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Hydrologic similarity among catchments under variable flow conditions

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Abstract. An assessment of regional similarity in catchment stream response is often needed for accurate predictions in ungauged catchments. However, it is not clear whether similarity among catchments is preserved at all flow conditions. We address this question through the analysis of flow duration curves for 25 gauged catchments located across four river basins in the northeast United States. The coefficient of variation of streamflow percentiles is used as a measure of variability among catchments across flow conditions. Results show that similarity in catchment stream response is dynamic and highly dependent on flow conditions. Specifically, within each of the four basins, the coefficient of variation is high at low flow percentiles and gradually reduces for higher flow percentiles. Analysis of the inter-annual variation in streamflow percentiles shows a similar reduction in variability from low flow to high flow percentiles. Greater similarity in streamflows is observed during the winter and spring (wet) seasons compared to the summer and fall (dry) seasons. Results suggest that the spatial variability in streamflow at low flows is primarily controlled by the dominance of high evaporative demand during the warm period. On the other hand, spatial variability at high flows during the cold period is controlled by the increased dominance of precipitation input over evapotranspiration. By evaluating variability over the entire range of streamflow percentiles, this work explores the nature of hydrologic similarity from a seasonal perspective.

1 Introduction

A number of problems in hydrology require estimation of regional similarity in catchment stream response. These include: regional flood frequency analysis (Acreman and Sinclair, 1986; Burn, 1997; Merz and Blöschl, 2005), parameter regionalization for lumped hydrologic models (Burn and Boorman, 1993; Merz and Blöschl, 2004), regional low flow predictions (Nathan and McMahon, 1990; Laaha and Blöschl, 2006), and water quality assessment (Wolock et al., 2004). A common goal in many of these studies involves the transfer of hydrologic information, such as flood quantiles (Burn and Goel, 2000), model parameters (Oudin et al., 2008; Zhang and Chiew, 2009) etc., from gauged to ungauged catchments. Unfortunately, a universally accepted metric of hydrologic similarity among catchments does not exist yet (McDonnell et al., 2007; Wagener et al., 2007).

Several approaches for quantification of catchment hydrologic similarity have been documented in the hydrology literature. One widely used approach involves the use of similarity in catchment physiographic characteristics. Acreman and Sinclair (1986) grouped 186 catchments in Scotland into five homogeneity regions based on six basin characteristics, viz., drainage area, stream frequency, channel slope, mean annual rainfall, fraction of basin covered by lakes and soil type index. Wiltshire (1986) grouped 376 British catchments into five homogeneous regions based on catchment attributes, viz., drainage area, stream frequency, channel slope, mean annual rainfall, fraction of basin covered by lakes and soil type index. Wiltshire (1986) grouped 376 British catchments into five homogeneous regions based on catchment attributes such as basin area, average annual rainfall and urban fraction. Burn and Goel (2000) grouped catchments in central India for flood frequency estimation using attributes such as catchment area, stream length and main channel slope. Wolock et al. (2004) used the hydrologic landscapes concept of Winter (2001) to group 43 931 catchments in United States into 20 regions based on identification of similarities in topography.
Our a priori assumption is that since catchments within each and inter-annual variability in their streamflow percentiles. Located within these four river basins and analyze the spatial term daily streamflow records from 25 gauged catchments in the long-term annual rainfall and runoff. We use long-ria for selecting catchments within each basin are similarity multiple gauged catchments within each basin. The crite-

basins in the northeast United States, and use the data from

vary with flow conditions. In this study, we explore the
pect the similarity among catchments to be dynamic and
fluctuations in flow regimes. In such a case, one might ex-

pends on hydrologic controls that are sensitive to seasonal

is possible that streamflow similarity among catchments de-
ments is preserved across flow conditions. For instance, it
also not clear whether similarity among two or more catch-
logic similarity are still poorly understood. Moreover, it is

information from 77 gauged catchments in Tanzania to parti-

data of annual maximum flood and physiographic attribute
hydrologic regions. Kachroo et al. (2000) used the combined
flow data to group catchments in southwest Nigeria into five
hydrologic regions. Ogunkoya (1988) used parameters such as runoff coefficient, flow variability index, annual runoff, etc. that were directly obtained from the daily stream-
flow data to group catchments in southwest Nigeria into five
hydrologic regions. Kachroo et al. (2000) used the combined
data of annual maximum flood and physiographic attribute
information from 77 gauged catchments in Tanzania to partition
the country into 12 homogeneous regions.

Regardless of the approach used, the controls on hydro-
logic similarity are still poorly understood. Moreover, it is
also not clear whether similarity among two or more catch-
ments is preserved across flow conditions. For instance, it
is possible that streamflow similarity among catchments de-

depends on hydrologic controls that are sensitive to seasonal
fluctuations in flow regimes. In such a case, one might ex-

pect the similarity among catchments to be dynamic and
vary with flow conditions. In this study, we explore the
controls on hydrologic similarity by considering four river
basins in the northeast United States, and use the data from
multiple gauged catchments within each basin. The crite-
ria for selecting catchments within each basin are similarity
in the long-term annual rainfall and runoff. We use long-
term daily streamflow records from 25 gauged catchments
located within these four river basins and analyze the spatial
and inter-annual variability in their streamflow percentiles. 
Our a priori assumption is that since catchments within each
chosen basin are in close proximity and also similar in an-
nual rainfall and runoff, their stream response is likely to be
similar across flow conditions. The questions addressed in
this study are: (1) does the stream response similarity among
catchments exist under all flow conditions, and if not, (2) un-
der which conditions are the catchments likely to be similar
in hydrologic response.

2 Data

We consider four river basins located in the northeast United
States, viz., Allegheny, Upper Delaware, Lower Susque-

hanna, and Lower Chesapeake (Fig. 1). Streams in the Up-
per Delaware, Lower Susquehanna, and Lower Chesapeake
basins flow eastwards into the Atlantic Ocean, while those in
the Allegheny basin flow westwards to join the Mississippi
river and ultimately flow into the Gulf of Mexico. The Al-

legheny basin is located within the Allegheny plateau, and
is underlain by sedimentary rocks that are fractured, faulted
and folded at several locations. The channel bedrock con-

sists of weathered rock material, Quaternary glacio-fluvial
deposits, and alluvium (Anderson et al., 2000). Soils in ar-

areas of steep slopes are shallow and poorly drained, while
the soils on gentler slopes are deep, well drained and fer-
tile. The Upper Delaware basin is located in the eastern
part of the Allegheny plateau and the northern part of the
Appalachian plateau. The existing topography of the river
basin was formed by recent glaciations, and the parent mate-
rial is composed of glacial till deposits in the uplands (Ayers
et al., 1994). The Lower Susquehanna basin contains Pre-
cambrian to Triassic bedrocks that are structurally complex
and lithologically diverse. The structural complexity across
its landscape is the result of periods of uplift and collision
of continental plates (Risser and Siwiec, 1996). The Lower
Chesapeake basin consists of Rappahannock River and its
tributaries that drain into the Chesapeake Bay. This basin
drains parts of the Blue Ridge and Piedmont physiographic
provinces in northeastern Virginia. The sediment in this
watershed is derived from the weathered felsic crystalline rocks

The US Geological Survey’s Hydro-Climate Data Net-
work (HCDN) (Slack et al., 1993) is used as the database
for catchment selection. The HCDN primarily consists of
data for catchments that are not severely affected by human
activity. While the streamflow records in HCDN span from
1874 to 1988, most catchments have consistent and contin-
uous records from water year 1970 onwards. Within each
basin, we examine all the gauged catchments that are part
of the HCDN database. Daily streamflow for each catch-
ment is obtained for the water years 1970 to 1988 (i.e., 1 Oc-
data for each catchment is obtained from the hydro-climatic
dataset developed by Vogel and Sankarasubramanian (2005).
Average annual rainfall (Pann) and average annual discharge
The coefficient of variation (CV) calculated for each catchment using the data spanning 19 years. The coefficient of variation (CV = Standard deviation/Mean) of $P_{\text{ann}}$ and $Q_{\text{ann}}$ is then calculated for each basin. If the CV of either $P_{\text{ann}}$ or $Q_{\text{ann}}$ exceeds 0.1 in a basin, the outlier catchments with $P_{\text{ann}}$ or $Q_{\text{ann}}$ value farthest from the basin mean are eliminated and the CV values are recalculated. The criterion of CV < 0.1 ensures that, within each of the four basins, only those catchments are chosen that have homogeneity in their long-term annual rainfall and streamflow. Based on the above criterion, we found 25 gauged catchments among our four basins with drainage areas varying from 65 km$^2$ to 4163 km$^2$ (see Fig. 1). The average annual rainfall of the selected catchments for the water years 1970–1988 ranged from 1025 mm to 1230 mm. Figure 2 shows the precipitation duration curves (percentile value vs. precipitation amount) of the 25 catchments. These curves are similar for catchments within each basin and suggest the existence of similarity in the precipitation input patterns. Estimates of monthly potential evapotranspiration (PET) for each catchment are obtained from the Vogel and Sankarasubramanian (2005) dataset, where they used the PET formulation introduced by Hargreaves and Samani (1982). The baseflow and the baseflow index (BFI), i.e., baseflow/total flow, of catchments are calculated using the one parameter single-pass digital filter method of baseflow separation (Arnold and Allen, 1999; Eckhardt, 2008). The physiographic and hydroclimatic information of the catchments is summarized in Table 1.

3 Methods

3.1 Flow duration curve

We use the variability in streamflow percentiles of flow duration curves (FDC) (Searcy, 1959; Vogel and Fennessey, 1994, 1995; Smakhtin, 2001) to examine similarity among catchments under varying flow conditions. The FDC graphically illustrates the amount of time (expressed as a percentage) a specific streamflow value is equaled or exceeded in a catchment within a specified period of hydrologic record. Traditionally, FDC is constructed over an entire chosen period of hydrologic record (Searcy, 1959). However, this makes the FDC sensitive to the period chosen, especially the exceptionally dry or wet years in the record, and might not reflect the typical hydrologic behavior of the catchment. To reduce the bias of a chosen period of record, Vogel and Fennessey (1994) suggested an alternate method for constructing FDC that is based on inter-annual calculations. Following Vogel and Fennessey (1994), considering the daily streamflow record of $n$ years, the flow percentile values are calculated for each of the $n$ years separately. The median of all $n$ values for each flow percentile is then calculated and the median FDC is constructed. Throughout this procedure, the FDC is less sensitive to the exceptional years of flood or drought in the record, and we obtain the FDC for a typical (or median) year for the catchment. A detailed review of the physical interpretation and water resources applications of the FDC is provided in Vogel and Fennessey (1995).

3.2 Assessing variability in flow percentiles

The median FDCs of all 25 catchments are constructed with $n = 19$ years. Flow percentiles are obtained for all integer values ranging from 0 (minimum flow) to 100 (maximum flow). Within each basin, we obtain the CV value of each flow percentile from the median FDCs of all the catchments. The CV of flow percentiles is used as a measure of variability among catchments across flow conditions. Since the CV is a dimensionless metric, we consider it more suitable for comparing variability across a wide range of streamflow magnitudes. We further measure the inter-annual temporal variability of flow percentiles by calculating the CV of each individual percentile among all the 19 years of record. The inter-annual CV of the flow percentiles is measured individually for each of the 25 catchments.

4 Results

4.1 Spatial and temporal variability in streamflow across flow percentiles

Figure 3 shows the FDCs of all 25 catchments, grouped by their respective river basin. The FDCs are plotted as streamflow value vs. the streamflow percentile (i.e., the amount of time the streamflow is below that particular value). The high flow percentiles appear similar within all the four basins. The low flow percentiles appear more divergent from each other, especially in the Upper Delaware and Lower Susquehanna basins. Figure 4 shows the CV of all streamflow percentiles for the four basins and quantifies the intra-basin variability in streamflow percentiles. In all the four basins, CV is high at low flow conditions and trends lower for high flow conditions.
percentiles (except for extremely high flow). However, the pattern of variability reduction is different within each river basin. In the Upper Delaware and Allegheny basins, the CV drops fast at lower percentiles (<20%), stays low at intermediate percentiles (approximately from 20% to 90%), and then increases again for extremely high flow percentiles. In Lower Susquehanna basin, the CV reduces almost at a constant rate until about 95th percentile and then increases sharply near the highest flow percentiles. In the Lower Chesapeake basin, the CV drops rapidly from 0th percentile (minimum flow) to about 10th percentile, increases again until about 25th percentile and then continues its gradual decrease. The lowest CV values are observed in the range of 40th and 75th percentiles in the Lower Chesapeake basin.

A sudden increase in the CV is observed at extremely high flow percentiles (>90%) in the Upper Delaware, Lower Susquehanna and Allegheny basins (Fig. 4). A sharp rise in CV, however, is not observed at high flow percentiles in the Lower Chesapeake basin, where there is a more gradual increase. In all the four basins, difference between the highest and the lowest CV values is significant (Fig. 4). In the Upper Delaware, Lower Chesapeake, and Allegheny basins, CV reduces from the highest value of about 0.3 to the lowest value near 0.1. In the Lower Susquehanna basin, the highest CV is about 0.45, while the lowest CV is approximately 0.05. Figure 5 shows the inter-annual CVs of flow percentiles for each individual catchment. High CV is observed at the low flow and extremely high flow percentiles,

Table 1. Details of the 25 catchments within the four river basins.

<table>
<thead>
<tr>
<th>River Basin</th>
<th>CV($Q_{ann}$)</th>
<th>CV($P_{ann}$)</th>
<th>USGS Station</th>
<th>Area (km$^2$)</th>
<th>Slope (m km$^{-1}$)</th>
<th>BFI</th>
<th>Annual $Q$ (mm)</th>
<th>Annual $P$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Delaware</td>
<td>0.09</td>
<td>0.03</td>
<td>01420500</td>
<td>623.9</td>
<td>6.3</td>
<td>0.657</td>
<td>842.3</td>
<td>1118.4</td>
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<td></td>
<td></td>
<td></td>
<td>01413500</td>
<td>422.0</td>
<td>2.9</td>
<td>0.662</td>
<td>702.9</td>
<td>1172.9</td>
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<td></td>
<td></td>
<td></td>
<td>01414500</td>
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<td>22.8</td>
<td>0.667</td>
<td>783.7</td>
<td>1162.0</td>
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<td></td>
<td></td>
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<td>750.2</td>
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<td></td>
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<td></td>
<td></td>
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<td>7.1</td>
<td>0.697</td>
<td>641.0</td>
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<tr>
<td>Lower Susquehanna</td>
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<td>0.05</td>
<td>01555000</td>
<td>779.3</td>
<td>3.6</td>
<td>0.710</td>
<td>579.7</td>
<td>1055.8</td>
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<td></td>
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<td>542.1</td>
<td>1077.1</td>
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<td></td>
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<td>1.3</td>
<td>0.632</td>
<td>479.3</td>
<td>1200.8</td>
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<td></td>
<td>01560000</td>
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<td>1.4</td>
<td>0.628</td>
<td>556.6</td>
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<tr>
<td>Lower Chesapeake</td>
<td>0.08</td>
<td>0.02</td>
<td>03011020</td>
<td>4162.9</td>
<td>1.0</td>
<td>0.663</td>
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<td>03010500</td>
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<td>0.653</td>
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<td>595.5</td>
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<td></td>
<td></td>
<td>03020500</td>
<td>776.7</td>
<td>1.6</td>
<td>0.615</td>
<td>672.1</td>
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<td></td>
<td>03034500</td>
<td>226.3</td>
<td>3.2</td>
<td>0.595</td>
<td>661.5</td>
<td>1160.0</td>
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</table>

![Fig. 3. Flow Duration Curves of all the catchments within (a) Upper Delaware, (b) Lower Susquehanna, (c) Lower Chesapeake, and (d) Allegheny basin.](image-url)
whereas low CV is observed at intermediate flow percentiles for the majority of catchments. There are a few catchments, especially within the Lower Susquehanna basin, that are exceptions to this trend. In those catchments, the CV in the 20th–60th percentile range is higher than the CV for flows below 20th percentile. Moreover, the relationships between inter-annual CVs and catchment properties such as drainage area and baseflow index (BFI) have considerable scatter and no significant trends are observed (result not shown). Overall, the intra-basin differences in inter-annual variability of catchment stream response exist mostly at lower flow percentiles. The magnitudes of CVs are more similar at higher flow percentiles.

Since the CV is a ratio of standard deviation and mean, we also analyze both these entities separately in order to explore the relative influence of each property on the CV values from low to high flow percentiles. Figure 6 shows the spatial mean (solid line) and standard deviation (dashed line) of all the flow percentiles for catchments in each of the four river basins. The mean value varies smoothly across the flow percentiles and appears similar to the flow duration curves shown in Fig. 3. On the other hand, the variations in standard deviation across flow percentiles do not follow the similar pattern as mean values and appear more fluctuating. From low to high flow percentiles, the mean increases at a faster rate than standard deviation, thus decreasing the CV values at higher flow percentiles. However, at extremely high flow percentiles (>90%), the standard deviation increases at a faster rate than mean, and increases the CV values at those flow percentiles. Similar trends as in Fig. 6 are observed for temporal variability of mean and standard deviation at individual catchments across flow percentiles (result not shown).

**4.2 Seasonal variations in the hydrologic similarity among catchments**

Next, we seek to identify the seasonal trends in similarity. Within each basin, we select two catchments that are located closest to each other. The condition of closest proximity is to ensure that the catchment pair has a high likelihood of receiving similar rainfall input at daily time-scale. Figure 7 shows the comparison of daily hydrographs of the two selected catchments within each basin for water year 1973. Streamflows of catchments in the Upper Delaware, Allegheny and Lower Chesapeake basins have similar magnitudes and fluctuate almost in unison from mid-November to mid-June period. On the other hand, the hydrologic response of catchments during the summer and early fall months is dissimilar when the flow is typically low. In contrast to the other three basins, the dissimilarity in streamflows for the catchment pair in Lower Susquehanna basin persists from February to November period (see Fig. 7b).

**5 Discussion**

Results suggest that the hydrologic response of two or more catchments within a region does not remain similar across flow conditions (Fig. 4). The intra-basin variability in streamflow among catchments is high at low flow percentiles, and the variability reduces at higher flow percentiles. The relationship between CV and streamflow percentiles is unique for catchments within each of the four basins (Fig. 4) and is suggestive of the conditions at which the similarity/dissimilarity among the catchments is manifested. As seen in Fig. 7, the hydrographs of catchments in Upper Delaware, Allegheny and Lower Chesapeake basins are similar during the winter and spring periods, while most
of the dissimilarity occurs during the low flow period in summer. Figure 8 shows the average monthly values of streamflow, precipitation and PET of a sample catchment within each of the four basins. In all the four basins, high flow period is characterized by low ET demand, whereas the low percentile flows mostly occur when the water balance of a catchment is heavily influenced by the high ET demand from atmosphere. Thus, the dominance of ET demand becomes a controlling factor on the magnitude and spatial variability of streamflow during the low flow summer period; whereas the dominance of precipitation input controls the streamflow magnitudes and variability during the higher flow periods in winter. However, the streamflows of catchments in the Lower Susquehanna basin exhibit greater dissimilarity than the catchments in other three basins. As seen in Fig. 7b, the similarity in streamflow is limited only to the early winter period when the ET demand from atmosphere is the lowest. From mid-November to April period, the peaks of hydrographs are similar between the two catchments, but their recession characteristics start to show differences as the year progresses (Fig. 7b). Therefore, dissimilarity in streamflows over a longer period results in higher CV values across low and intermediate streamflow percentiles within the Lower Susquehanna basin (Fig. 4b).

The seasonal fluctuations in streamflow variability also suggest that different physical factors govern the spatial streamflow patterns at different periods within a year. During low flow conditions, typically in summer when the ET demand is high (Fig. 8), water fluxes are predominantly vertical (Tromp-van Meerveld and McDonnell, 2006; James and Roulet, 2007), and the spatial patterns of soil moisture are unorganized and strongly influenced by the local terrain (Grayson et al., 1997; Stieglitz et al., 2003). At these low flow conditions, disparate regions within a catchment are hydrologically disconnected (due to a lack of lateral water movement) and the catchment discharge is most likely controlled by the geologic factors such as the intricacies of landscape micro-topography, subsurface structure, soil texture and structure, etc. This local geologic control on hydrologic conditions can result in higher variability of streamflow response. However, even though geologic properties of the landscape might be playing an important role in streamflow variability at low flow conditions, a further examination of geologic data (permeability, % organic matter, % clay content) in all our 25 study catchments showed that a large variability exists in soil properties within each catchment, and no distinct differences are observed between catchments that can be quantitatively attributed to the variability at low flows. On the other hand, increased similarity among catchments at higher flow percentiles indicates a shift from “local” to “non-local” (climatic) controls as the catchments transition from low flow to high flow conditions. As the atmospheric evaporative demand reduces, a higher proportion of the precipitation gets converted into streamflow (Fig. 8). The high flow conditions reflect the period when the lateral fluxes of water are dominant (Grayson et al., 1997), the near surface and subsurface flow paths are connected (Meyles et al., 2003; Uchida et al., 2004; Tromp-van Meerveld and McDonnell, 2006; Stieglitz et al., 2003), and the streamflow variability is increasingly controlled by larger scale climatic forcing.

The CV values increase rapidly for the highest flow percentiles (>90th percentile). This increase is observed not only in the spatial variation of streamflows (Fig. 4) but also in the inter-annual streamflows in individual catchments (Fig. 5). A potential cause for this rapid increase could be that during the very high flow events the hydraulic properties of stream channels play an important role in controlling the streamflow. The control of these hydraulic properties can: (1) increase the variability in space (between catchments) at any given year, and (2) increase the variability in time (year-to-year) within a single catchment. Another potential cause for increased CV values could be the dependence of peak flow variability on catchment drainage areas (Smith, 1992; Blöschl and Sivapalan, 1997; Eaton et al., 2002). However,
examination of the relationship between the CV values and drainage areas of our study catchments showed no clear trend in this relationship at any flow condition. We further examined the timing of peak flow events in our catchments to verify whether high flow variability is caused by peak flows occurring in response to local-scale convective storms in summer months. We found that majority of the peak flow events occur during the winter and spring period when larger scale frontal precipitation events are more likely.

The choice of using CV as our variability metric directly affects how the controls on streamflow similarity are interpreted. The CV measures relative variability (around the mean value), and therefore, high CV at low flow percentiles can be expected due to small mean values. With an increase in streamflow from dry to wet conditions, the mean flow value increases steadily while the standard deviation increases at a much slower rate and causes the CV value to decrease from low flows to high flows. Although we attribute these changes in CV to shift in hydrologic controls under variable flow conditions, it can be argued that our results do not genuinely reflect the shifting hydrologic controls and are an artifact caused by use of CV as a similarity measure. To test this, we consider 25 synthetically generated random time-series, each representing one of our 25 study catchments by having the same probability distribution (log-normal) as the actual streamflow series. We repeat our analyses on these 25 synthetic time-series to obtain the spatial and temporal CV patterns, similar to those shown in Figs. 4 and 5. Figure 9 shows the spatial and temporal CV patterns of the synthetic time-series within the Lower Susquehanna basin. The synthetic series show that the intermediate percentiles have low CV values, while the extreme percentiles have high CVs. However, when compared with actual streamflow in Lower Susquehanna basin (Figs. 4b and 5b), the CV patterns of the synthetic series (Fig. 9) are distinctly different. Specifically, the synthetic time-series is unable to capture the monotonously decreasing spatial CVs of actual streamflows in Lower Susquehanna basin (Fig. 4b). Moreover, the CV patterns obtained by these synthetic series are similar (and indistinguishable) in all the four basins (results not shown) and do not inform us about the differences in CV patterns across the four basins. Therefore, although the random series display somewhat similar CV trends as the actual streamflow series (due to similar probability distributions), the changes in CV values observed in our study (Figs. 4 and 5) are most likely caused due to the underlying shift in hydrologic controls, and not an artifact of our methodology.

The results of this study have ramifications for predicting streamflow in ungauged catchments. Specifically, during low flows, the variability of streamflow among catchments is high, and the predictive capability at ungauged catchments using information from nearby gauged catchments is likely to be low. However, although the relative variability is high at low flows, the variability in absolute streamflow values will be low during the low flow periods. Therefore, depending on the error tolerance that is acceptable to the end user, streamflows at low flow periods can be simulated with limited success. During wet conditions, the variability of streamflow among catchments is low, which increases the similarity among catchments within a region and improves the prediction capability at ungauged catchments. This suggests that regions with predominantly wet conditions, i.e., humid regions would be more favorable for information transfer from nearby gauged catchments to the ungauged catchments. In such regions, one can expect a larger range of low variability at intermediate flow percentiles, as observed in the Upper Delaware and Allegheny basins (Fig. 4a, d). Dissimilarity among catchments can also be identified by abnormal CV patterns, as observed in Lower Susquehanna basin (Fig. 4b). High regional variability at low flow and extremely high flow percentiles suggests that similarity in physiographic attributes should be considered while making regionalized predictions at the low flow and extremely high flood events.

Our a priori criteria of catchment selection, i.e., similarity in annual rainfall and runoff, put limits on the size of basins from which the catchments were chosen. Although a limited number of gauged catchments are available within each of our four basins, every catchment has a long and consistent hydrologic record (WY 1970–1988). Ideally, a larger sample size of gauged catchments (if available) within a basin might provide a clearer picture, in quantitative terms, of spatial variability across flow conditions. However, we think it is unrealistic that we will ever have a large number of gauged catchments within a small basin that satisfies our a priori criteria of homogeneity. Moreover, the direct comparison of catchment streamflow and its analysis from an inter-seasonal perspective (Figs. 7 and 8) shows consistency with our observation that regional variability in streamflows is higher at low flow conditions and reduces at higher flows (Fig. 4). Due to the limited number of catchments, the CV patterns in our study might not provide an accurate quantification of variability, but they do provide a preliminary view
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