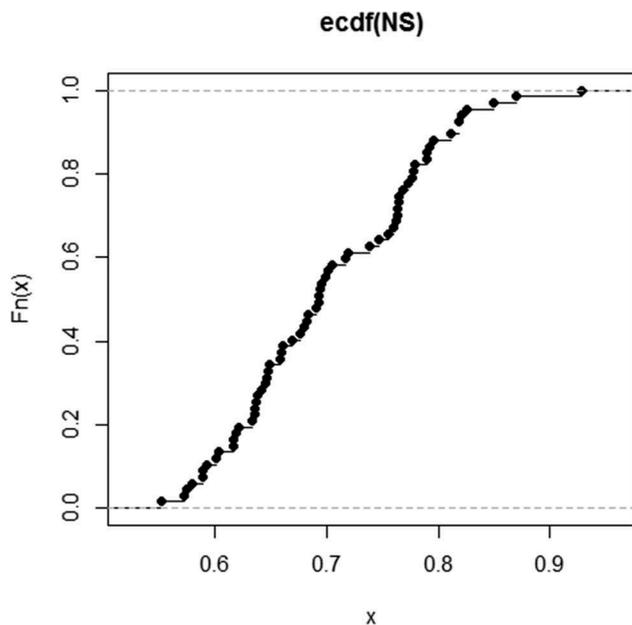


Figure 2. Performance of the study catchments after calibration using the NS coefficient.

Yaeger *et al.* (2012). We calculated the slopes of the normalized FDCs using the 33rd and 66th flow percentiles (Equation 1). This is the most linear portion of the curve at a semi-logarithmic scale (Yadav *et al.* 2007, Zhang *et al.* 2008). This portion of the

curve indicates the value of the flow variability (Sawicz *et al.* 2011). The slope of the FDC, SFDC, is defined as:

$$\text{SFDC} = \frac{\ln(Q33\%) - \ln(Q66\%)}{(0.66 - 0.33)} \quad (1)$$

where $Q33\%$ is the flow of the 33rd percentile and $Q66\%$ is the flow of the 66th percentile. We calculated the slope of the normalized MM_FDC (SMM_FDC) from the value of the highest and lowest flow percentiles, as in Yaeger *et al.* (2012). We examined the correlation between the slopes of MM_FDC and FDC using a linear regression. We wanted to determine how well correlated the two curves are before developing a detailed analysis of the MM_FDC. The SFDC helped us differentiate between the characteristics of the flow response in the study catchment. In catchments with SFDC below the average (across all catchments), the flow variability is regarded as low, with a flatter shape of the FDC. In catchments with SFDC above the average, the flow variability is higher, with a steeper slope of the FDC.

We compared the spatial pattern of the SMM_FDC and SFDC to determine whether a catchment with a steep SFDC had a steep SMM_FDC. This comparison revealed whether the spatial pattern of the FDC was similar to that of the MM_FDC. We compared each of the FDC portions (the upper, middle and lower thirds of the FDC) to the MM_FDC, as in Yokoo and Sivapalan (2011). However, our

comparison differentiated between categories of the flow variability and used real catchments instead of hypothetical catchments. The meta-analysis accounts for the disparities in landscape properties. The real combinations of catchment characteristics reveal the physical conditions where it is (or is not) possible to predict FDC from the MM_FDC. The meta-analysis uses also the flow components of the FDC to explain the processes underlying each of the FDC portions and further explore the physical conditions allowing prediction of the FDC from the MM_FDC.

4 Results

4.1 Variation of the MM_FDC in comparison to the FDC

The regional variation of the SMM_FDC is equivalent to the regional variation of the SFDC (Fig. 3(a) and (b)). The catchments with large SFDC in Fig. 3(a) are mostly those having steeper slope of the MM_FDC in Fig. 3(b). This is corroborated by a statistically significant correlation between the middle thirds of the FDC (SFDC) and the SMM_FDC ($p < 0.05$) (Fig. 3(c)). However, the SMM_FDC explains 38% of the SFDC variation.

The difference in shape of the FDCs based on their slope is equivalent to the difference in shape of the MM_FDCs. The MM_FDCs of catchments with large SFDC have steeper slopes than those of catchments with small SFDC (Fig. 4(a) and (b)).

4.2 FDC portions in comparison to the MM_FDC

With regard to the upper third of the FDC, we do not observe a difference in the shape of the MM_FDC between both categories of flow variability (Fig. 5). The changes in shape of the upper third of the FDC are explained by the shape of surface and subsurface flow FDCs that track the total flow FDC (Fig. 6). In the upper third, the surface flow and subsurface flow FDCs are steeper in catchments with large flow variability (Fig. 6(a) and (b)) compared to those with small flow variability (Fig. 6(c) and (d)).

In the middle third of the FDC, we found that the MM_FDCs deviate from the FDCs in catchments with large flow variability (steeper slope of the FDC) and track the FDCs in catchments with small flow variability (flatter slope of the FDC) (Fig. 5). In this portion of the FDC, we find that the surface flow FDC dips at lower flow percentiles (80%) in all the study catchments irrespective of their flow variability (Fig. 6). The subsurface flow FDC tracks the total flow FDC in the middle third in all study catchments. The slopes of both curves (SSFDC and SFDC, respectively) are proportional, with a statistically significant correlation ($p < 0.05$) (Table 2). The slopes of the SSFDCs were larger than SFDCs in both groups of the flow variability (Fig. 7). We note that in some catchments of large SFDCs, the subsurface flow tracks the total flow; the slope of the SSFDC is nearly equal to SFDC (Fig. 7(a)).

In the lower third, the MM_FDC deviates from the FDC regardless of the level of flow variability (Fig. 5). The catchments with smaller SFDC have sharper change in slope than those with larger SFDC (Fig. 5(a) and (b) vs Fig. 5(c) and (d)). In the lower third, the subsurface flow FDC displays

differences in shape between categories of flow variability (Fig. 6(a) and (b) vs Fig. 6(c) and (d)).

5 Discussion

5.1 Interpretation of the FDC portions in comparison to the MM_FDC

5.1.1 FDC upper third

The upper third of the FDC comprises the largest flows. The MM_FDC diverged from the FDC upper third independently of the value of flow variability (flatter/steeper slope of the FDC). The MM_FDC did not help to differentiate between FDC upper thirds in catchments with different categories of flow variability (Fig. 5). Therefore, it is not possible to use the MM_FDC in predictions of the upper third of the FDC. The shape of FDC upper third is explained using the surface and subsurface flow FDCs (Fig. 6). In this range of flows ($Q_{0\%} > Q > Q_{33\%}$), the shapes of FDC that can be distinguished between different categories of flow variability illustrate the effect of the antecedent moisture condition (AMC) dynamics, in the subsurface, in combination with the soil hydraulic properties and the pattern of extreme precipitation. Atieh *et al.* (2017) showed recently that precipitation is among the most influential parameters in the shape of the FDC, including the upper third. We acknowledge that the effect of AMC dynamics and the soil hydraulic properties on extreme precipitation encapsulate the controls of the catchment response, namely, land cover, catchment geomorphology and topography (e.g. shape, Strahler order and slope). In fact, the land cover conditions influence the infiltration conditions of the soil surface and, therefore, the moisture conditions (Niehoff *et al.* 2002). This is due to linkages between the land cover, soil macroporosity and unsaturated zone dynamics controlling the infiltration excess runoff mechanism (Niehoff *et al.* 2002). Moreover, the subsurface flows play a role in the soil moisture redistribution between storm events and in setting up the initial wetness conditions that govern the streamflow generation of subsequent rain events. A dominant control of the impact of subsurface flows on the moisture redistribution is the local topography (Wood *et al.* 1990). The redistribution of moisture between storm events led us to emphasize the effect of storm seasonality (pattern of change in the seasonal behaviour of storms) in addition to the effect of the magnitude and frequency of extreme precipitation.

In the upper third of the FDC, the effect of AMC dynamics is more likely to be pronounced in catchments of low flow variability, given the flatter shape of flow component FDCs (surface and subsurface flow FDCs in Fig. 6). This is a hypothesis that requires further testing. In these catchments of low flow variability, the soil is well drained (Chouaib *et al.* 2018). Physically, the larger the infiltration rate, the more likely the rainwater will infiltrate and overland flow will take place as a result of saturation excess runoff mechanisms. With this effect, more changes in the AMC will be visible. The larger infiltration rates delay the soil saturation; the saturation excess mechanism becomes prevalent over the infiltration excess mechanism (Weiler and Naef 2003). The effects of the runoff generation mechanisms on high flows were analysed by Sivapalan *et al.* (1990) and tested within a stochastic

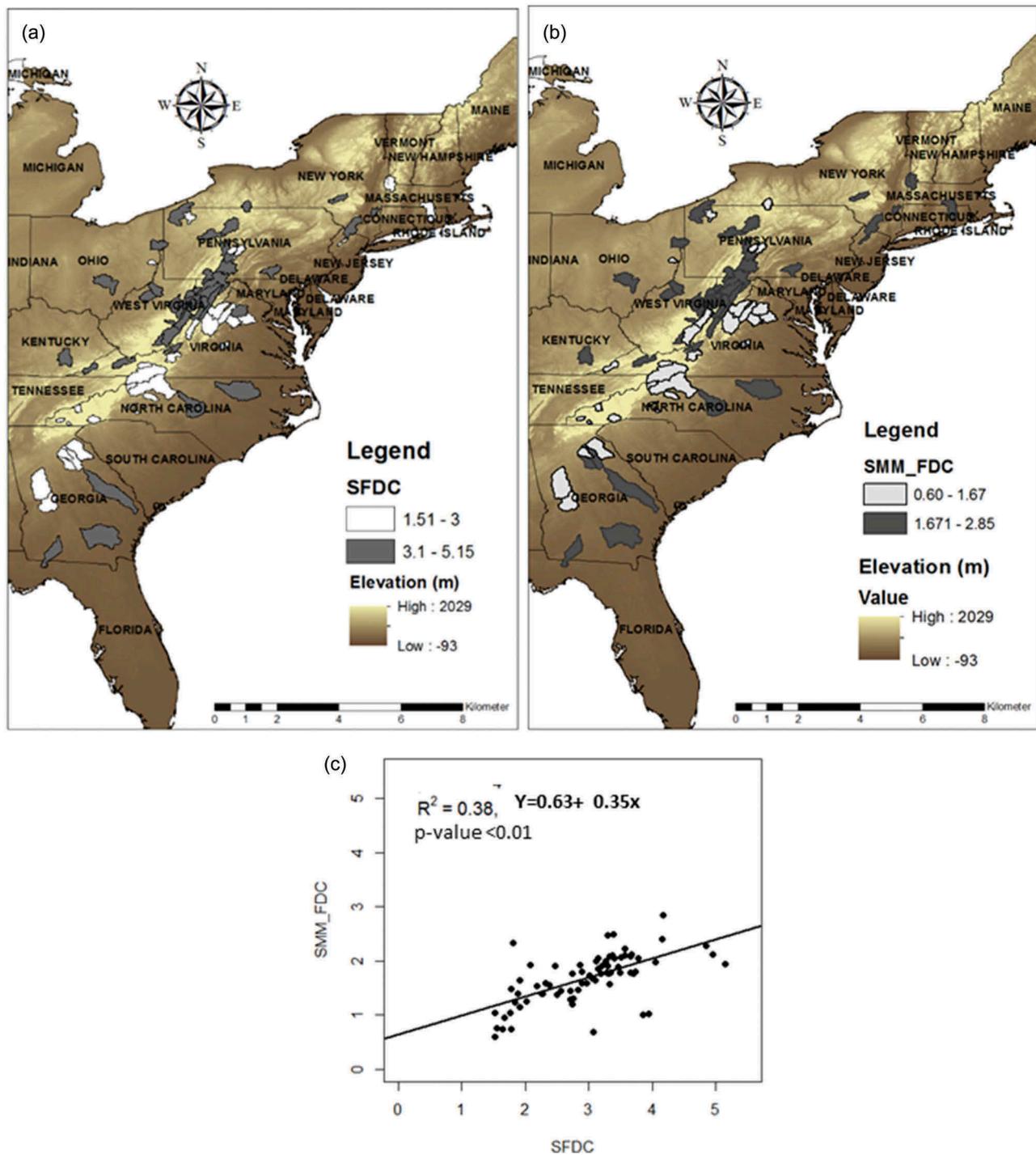


Figure 3. Regional variation of (a) the slope of the FDC (SFDC), (b) the mean monthly FDC (MM_FDC), and (c) the correlation between the SFDC and the slope of the MM_FDC (SMM_FDC).

framework. The surface runoff generation mechanisms (saturation excess and infiltration excess overland flow) influence flood frequency shapes research (e.g. Sivapalan *et al.* 1990). This is a first step towards further analysing whether limited flow variability and predominant saturation excess overland flow flattens the upper third of the FDC. Consequently, predictions of high flows have to account for the effect of AMC that should vary between the storms of particular seasonality specific to the study region. Note that, as shown in Chouaib *et al.* (2018), the eastern USA portrays

a systematic variation in the seasonality of storm events from northeast to the southeast. The storm seasonality and the effect of the between storms timing on high flows was analysed by Sivapalan *et al.* (2005). The AMC dynamics effect has been underscored in several studies investigating streamflow predictions within a deterministic framework (e.g. Kirchner 2009). Notably, isotope hydrology studies showed the large contribution of pre-event water to the hydrograph compared to event water (e.g. Buttle 1994, Uhlenbrook and Leibundgut 2002). These findings from other studies support the claim

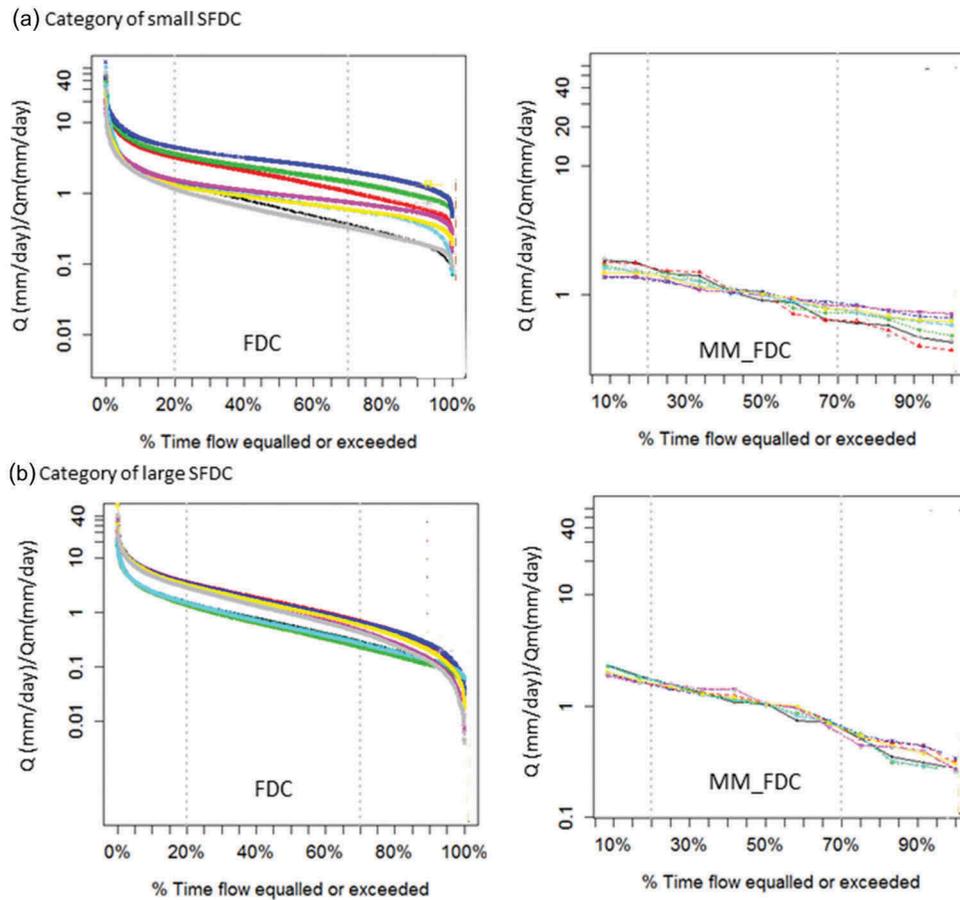


Figure 4. (a) FDC and (b) MM_FDC in catchments with small SFDC, (c) FDC and (d) MM_FDC in catchments with large SFDC.

about AMC dynamics affecting the upper third of the FDC. Muneeppeerakul *et al.* (2010) showed that surface flow FDC can be derived from the precipitation. In our study, based on findings on the upper third FDCs, the flow component properties and the physical explanations from previous studies, we conjecture that the derivation of large flows should not only use a simple function of precipitation but also account for the AMC effect.

5.1.2 FDC middle third

The MM_FDC diverged from the middle third of the FDC in catchments with steeper SFDC (Fig. 5(a) and (b)), with larger root mean square error (RMSE; Sorooshian *et al.* 1993), as shown in Table 3. However, the MM_FDC tracked the middle third of the FDC in catchments with flatter SFDC (Fig. 5(c) and (d); smaller RMSE in Table 3). Therefore, it is possible to use the MM_FDC to predict the middle third of the FDC only in catchments with low flow variability. These findings can be further understood from differences in the catchment characteristics and runoff processes between categories of flow variability.

In the middle third of the FDC ($Q_{33\%} > Q > Q_{66\%}$), the surface flow effect on the response was maintained irrespective of the value of flow variability (the surface flow FDC extends to lower flow percentiles, 80%; Fig. 6). Thus, surface and subsurface flow FDCs jointly affect the flow variability. Previous studies

have demonstrated that surface runoff is dominant in the rising limb of the hydrograph and to a lesser extent in the falling limb (McDonnell 2003), which further explains the interaction between surface and subsurface flow in this part of the FDC. The subsurface flow FDC displays the effect of subsurface processes, namely deep percolation and evapotranspiration (e.g. Botter *et al.* 2009). The steeper slope of the subsurface flow FDC compared to that of the total flow FDC, though they are proportional (Table 2), suggests that the subsurface flow response is more sensitive to the effect of subsurface processes than total flow (Fig. 7).

Given the complex combined effect of surface and subsurface flow in this range of the FDC, the mean monthly runoff did not fully capture the variation of the FDC slopes across the study catchments. The SMM_FDC explains only 38% of the total variation of SFDC in the study area (Fig. 3(c)). In catchments with low flow variability, it appears that the differences between high and low flows of the mean monthly runoff – used to calculate the SMM_FDC – can approximate the value of flow variability that is dominated by the effect of both surface and subsurface flow processes.

In catchments with high flow variability, the slopes of the subsurface flow FDCs are larger than their values in catchments with low flow variability (Fig. 7(a) and (b)). In these catchments of steep SFDC, Chouaib *et al.* (2018) found that subsurface stormflow is predominant. According to Fig. 7(a),

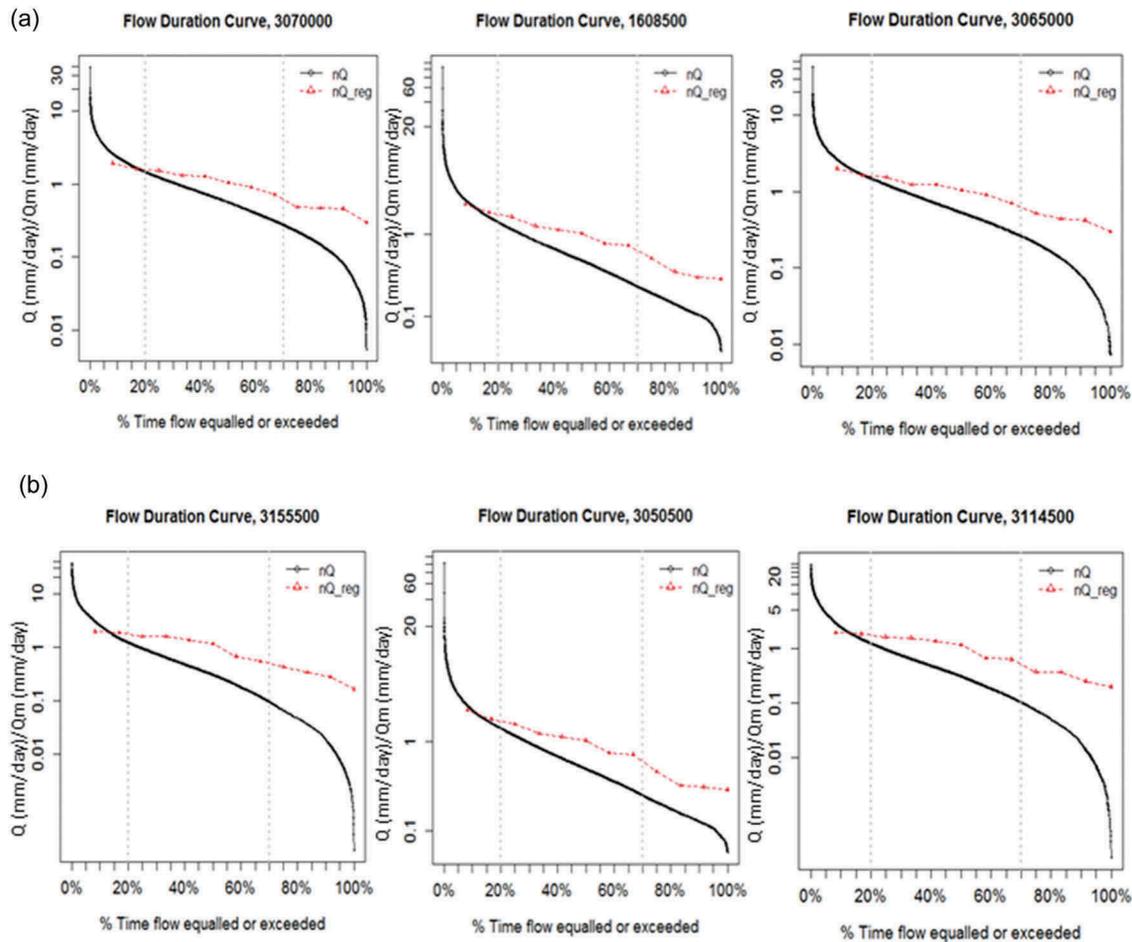


Figure 5. Normalized flow (nQ) and normalized MM_FDCs (nQ_{reg}): (a) and (b) nQ and nQ_{reg} in catchments with steeper slope of the FDC, (c) and (d) nQ and nQ_{reg} in catchments with flatter slope of the FDC. The curves were normalized by the mean annual daily flow.

some catchments have equivalent slopes of FDC and subsurface flow FDC; these are mountainous and forested catchments. In these mountainous and forested conditions, most likely the surface and subsurface flows are equally dominant. Therefore, they cannot be differentiated in terms of runoff generation mechanisms, which explain the subsurface flow variability being nearly equal to the total flow variability. McDonnell (2013) considered that the lateral connectivity in the subsurface zone increases with increasing catchment slope. The lateral connectivity is larger in catchments in hillslopes and fosters patches of saturation, which makes surface and subsurface runoff generation mechanisms less distinguishable.

It appears that the interaction between surface and subsurface flow yielding the total flow variability cannot be represented by the mean monthly runoff in catchments with steeper slope of the FDC. The differences between the high and low flows from the mean monthly runoff used in SMM_FDC are not helping to predict the real flow variability; monthly averaging attenuates the flow response and masks the behaviour of the flow regime when expressed as FDC.

5.1.3 FDC lower third

The lower third of the FDC is the range of low flows and limited precipitation where the evapotranspiration (ET) effect is dominant (Vitvar *et al.* 2002).

The MM_FDC diverged from the FDC lower third independently from the value of the flow variability (flatter/steeper slope of the FDC). The MM_FDC did not help to mimic the differences of FDC lower thirds in all study catchments. It is, therefore, not possible to use the MM_FDC in predictions of the lower third of the FDC. This can be further understood by explaining FDC lower thirds between categories of flow variability.

Provided that the FDC has a sharp dip in catchments with high flow variability and a flatter dip in catchments with low flow variability (Fig. 6), it appears that the dominant effect of ET on low flows (lower third of FDC) changes with the catchment flow variability (steeper vs flatter slope of the FDC) and so with their respective landscape properties. Note that Chouaib *et al.* (2018) found that in the eastern USA all mountainous catchments have smaller soil moisture storage capacity (SMSC) (<280 mm) and all lowland catchments have larger SMSC (>280 mm) independently from the flow variability.

In catchments with steeper SFDC (high flow variability), the ET effect on low flows was not discernible between total and subsurface flow FDCs as both had a sharp dip (Fig. 6(a) and (b)). In this category, all catchments have limited infiltration rates (HGC predominant; Fig. 1(b)). The sharp dips of subsurface and total flow FDCs suggest that the conditions limited infiltration rates in large/small SMSCs is

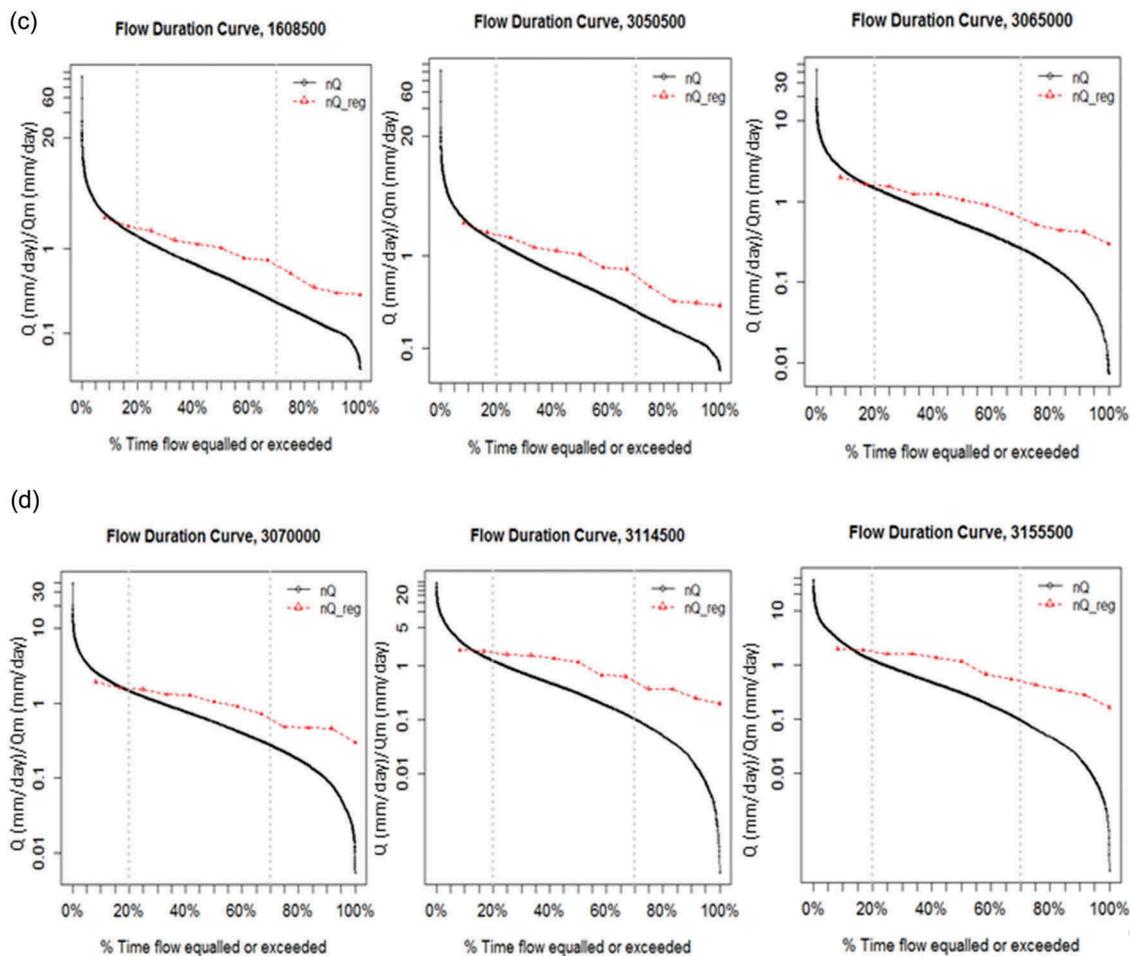


Figure 5. (Continued)

a chief regulator of the influence of ET on the lower third of the FDC.

In catchments with low flow variability, the subsurface flow had a flatter dip than the total flow. The subsurface flow is then more sensitive to the effect of ET at the lower third. The subsurface zone is where the rain water infiltrates and the infiltration rates change non-linearly with depth (Ameli *et al.* 2016). The improved soil drainage in these catchments of large/small SMSC and the non-linear change of infiltration with depth explains the ET effect and hence the flatter shape of subsurface and total flow FDCs at the lower tail.

In a forested catchment of steep slope in British Columbia, Canada, Moore (1997) demonstrated that at early stages, after a storm event, when the catchment is wetted, the hydrograph recession limb is exponential (linear). However, at later stages, as the drainage from the upslope zones or the recharge from the vadose zone starts, the recession limb becomes non-linear and fits better to a power law function. The two stages of the recession could not be distinguished in the absence of the ET (e.g. during dormant season) (Moore 1997). This explanation of the hydrograph recession limb explains further the effect of ET on low flows and demonstrates that it is one of the major factors making low flows prediction non-linear and highly affected by the catchment characteristics (the soil infiltration rates and the soil storage characteristics). The studies by Botter *et al.* (2009, 2010) are consistent with the findings of Moore (1997) regarding

the non-linear aspect of low flows. Botter *et al.* (2009, 2010) showed that in conditions of humid climate in northern Italy, the prediction of FDC from the probability of observing the water volume in the subsurface zone provided a more accurate assessment of low flow when the power law (non-linear) is fitted instead of the exponential distribution (linear). This understanding supports our claim about the FDC lower tail and explains the diverging MM_FDC at the lower third irrespective of the value of flow variability. The averaging in the mean monthly runoff does not capture the non-linearity in the low flow response caused primarily by ET, but also to episodic drought conditions. The ET impact changed with properties of the soil infiltration rates in condition of small/large SMSC.

5.2 Catchments and flow conditions to predict the FDC using the MM_FDC

The meta-analysis of the FDCs and the MM_FDCs based on differences in the flow variability showed that FDC prediction using the MM_FDC is only partially applicable. Given the effect of averaging in the mean monthly runoff that smoothes the flow response, the method is limited to specific characteristics of flow variability (flatter vs steeper slope of the FDC) and landscape properties. Chouaib *et al.* (2018) found that catchments with flatter SFDC are mostly dominated by

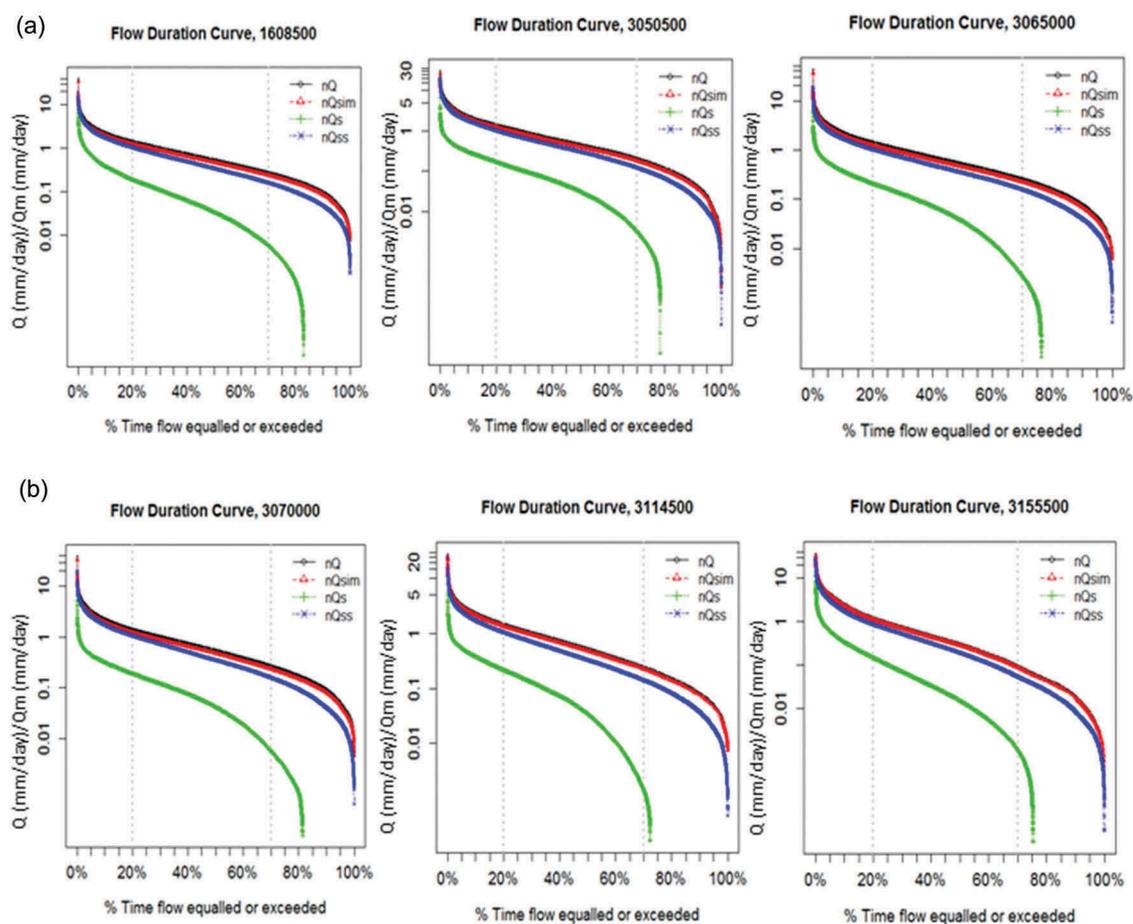


Figure 6. Normalized flow (nQ), normalized simulated flow (nQ_{sim}), normalized surface flow (nQ_s) and normalized subsurface flow (nQ_{ss}) in catchments with: (a) and (b) steeper FDC, and (c) and (d) flatter FDC. The curves were normalized by the mean annual daily flow.

saturation excess overland flow, whereas those with steeper SFDC are mostly dominated by subsurface stormflow.

In catchments with flatter slope of the FDC, the findings suggest that MM_FDC can be used to predict medium flows; that is, the middle third of the FDC but not the upper and lower thirds. In these catchments, the middle third of the MM_FDC should be able to represent the full range of flows (a portion of fast and slow flows). The catchments in this category have well-drained soils (Fig. 1(a)); few are mountainous and most are located in lowland areas of predominant saturation excess overland flow (Fig. 3(a)).

In catchments with steeper slope of the FDC, it does not appear that FDC portions can be predicted from the MM_FDC, including the middle third. In these catchments the soil is poorly drained (Fig. 1(a)) and most are located in highland areas (Fig. 2(a)) of predominant subsurface stormflow. Few catchments are in lowlands with poorly drained soils (Fig. 2(a)).

The MM_FDC slopes were smaller than those of the FDCs. Thus, even when it is possible to use MM_FDC to predict FDC, the simulated middle third of the FDC might be used as indicative rather than a firm estimation.

Our findings partially agree with the theoretical study of Yokoo and Sivapalan (2011), who suggested that the middle and lower thirds of the FDC can be estimated by mean monthly runoff in catchments with perennial streamflow

and humid climate. The method is constrained by the value of flow variability and is applicable only for the middle third of the FDC. The upper third prediction should involve non-linear filtering of the precipitation that has to account for the AMC effect on large flows. The high flow predictions should include the surface flow and a portion of the slow flows.

At the lower third, the FDC predictions ought to consider the non-linear effect of ET on low flows. The ET effect may be studied in future investigations by simulating the dynamics of the saturated area near the stream during low flows (Yokoo and Sivapalan 2011).

The meta-analysis in real catchments and the large dataset made our results complementary to the findings from using a hypothetical catchment. The regional scale helped to combine a wide range of flow response properties with complexity in the physiography of real catchments. Analysis of observed flows and simulated flow components allowed us to reveal facets about the use of MM_FDC not explored within the context of a theoretical study. Future research may extend our work and investigate the use of monthly FDCs to predict FDCs in ungauged catchments.

5.3 Conceptual model of the FDC and MM_FDC

The outcomes of the meta-analysis are summarized in a conceptual illustrative model of the FDC in relation to the

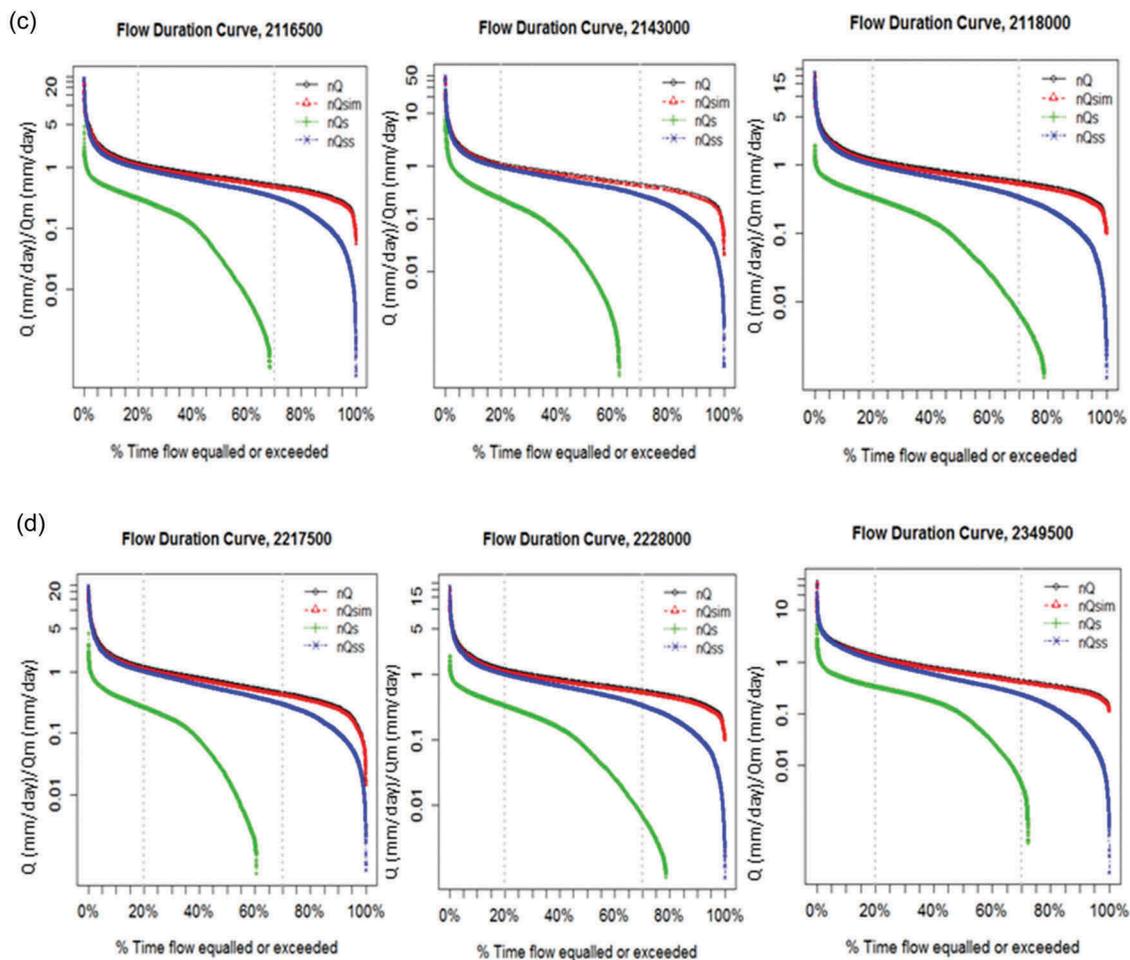


Figure 6. (Continued)

Table 2. Correlation between the slopes of subsurface flow FDC and the FDC.

Catchment	R^2	r	p value
Flatter FDC	0.81	0.9	<0.001
Steeper FDC	0.88	0.93	<0.001

MM_FDC shown in Fig. 8. The conceptual model states hypotheses about controls of the FDC portions and predictions using the MM_FDC. The findings will serve as guidance for future studies to develop a physically based prediction model of the FDC in ungauged catchments. The shapes of FDC that are distinguished between different categories of flow variability illustrate the effect of the AMC dynamics and other factors, namely, the soil hydraulic properties, the extreme precipitation magnitudes and patterns of the storm seasonality. The upper and the middle thirds of the FDC are controlled by the subsurface and surface flow. In catchments with flat slope of the FDC, the upper third is flatter due to the effect of well-drained soils and predominant saturation excess overland flow in most of the catchments. The middle third of the FDC can be represented by the MM_FDC. For the lower third, the subsurface flow is more sensitive to the ET effect than the total flow. The subsurface flow FDC has a flatter dip than the total flow FDC due to large soil infiltration rates in catchments of large/small SMSCs (Fig. 8(a)). The MM_FDC does not capture the dominant effect of ET during low flows and deviates from FDC at the lower third.

In catchments with steeper FDCs, the upper third is steeper due to the effect of poorly drained soils and predominant subsurface stormflow in most of the catchments, while the middle third is very steep and cannot be represented by the MM_FDC. The subsurface flow FDC and FDC overlap and have equal slopes in the steepest mountainous catchments. At the lower third, the subsurface flow and total flow are equally sensitive to the ET effect, where both have a sharp dip irrespective of the value of the SMSC (Fig. 8(b)). The MM_FDC does not capture the dominant effect of ET during low flows and deviates from the FDC at the lower third.

6 Conclusions

This study sought to investigate the catchment and climate conditions under which the mean monthly runoff, represented in the stochastic form of the FDC (MM_FDC), can be used to predict the FDC. This investigation is an initial step in gaining understanding to quantify the FDC in ungauged catchments following a physically based approach and more readily available monthly flow data. The mean monthly flows are available from predictions of global models and/or from regionalization methods. The study used the data of 73 catchments from the eastern USA, where the climate is humid and the precipitation is of limited seasonality. In these catchments of perennial

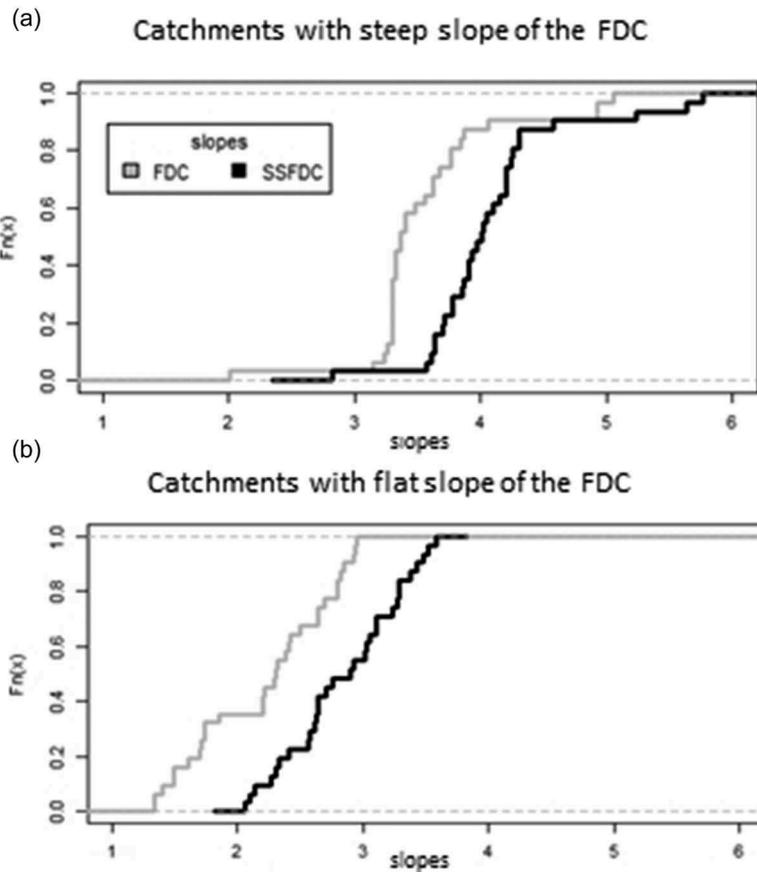


Figure 7. Cumulative distribution function (cdf) of the SFDC and the SSFDC slopes in catchments with (a) steeper FDCs and (b) flatter FDCs.

Table 3. RMSE between the slope of the FDC and that of the MM_FDC for the two catchments category.

	RMSE
Flatter FDC	1.69
Steeper FDC	0.99

runoff, the results show that it is applicable to use the MM_FDC in predicting the middle third of the FDC. However, the MM_FDC does not distinguish the shapes of the upper or lower thirds dominated by the varying effect of antecedent moisture conditions and the effect of evapotranspiration, respectively. The averaging in the mean

monthly runoff smoothes the flow response. Our results show that the use of MM_FDC to predict the middle third of the FDC is primarily constrained by the characteristics of the flow variability and landscape properties. Only in catchments of low flow variability (flatter slope of the FDC), could the MM_FDC track the middle third of the FDC. These catchments have mostly predominant saturation excess overland flow in well-drained soils of large SMSC. Few other catchments are mountainous with soils of large infiltration rates and limited SMSC. It is important to recognize that the non-applicability of the method in catchments with steeper SFDC (high flow variability)

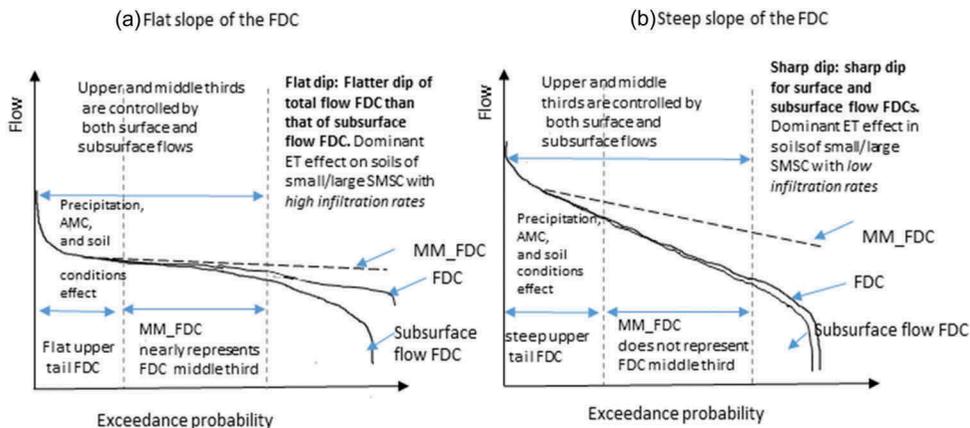


Figure 8. Conceptual model of the FDC in conditions of humid climate and perennial runoff in catchments with (a) flatter FDCs and (b) steeper FDCs. AMC: antecedent moisture conditions.

indicates the complexity of the hydrological response and highlights the scope for future research.

We recommend similar empirical analysis in other regions of different climate and flow characteristics elsewhere in the USA and worldwide. For instance, the precipitation seasonality would have an impact when compared to seasonality of the ET (being in phase *vs* out of phase) given the dominant effect of ET during low flow periods. Our empirical study can be aided by numerical experiments to test the several hypotheses and investigate a prediction model of the FDC using the MM_FDC under several complex combinations of real climate and physiographic conditions. These future empirical and numerical analyses will provide the opportunity to refute or corroborate our conclusions and get more evidence about the use of MM_FDC. Our study is limited in revealing the effect of non-stationarity to make predictions of the FDC using the MM_FDC. The non-stationarity in the study catchments is mainly caused by the climate variability because the anthropogenic activity is limited. Our conclusions may not hold in the future under non-stationarity caused by future anthropogenic climate or land-use change. Despite the limitations, the understanding we gained helped to provide an illustrative conceptual model of the FDC in relation to the MM_FDC, which will serve for future works investigating process-based methods to predict FDC in ungauged catchments.

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