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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 mostly 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 an inter-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 Bloschl, 2005), parameter regionalization for lumped hydrologic models (Burn and Boorman, 1993; Merz and Bloschl, 2004), regional low flow predictions (Nathan and McMahon, 1990; Laaha and Bloschl, 2006),

HESSD

7, 8607–8630, 2010

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 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 (% slope), soil (% sand) and climate (annual rainfall, potential evapotranspiration).

Another approach for characterizing regional similarity among catchments uses hydrologic information directly derived from streamflow data of gauged catchments. Mosley (1981) clustered 174 New Zealand catchments into hydrologically homogeneous regions based on similarities in specific mean annual flood and the coefficient of variation of instantaneous flood discharge. Ogunkoya (1988) used parameters such as runoff coefficient, flow variability index, annual runoff, etc. that were directly obtained from the daily streamflow 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 and partitioned the country into 12 homogeneous regions.

HESSD
7, 8607–8630, 2010

Regardless of the approach used, however, it is also not clear yet whether hydrologic similarity among two or more catchments is preserved across flow conditions. To address this question, we consider four river basins in the northeast United States and use data from multiple gauged catchments within each basin. The criteria for selecting catchments within each basin are similarity in the long-term annual rainfall and runoff. Our a priori assumption is that since catchments within each basin are in close proximity and also similar in their annual rainfall and runoff, their stream response is likely to be similar across flow conditions. 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. The questions addressed in this study are: (1) does the stream response similarity among catchments exist under all flow conditions, and if not, (2) under 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 Susquehana, and Lower Chesapeake (Fig. 1). Streams in the Upper Delaware, Lower Susquehana 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 to the south. The U. S. Geological Survey's Hydro-Climate Data Network (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 continuous 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 catchment is obtained for the water years 1970 to 1988 (i.e., 1 October 1969 to 30 September 1988). Precipitation data for each

HESSD
7, 8607–8630, 2010

catchment is obtained through inverse distance-weighted interpolation from the five nearest National Climate Data Center's (NCDC) weather stations. Average annual rainfall (P_{ann}) and average annual discharge (Q_{ann}) are calculated for each catchment using the daily data of 19 years. The coefficient of variation (CV = Standard deviation / Mean) of P_{ann} and Q_{ann} is then calculated for each basin. If the CV of either P_{ann} or Q_{ann} exceeds 0.1 in a basin, the outlier catchments with P_{ann} or Q_{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. We select 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. Estimates of monthly potential evapotranspiration (PET) for each catchment are obtained from the hydro-climatic dataset developed by Vogel and Sankarasubramanian (2005), 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; Sawicz et al., 2010). The physiographic and hydro-climatic 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,

HESSD
7, 8607–8630, 2010

S. Patil and M. Stieglitz

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 which 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. Through 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. 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.

HESSD
7, 8607–8630, 2010

4 Results

4.1 Spatial and temporal variability in streamflow across flow percentiles

Figure 2 shows the FDCs of all 25 catchments, grouped by their respective river basin. The FDCs are plotted as streamflow value vs. the percentage of time it is exceeded. The percentage time of exceedance is reverse of a streamflow percentile, i.e., a 90th percentile streamflow value is exceeded 10% of the time in a catchment. The high flow percentiles (i.e., lower % time exceeded flows) appear similar within all the four basins. The low flow percentiles appear more divergent from each other, especially in the Upper Delaware and Lower Susquehana basins. Figure 3 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 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 Susquehana 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 Susquehana and Allegheny basins (Fig. 3). 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. 3). 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 Susquehana basin, the highest CV is about

HESSD
7, 8607–8630, 2010

0.45, while the lowest CV is approximately 0.05. Figure 4 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, whereas low CV is observed at intermediate flow percentiles for the majority of catchments. There are a few catchments, especially within the Lower Susquehana basin, that are exceptions to this trend. In those catchments, the CV in the 20th–60th percentile range is higher than the CV for below 20th percentile flows. 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.

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 5 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 (Fig. 5a, 5c and 5d) when the flow is typically high, and suggests that these catchment are responding to same climatic inputs. On the other hand, the hydrologic response of catchments appears decoupled during the summer and early fall months (July–October) when the flow is typically low. In contrast to the other three basins, the dissimilarity in streamflows for the catchment pair in Lower Susquehana basin persists from February to November period (see Fig. 5b).

HESSD
7, 8607–8630, 2010

5 Discussion

Results suggest that the hydrologic response of two or more catchments within a region does not remain similar across flow conditions (Fig. 3). 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. 3) and is suggestive of the conditions at which the similarity/dissimilarity among the catchments is manifested. As seen in Fig. 5, 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 6 shows the average monthly values of streamflow, precipitation and PET of a sample catchment within all the four basins. Although the patterns of precipitation and evaporative demand appear similar among all the four basins, marked differences are observed in their monthly streamflows. The difference between the highest and lowest monthly flow is greatest in the Upper Delaware basin, while the catchment in Lower Chesapeake basin has the most damped response. 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 (Fig. 6). Thus, an increase in ET demand during the summer period decreases the flow magnitudes and increases the spatial variability of streamflow. The streamflows of catchment pair in Lower Susquehana basin, however, exhibit greater dissimilarity than the catchments in other three basins. As seen in Fig. 5b, 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 among the two catchments, but their recession characteristics start to show differences as the year progresses (Fig. 5b). Therefore, dissimilarity in streamflows over a longer period results in higher CV values across low and intermediate streamflow percentiles within the Lower Susquehana basin (Fig. 3b).

HESSD

7, 8607–8630, 2010

Due to high ET demand at low flow periods (Fig. 6), the isolated nature of intra-catchment hydrological processes play an important role in controlling the variability at low flow percentiles. During the low flow conditions, vertical fluxes of water are more dominant and the distribution of soil moisture is strongly influenced by local terrain (Grayson et al., 1997; Stieglitz et al., 2003). Field observations in experimental catchments have shown a lack of lateral flow in the upper unsaturated soils at low flows (Tromp-van Meerveld and McDonnell, 2006; James and Roulet, 2007), which hampers the rapid movement of water, as well as nutrients, from hillslopes to the valleys (Creed et al., 1996; Creed and Band, 1998; Stieglitz et al., 2003). Increased similarity among catchments at high flow percentiles indicates a shift from "local" to "non-local" 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. 6). Figure 7 shows the average monthly baseflow values for a sample catchment in each of the four basins. In all the four basins, baseflow magnitude is higher during the winter and spring seasons than in the summer period. Therefore, during high flow conditions, the contribution from faster flow paths, viz., surface flow and shallow subsurface flow, becomes increasingly important. This phenomenon has been observed in several experimental studies, either through the presence of pipe flows (Tromp-van Meerveld and McDonnell, 2006), increase in hillslope pore pressure (Uchida et al., 2004), or higher degree of spatial organization in soil moisture patterns (Grayson et al., 1997; Meyles et al., 2003; James and Roulet, 2007).

An increase in CV for the highest flow percentiles (>90th percentile), however, suggests a break in the spatial similarity as the catchments reach flows close to annual peak values (Fig. 3). Commonly identified factors for variability at peak flows include channel response time, storm duration and intensity, routing mechanisms, etc. (Gupta et al., 1994; Gupta and Dawdy, 1995; Robinson and Sivapalan, 1997). The dependence of peak annual floods (in terms of their magnitude as well as temporal variability) on catchment drainage area has also been widely reported in the literature (Smith, 1992; Bloschl and Sivapalan, 1997; Eaton et al., 2002). During the high flood events, the hydraulic properties of stream channels of individual catchments assume an increasingly important role in controlling the streamflow within these basins, and therefore, might be causing an increase in regional variability.

The results of this study highlight the strong dependence of catchment similarity on flow conditions, and have ramifications for predicting streamflow in ungauged catchments. Specifically, during low flow periods, the variability of streamflow among catchments is high, and the prediction capability at ungauged catchments using information from nearby gauged catchments will be low. During high flow periods, 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. 3a and 3d). Dissimilarity among catchments can also be identified by abnormal CV patterns, as observed in Lower Susquehana basin (Fig. 3b). 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. We selected basins from the northeast United States since it has the highest density of long-term gauging stations. Although a limited number of gauged catchments (less than 10) 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

HESSD
7, 8607–8630, 2010

and its analysis from an inter-seasonal perspective (Figs. 5 and 6) shows consistency with our observation that regional variability in streamflows is higher at low flow conditions and reduces at higher flows (Fig. 3). 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 on the variable nature of hydrologic similarity that is consistent across different basins. In our opinion, one of the main challenges in hydrology, especially from the prediction in ungauged basins (PUB) perspective (Sivapalan et al., 2003), is to work within the constraints of limited measurement locations and learn as much as possible from their observed patterns. We view and analyze the results of this study from that same perspective.

6 Summary and conclusion

This study focused on testing whether stream response similarity among catchments within a region is preserved at all flow conditions. Results show that similarity among catchments is dynamic and highly dependent on the flow conditions. Regional variability in stream response is high at low flow conditions, and it gradually reduces at high flow conditions. Results also suggest that as catchments transition from low to high flow, the dominant control over streamflow variability shifts from evaporative demand to precipitation input. Analysis of the temporal variability of streamflow percentiles shows a similar pattern, i.e., high variability at dry conditions and low variability at wetter conditions. Thus, the evaluation of regional variability over the entire range of streamflow percentiles provides a framework for identifying hydrologic conditions at which stream response among catchments is more likely to be similar. Although our analysis is limited to catchments within the Northeastern United States, the key findings of this study (i.e., dependence of catchment similarity on the flow conditions) should be applicable over a wide range of environments. By identifying the important physical factors that control regional variability in stream response under different wetness conditions, a better understanding and prediction capability of catchment behavior can be achieved at the ungauged sites.

HESSD
7, 8607–8630, 2010

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HESSD

7, 8607–8630, 2010

Hydrologic similarity among catchments under variable flow conditions

S. Patil and M. Stieglitz

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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HESSD

7, 8607–8630, 2010

Hydrologic similarity among catchments under variable flow conditions

S. Patil and M. Stieglitz

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HESSD

7, 8607–8630, 2010

Hydrologic similarity among catchments under variable flow conditions

S. Patil and M. Stieglitz

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

River Basin	CV(Q_{ann})	CV(P_{ann})	USGS Stn No.	Area (km^2)	Slope (m/km)	BFI	Annual Q (mm)	Annual P(mm)
Upper Delaware	0.09	0.03	1420500	623.9	6.3	0.657	842.3	1118.4
			1413500	422.0	2.9	0.662	702.9	1172.9
			1414500	65.2	22.8	0.667	783.7	1162.0
			1439500	302.9	6.6	0.708	750.2	1150.1
			1440400	170.6	15.3	0.685	786.2	1227.9
			1440000	165.7	7.1	0.697	641.0	1152.3
Lower Susquehana	0.09	0.05	1555000	779.3	3.6	0.710	579.7	1055.8
			1555500	419.4	2.1	0.617	542.1	1077.1
			1562000	1957.2	1.3	0.632	479.3	1200.8
			1560000	445.3	8.1	0.590	519.9	1194.8
			1564500	530.7	2.7	0.578	457.2	1154.6
			1568000	517.8	1.4	0.628	556.6	1099.4
Lower Chesapeake	0.08	0.02	1664000	1605.1	1.8	0.658	420.8	1047.4
			1667500	1222.0	2.8	0.669	442.9	1064.9
			1663500	743.0	5.6	0.668	459.9	1025.1
			1666500	463.4	6.6	0.670	489.4	1063.4
			1668000	4131.9	1.3	0.628	399.4	1075.4
Allegheny	0.07	0.04	3011020	4162.9	1.0	0.663	622.2	1087.6
			3010500	1423.9	2.1	0.653	633.6	1025.3
			3015500	831.0	1.4	0.603	688.7	1175.4
			3011800	120.1	6.7	0.661	595.5	1128.0
			3020500	776.7	1.6	0.615	672.1	1107.7
			3028000	163.1	7.9	0.656	738.9	1148.0
			3032500	1366.9	1.0	0.637	631.2	1130.5
			3034500	226.3	3.2	0.595	661.5	1160.0

HESSD
7, 8607–8630, 2010

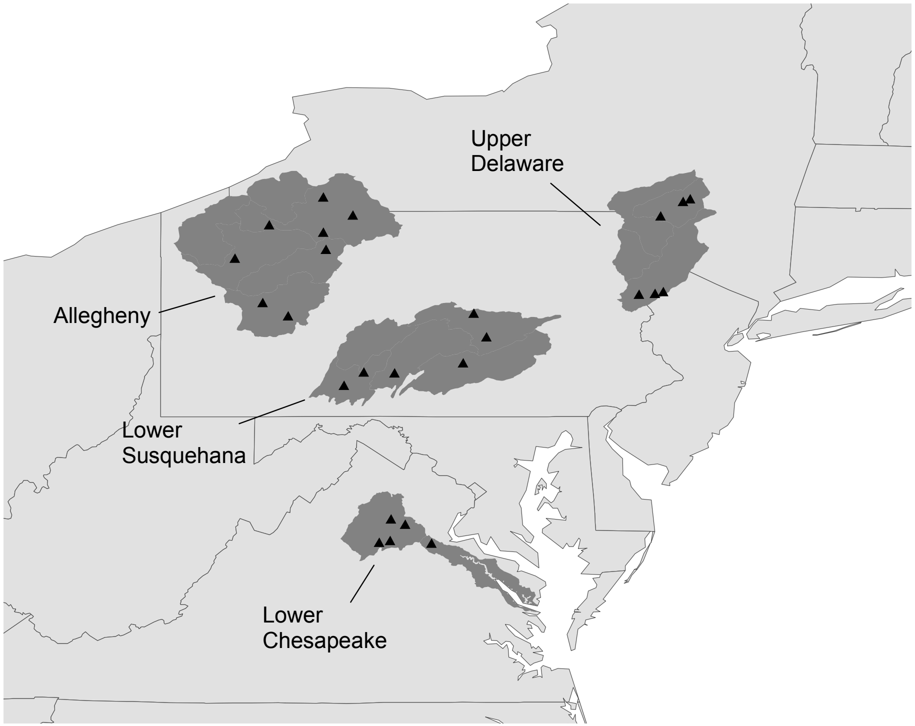

Fig. 1. Four River basins and 25 nested catchments in northeast United States.

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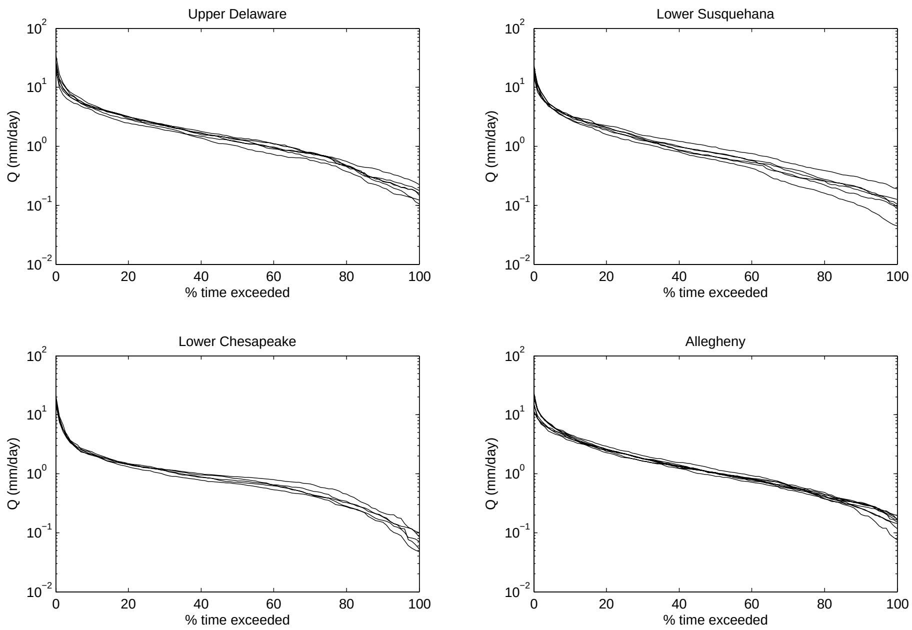

Fig. 2. Flow Duration Curves of all the catchments within **(a)** Upper Delaware, **(b)** Lower Susquehana, **(c)** Lower Chesapeake, and **(d)** Allegheny basin.

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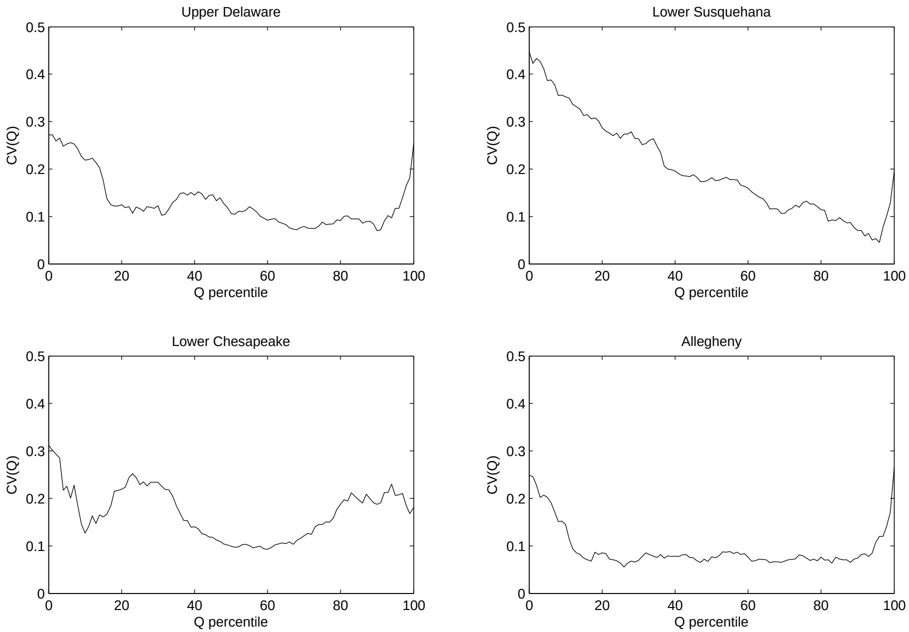

Fig. 3. Coefficients of variation of catchment streamflow percentiles within **(a)** Upper Delaware, **(b)** Lower Susquehana, **(c)** Lower Chesapeake, and **(d)** Allegheny basin.

HESSD

7, 8607–8630, 2010

Hydrologic similarity among catchments under variable flow conditions

S. Patil and M. Stieglitz

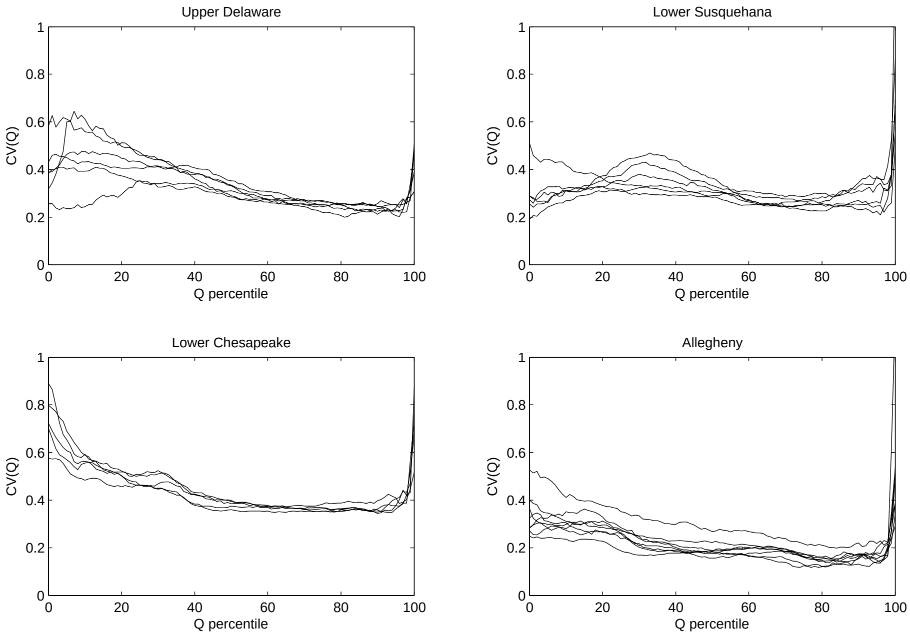

Fig. 4. Inter-annual coefficients of variation of streamflow percentiles for all the 25 catchments within **(a)** Upper Delaware, **(b)** Lower Susquehana, **(c)** Lower Chesapeake, and **(d)** Allegheny basin.

HESSD
7, 8607–8630, 2010

Hydrologic similarity among catchments under variable flow conditions

S. Patil and M. Stieglitz

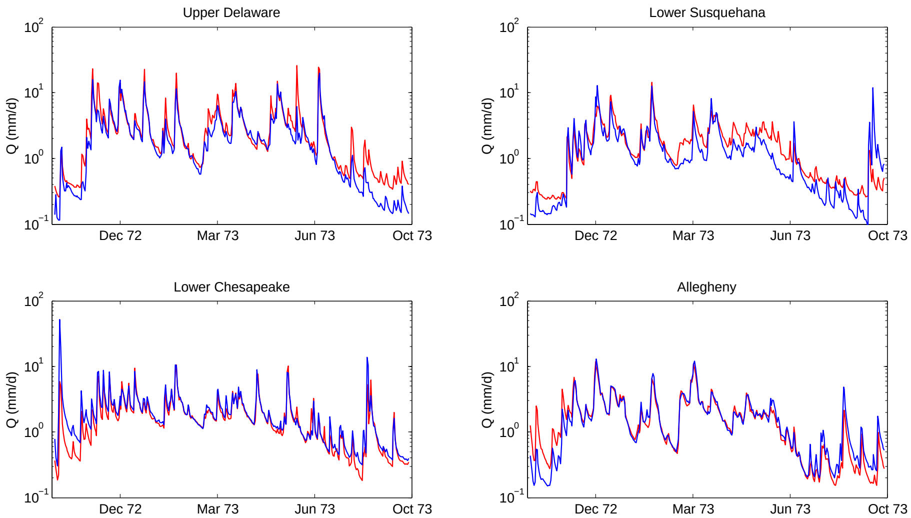

Fig. 5. Hydrograph comparison of the two selected catchments for water year 1973 within **(a)** Upper Delaware, **(b)** Lower Susquehana, **(c)** Lower Chesapeake, and **(d)** Allegheny basin.

HESSD
7, 8607–8630, 2010

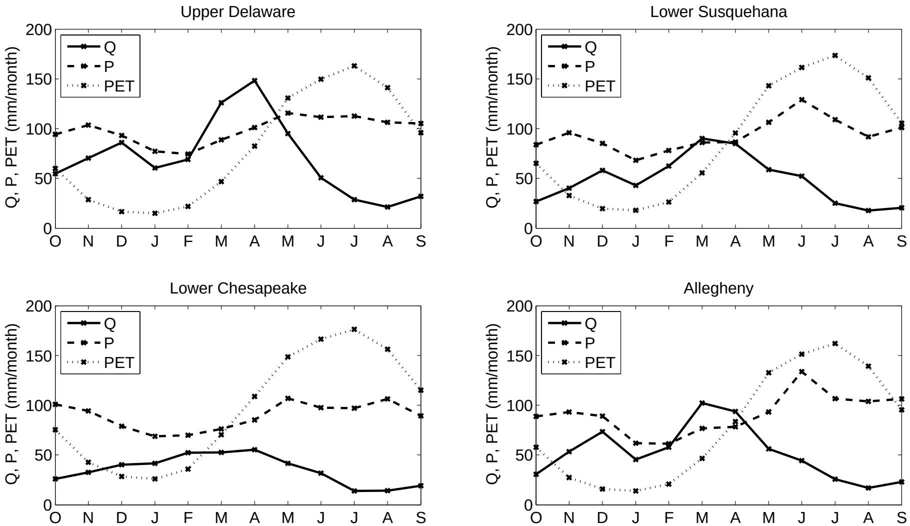

Fig. 6. Average monthly values of streamflow, precipitation and potential evapotranspiration of a sample catchment in **(a)** Upper Delaware, **(b)** Lower Susquehana, **(c)** Lower Chesapeake, and **(d)** Allegheny basin.

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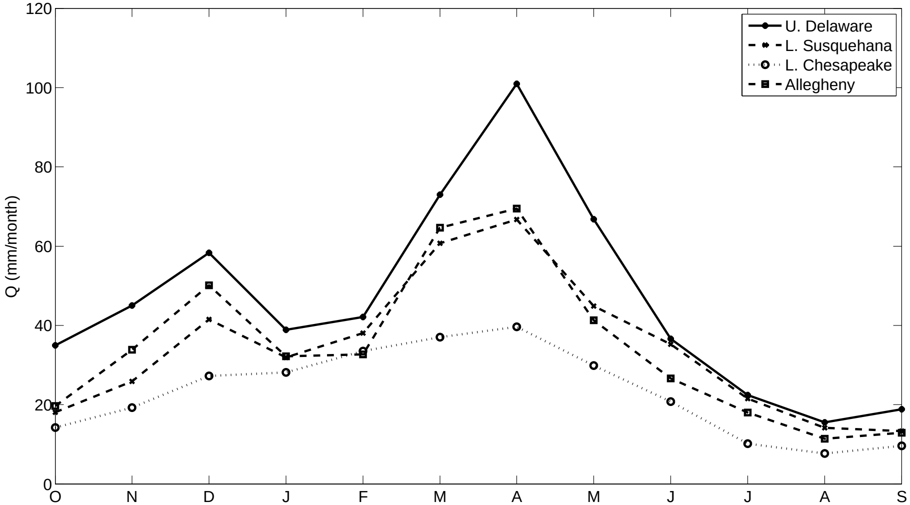

Fig. 7. Average monthly baseflow values of a sample catchment in each of the four basins.

HESSD

7, 8607–8630, 2010

Hydrologic similarity among catchments under variable flow conditions

S. Patil and M. Stieglitz