Does Evapotranspiration reduction due to urbanization increase stream base flow discharge?

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Abstract

Urbanized watersheds have impervious surfaces that impede infiltration, which can reduce groundwater recharge. They also often exhibit disturbed riparian zones with channelized structures or other alterations that can affect floodplain and watershed evapotranspiration (ET) rates. Studies of small, urbanized watersheds have often reported reductions in stream base flow in urban streams. Urbanization and channelization of riparian corridors in larger watersheds (25 -258 km^2) may result in decreases in evapotranspiration and thus increases in base flow in comparison with adjacent non-urban streams. In this study, I selected paired (urban, non-urban) watersheds with similar basin areas, geology, and climate in four major hydro-climatic regions of the U.S.: the Northeast (New York, New Jersey), Pacific Northwest (Washington), Upper Midwest (Montana, South Dakota) and the Southeast (Georgia). These different hydro-climatic regions were described using precipitation and temperature data from the Portal Resources for Indiana Science and Mathematics (PRISM). USGS daily average discharge data were separated into cool season and warm season data sets and the resulting flow duration curves for each set of paired watersheds were compared. The resulting analysis showed warm season base flow had smaller variation (higher seasonality ratios) in most of the streams suggesting reduced evapotranspiration in these regions during the warm season. There is also a much stronger linear relationship between the urbanization ratios and the impervious surface ratio during the warm season compared to the cool season. These data indicate significant impacts of urban land use changes on ET and both water and energy flows in urban streams. Urbanized streams also tend to exhibit a smaller variation compared to the non-urban streams in all regions in the flow duration curves.

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Introduction

Watersheds link landscapes to streams and coastal regions. Urbanization modifies the permeability of watershed soils, changing the water balance, which is a concern for the management of water resources. The proportion of the world's population living in urban areas has steadily increased in the past 100 years. Since 2008, more than half of the world's population resides within an urban center (Grimm et al., 2008). As human population and the urban proportion of this population has increased, the size or urban areas has also increased. In the United States, most regions, especially coastal regions, have experienced urban growth and the expansion of urban and suburban communities. Urbanization has a great impact on watershed hydrological processes. Trees and other plants growing in permeable soils are replaced by disturbed soils (lawns) and impervious surfaces such as sidewalks, parking lots, roadways, and rooftops that prevent or reduce the infiltration of water into the soil (Barnes et al., 2002). This decline in infiltration rates results in an increase in storm runoff, which often leads to increased peak flow discharge. In small watersheds, this increase in impermeable surfaces results in increased storm runoff, stream incision and headward migration of stream channels, and lower base flow discharge in compared to adjacent non-urban streams (Booth and Jackson, 1997; Fanelli et al., 2017). An increase in high discharge values and a decrease in low discharge values could represent an increase in total annual runoff or a maintenance of runoff values with different temporal distribution.

There are many studies (e.g. Duval & Hill, 2006, Clauson-Kass et al., 2016, Olson et al., 2012) on the effect of urbanization and other land uses on stream hydrology, chemistry, and aquatic ecology. Urbanized streams have a high level of impervious surfaces such as concrete, tarmac, and brick that replace soil and vegetated surfaces thereby altering the infiltration of water into the soil (Gregory et al., 2006). Generally, urban streams with small drainage areas have an increased peak flow and lower base flow compared to the non-urban ones (Fanelli et al., 2017, etc.). However, evapotranspiration is an important factor that can cause a different trend in base flow and peak flow especially on streams with bigger drainage areas. Analyzing the flow processes such as base flow and peak flow in urban streams is important to understand how human activities and constructions can impact the watersheds around us and aid watershed management.

Most studies of the effects of urbanization on streamflow have been designed to evaluate a range of impermeable surface areas. Very high percentages of impervious surface areas are observed in small watersheds, with drainage areas less than 1- 10 km^2. Some of these studies show that over time, urban streams have a higher peak discharge, higher volume and lower base flow (e.g. Leopold, 1968; Booth and Jackson, 1997). Urbanization extends stream networks, which can have significant consequences on small streams (Fanelli et al., 2017). Urbanization of moderate to large streams (with drainage areas of about 20 km^2 or greater) can be more complex due to several reason. Riparian corridors and floodplains are often retained along larger stream channels. Flood discharges from upstream tributaries can flow overbank and infiltrate into these riparian floodplains. The differential timing of flood peaks on tributaries with different stream lengths and impervious surfaces can attenuate peak flows in downstream regions. From a water balance perspective, runoff from impervious surfaces that is transported downstream can infiltrate into wetlands and floodplains and thus be available for evapotranspiration. Therefore, losses due to evapotranspiration and thus base flow discharge could be significantly influenced by these processes in larger urban watersheds with intact floodplains and riparian corridors.

Transpiration is a water loss mechanism where plants pull water up through their roots release water to the atmosphere through stomata in their leaves (Eagleson, 1978). Direct evaporation from ground and leaf surfaces also returns water to the atmosphere. Transpiration varies significantly with vegetation type and rooting depth, with forest evapotranspiration rates being significantly higher than row crops or urban lawns. The effects of evapotranspiration on the urban water balance are poorly understood, as illustrated by the following diagram, which doesn't match published data on forested regions for either storm event or annual water balances. In forested areas, storm evapotranspiration might be 10-25%, with infiltration accounting for 65-80% of storm precipitation. On an annual basis, infiltrated water supports tree growth through transpiration and it also supports stream base flow. Evapotranspiration from forested humid temperate watersheds in regions like Maryland is 70-80% of the annual water balance, leaving only 10-20% of annual precipitation to support stream base flow. Urban land uses that increase storm discharges but decrease base flow discharges (e.g. Leopold, 1968, etc.) could modify the distribution of stream discharges without changing annual runoff volumes or the annual water balance. By reducing vegetative cover, however, urbanization could significantly reduce evapotranspiration and modify the annual water balance.

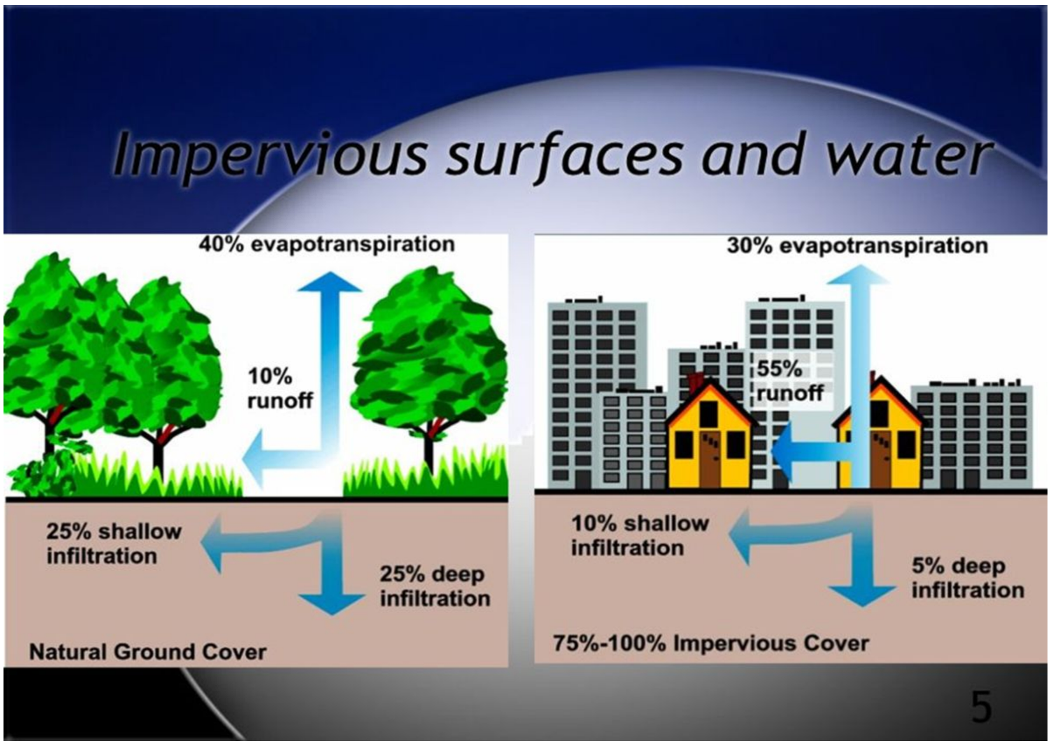


Fig. 1: Depiction of water balances in forested and urban systems. Source: EPA

Urban modification of the land could affect both the distribution of discharges and evapotranspiration, which would affect seasonal and annual water balances. Forested watersheds should have significantly higher annual evapotranspiration rates and lower warm season base flow than urban and suburban areas. Evapotranspiration varies by the position on the earth (latitude), season of the year and precipitation (Yu et al., 2016). This suggests that the effect of evapotranspiration on lowering base flow should be seasonal. Urbanization, however, also effects base flow by inhibiting soil groundwater recharge. This urban impervious surface effect on base flow reduction should not be strongly seasonal. This implies that in forested regions, base flow should be significantly lower than average during the growing season when evapotranspiration rates are high, but base flow levels should be higher in winter (cool seasons). This leads to several questions, what is the effect of urbanization on warm season and cool season stream discharge? Does the timing of precipitation affect the differences in evapotranspiration rates and base flow discharge in urban and non-urban regions? To evaluate these questions, I will examine the seasonal distribution of runoff using probability analysis of daily discharge values (flow duration curves) in moderately sized streams (25-258 km^2) in different hydro-climatic regions with varying patterns of seasonal precipitation.

Study Implications

Urbanization affects stream discharge in many different ways. Understanding how peak discharge and base flow in urban streams differ from rural streams gives an insight into the physical processes. There are many factors that can affect the flow system in urban streams. Analyzing flow processes such as base flow and peak flow in urban streams is important to understand how human activities can impact the watersheds around us and aid in watershed management. Flow processes also aid in qualifying stream water by calculating or predicting amounts of different minerals in the stream (Peters, 2009, Fitzgerald, 2015). Previous work has been performed on many small sized urban streams (Fanelli et al., 2017). I selected moderately sized urban and non-urban streams in various hydro-climatic regions with distinct flow regimes to examine how urbanization affects watersheds. The results give insight into the effect of evapotranspiration on the base flow of streams. This insight leads to a better understanding of how urbanization affects bigger streams and how these factors affect the streams. In the future, this knowledge can help to predict and model the effects of urbanization on a larger scale.

Hypotheses

- Urbanization increases annual runoff in moderate sized basins in the studied regions
    - Null: Annual runoff values are similar for urban and non-urban streams but it varies among hydro-meteorological regions
- Urban land use decreases evapotranspiration, which lessens the seasonal difference in the stream base flow, and can be evaluated with seasonal flow duration curves for urban and non-urban streams
    - Null: seasonal variations in the flow duration curves are similar for urban and non-urban streams

Explanation: Urbanization decreases recharge and thus could reduce stream base flow in comparison to non-urban streams, but evapotranspiration also reduces base flow. The reduction in base flow due to urbanization alone will be most pronounced during the cool season, but will vary among hydro-climatic regions. Reduction in base flow due to evapotranspiration should be highest during the warm (growing) season. The warm and cool seasons' temperature and precipitation vary among the selected hydro-climatic regions. I expect that during the warm season when there is potentially a higher rate of evapotranspiration, the non-urban streams will have higher ET rate than the urban streams which will lead to lower stream base flow in the warm season. This effect will be most pronounced in regions that receive significant warm season precipitation.

Experiment Design and Methods

The approach of this study is to use a paired watershed design to compare flow characteristics for urban and non-urban watersheds. To develop the database of paired streams, I sorted streams in states with targeted urban areas by hydrologic units. Two streams in close in proximity were then selected in each watershed. In each pair, the two streams are from the same hydrologic unit, with similar topography, climate, basin area, but different land uses. One of the streams in each pair is an urban stream with a higher level of impervious surface (greater than 10%) while the other is a non-urban stream with significantly lower level of impervious surface (less than 10%). The 10% criteria was chosen because previous studies indicate this value as one that causes significant hydrological or ecological change. All the selected streams are moderately sized, greater than 25 km^2 in drainage area but less than about 300 km^2. The streams in each pair were selected for their similarity in drainage areas with the difference in basin area limited to 15%.

Characteristics of selected watersheds

Two paired watersheds in 4 distinct hydro-climatic regions defined by mean annual temperature (MAT) and the timing of precipitation: Upper Midwest (summer precipitation), Southeast (high MAT; low precipitation seasonality), Pacific Northwest (winter precipitation), and Northeast (low MAT; low precipitation seasonality) have been selected. Stream pairs were selected that were in the same hydro-climatic setting, with similar basin areas. Sites were selected for differences in the timing and amount of warm season precipitation. The seasonality of precipitation was determined by taking the ratio of warm season precipitation to total annual precipitation (table I). Selected hydro-climatic regions have precipitation seasonality ratios that range from 0.3 (winter precipitation dominated) in Washington State to 0.77 (Summer Precipitation dominated) in N. Dakota. Northeastern and Southeastern U.S. have seasonally distributed precipitation, but variations in mean annual temperature.

The paired watersheds are in 6 states: Washington, South Dakota, Montana, Georgia, New York and New Jersey. The streams were all selected to ensure that the sites are not heavily irrigated during the summer. All watershed pairs were evaluated with the impervious cover of the United States (NLCD data) and the impervious area for each watershed was measured in ArcGIS using built-in tools. For each watershed pair, an impervious surface ratio was calculated as:

$$Impervious\ cover\ ratio = \frac{Urban\ stream\ impervious\ cover}{Non{-}urban\ stream\ impervious\ cover}$$

Values of the impervious cover ratio varied from 1.7 to 3.8 among the watersheds with a range of impervious cover ratios in each region. There is no correlation between the precipitation seasonality ratio and the impervious surface ratio ($R^2 = 0.0042$). Selected stream pairs, their watershed name, watershed areas, impervious cover ratios, and precipitation seasonality ratios are shown in table I.

State	Site #	Watershed Name	Watershed Area (mi^2)	Impervious Area (%)	Impervious Cover Ratio	Precipitation Seasonality
Washington	12143600	Snoqualmie River	65.9	11	1.73	0.30
Washington	12137800	Sultan River	77.1	19		
New York	01414000	Platte Kill	34.9	15	2.67	0.56
New York	01415000	Tremper Kill	33.2	5		
Georgia	02335700	Big Creek	72	26	2.17	0.50
Georgia	02336300	Peachtree Creek	86.8	12		
South Dakota	06404000	Battle Creek	58.5	15	2.50	0.77
South Dakota	06409000	Castle Creek	79.1	7		
Washington	12120000	Mercer Creek	12	6	3.00	0.30
Washington	12148000	South Fork River	19.7	16		
Georgia	02385800	Holly	64	8	1.88	0.47
Georgia	02387600	Oothkalooga	62.6	20		
Montana	12375900	South Fork	7.61	10	1.60	0.57
Montana	12377150	Mission	12.4	16		
New Jersey	01384500	Ringwood	17.9	8	2.14	0.55
New Jersey	01386000	Westbrook	11.8	15		
Maryland	01660920	Zekiah Swamp	79.9	6	3.83	0.54
Maryland	01649500	NE Anacostia	72.8	23		
Wyoming	06289600	West pass	15.4	9	2.11	0.67
Wyoming	06289820	East Pass	21.7	19		
Iowa	05485605	Fourmile Creek at Antheny	62	9	1.78	0.69
Iowa	05485640	Fourmile at Des Moines	92.7	16		

Table 1: Characteristics of the paired watersheds selected in the different hydro-climatic regions. The impervious cover ratio represents the urban/non-urban impervious cover. The precipitation seasonality is the amount of summer (May-Oct) precipitation / total precipitation.

Precipitation acquisition and analysis

For this project, I acquired precipitation and temperature data from PRISM (Parameter-elevation Regressions on Independent Slopes Model); which is a spatially-distributed precipitation product that fills in missing data, adjusts for orographic precipitation, interpolates precipitation between measurement stations, and makes other corrections to the ground-based precipitation data base (Daily et al., 2008). Data were acquired from the PRISM data explorer web site (PRISM for Oregon State, 2018). These data, which include monthly and annual precipitation and temperature data, are used to characterize each hydro-climatic region.

I used several types of precipitation data in this study. The first type of precipitation data are monthly 30-year normal (in mm), which were used to calculate the precipitation seasonality ratio. The precipitation seasonality ratio is: (Σ May to November precipitation)/ Annual precipitation (table I). I also used annual precipitation data for the most recent 10 years of record, which are used to compare with annual streamflow data and to determine annual runoff ratios.

Annual runoff data

Discharge data is measured by the USGS and presented on the United States Geological Survey (USGS) website as different data products. The annual discharge statistic presents the average annual discharge in cubic foot per second (cfs). These average annual discharge values can be converted to an annual volume of water (ft^3) by multiplying the average annual discharge by the number of seconds in a year ($3.154 * 10^7$). To convert this annual volume term to runoff (a length-scale parameter), the total volume of water is divided by the watershed area (ft^2). This length scale term represents the annual point runoff (ft), which is converted to mm for comparison with precipitation data and calculation of runoff ratio (runoff, mm/precipitation, mm). The relationship between annual runoff and precipitation was evaluated for each year, and the runoff ratios were compared for each year and across sites.

Daily discharge data and analysis of seasonal flow duration curves

The USGS also provides time series of daily discharge data. These time series include the daily average of the instantaneous discharge evaluated at 5-30-minute intervals for each day at each measurement station. These data are used to calculate the probability of daily discharge, which is termed a flow duration curve. The data series used for this analysis is the mean daily discharge for 10 years (2008-2017). After acquiring these data, the 10-year daily discharge data were separated into two seasons: warm and cool producing the 'seasonally-separated' daily discharge data. The cool season represents all the data from each day in the months from November through April while the warm season represents the data from each day from the months from May through October. In this paper, I will be comparing watershed pairs that have similar, but different basin areas. Therefore, all discharge values were normalized by dividing daily discharge (cfs) by basin area (mi^2). This generates a unit discharge (cfs/mi^2), which can also be expressed as units of runoff, mm.

The seasonal flow duration analysis is probability analysis of the seasonally-separated unit discharge data series. The normalized discharge data were sorted and ranked from the largest to the smallest daily values. To determine exceedance probability, the rank associated with each unit discharge value is divided by the total number of data points (and multiplied by 100 to express as a %time that the flow is equaled or exceeded). Flow duration curves are graphs of the % of time that the normalized discharge values are equaled or exceeded (Daly et al., 2008) The flow duration curve illustrates normalized discharge values associated with storms (low frequency events) and base flow (high frequency events). Flow quantiles (e.g. 10%, 50%, and 90% exceedance values) can be determined from these flow duration analyses. Below is an example of a 10-year average annual flow duration curve, showing the normalized daily runoff values (converted to mm) for the 10, 50, and 90% exceedance values.

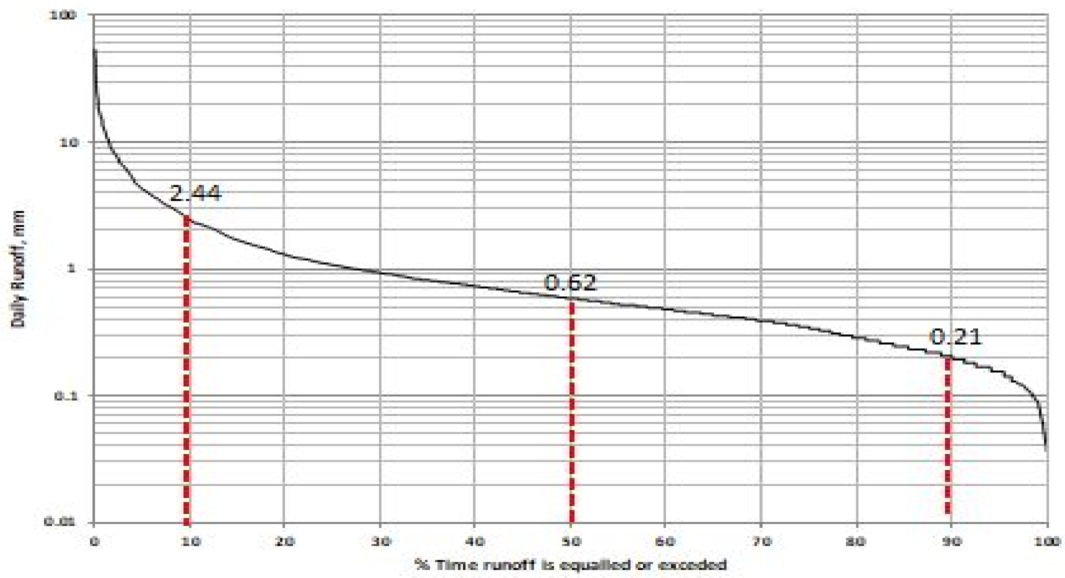


Figure 2: This graph shows how the percentiles are extracted from the flow duration curve.

Determination of Urbanization and Seasonality ratios based on flow duration analysis

The seasonally-separated daily discharge data were used for flow duration analyses, which were then evaluated to determine and separate the effects of seasonal precipitation and urbanization on stream discharge.

The effects of seasonality of precipitation on discharge was evaluated by comparing the warm and cool season flow duration curve quantiles (10, 50, and 90 %) for each stream. For example, for the Q 10 for this would be:

$$Seasonality\ ratio = \frac{flow\ Q10\ in\ cool\ season}{flow\ Q10\ \ in\ warm\ season}$$

This seasonality ratio is evaluated for the both the urban and non-urban stream in each pair. Data are analyzed for individual flow percentiles. Seasonality ratios for both urban and non-urban streams are compared to see which stream type (urban vs non-urban) has more variation in each season. The percentiles to be analyzed are 10^{th}, 50^{th} (median) and 90^{th}. The 10^{th} percentile is chosen to represent the high flows in the flow duration curves. These are expected to represent storm discharges in each of the streams. The 50^{th} percentile shows the median of the base flow and is the percentile of most interest for the seasonality and urbanization ratio trends. The 90^{th} percentile represents the low base flow, which would be expected to illustrate the impacts of evapotranspiration during warm seasons.

The seasonally separated flow duration analyses can also be used to evaluate an urbanization ratio, by comparing discharge quantiles (10, 50, and 90) for each urban stream to each non-urban stream in each stream pair.

$$Urbanization\ ratio = \frac{Urban\ base\ flow}{Non\text{-}urban\ base\ flow}$$

The urbanization ratio is calculated twice, first for the warm season and then for the cool season. This step is repeated multiple times in all the percentiles being analyzed.

Error Analysis and Statistical Analysis

The major type of data that was be used for my analysis are discharge data. According to the USGS publications by Turnipseed and Sauer (2010), some of the possible sources error in the measurement for discharge by the US Geological Survey include uncertainty in the measure of the parameters used to calculate discharge: cross-sectional area and velocity and other random errors. USGS evaluates errors in discharge measurements to be less than 2-10% for most stream sites (~ 5%). Regression coefficients for discharge-gauge height relationships are often between 0.980 and 0.998; this relationship indicates that errors in discharge are systematic, not random, thus error bars are not put on discharge data. Seasonal separation of data generated from the same rating curve (gauge height-discharge relationship) incorporate the same systematic errors in the measurement of discharge and thus can be used to evaluate seasonal differences in discharge. Comparison of discharge between streams involves the accuracy of separate rating curves (one for each station).

Analysis of variance test was conducted on the discharge data (for individual flow quantiles) differed at each site among seasons and between urban and non-urban streams. Regression analysis was used to evaluate whether the multiple regressions are calculated to test for the effect of the impervious cover area, urbanization ratio compared to impervious surface, and seasonality ratio compared to % summer precipitation.

Results

The results are presented in the following order: a) comparison of hydro-meteorological data (annual temperature, precipitation, and runoff) among the regions, b) comparison of the annual water balance components (runoff and evapotranspiration) among regions, c) presentation of the seasonally-separated flow duration curves, and d) evaluation of whether the impervious surface difference among watersheds explains the difference in flow between urban and non-urban watersheds using the flow urbanization and flow seasonality ratios.

Hydro-meteorological comparisons of the study sites.

The 10-year mean annual precipitation (MAP), mean annual temperature (MAT), annual runoff, and precipitation seasonality ratios were all determined for each watershed pair. These data are summarized in table II.

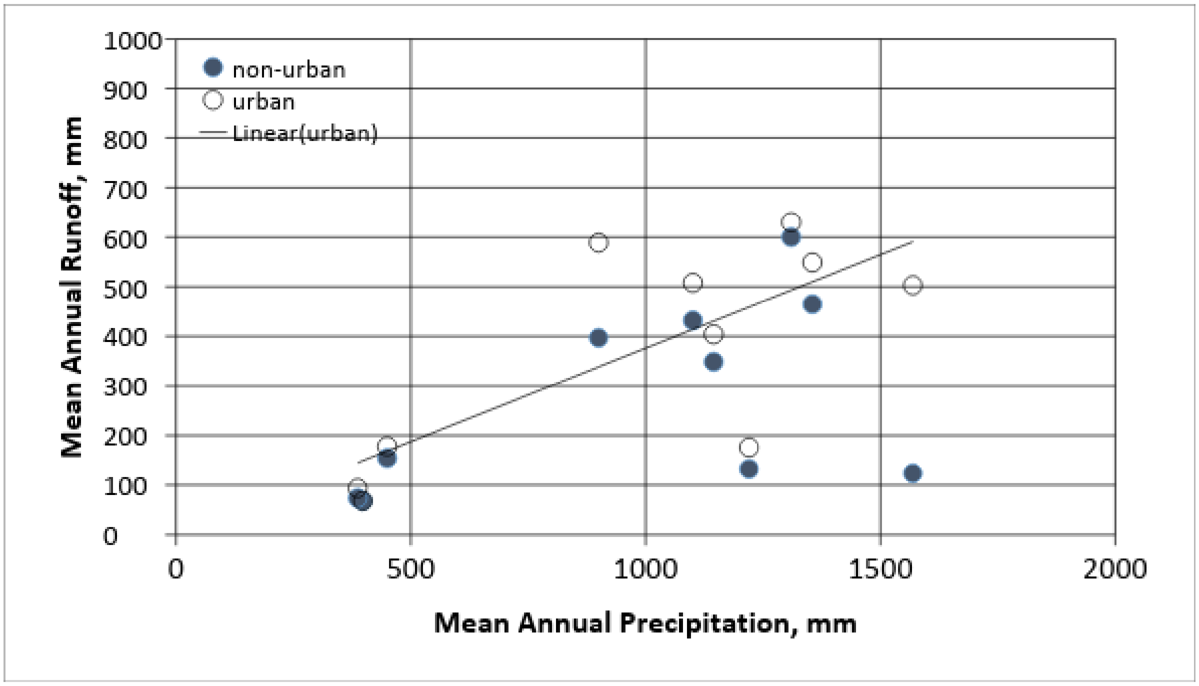
Stream	***MAT, °C***	***MAP, mm***	***Precipitation Seasonality ratio***	***10-year Ave runoff ratio***	***10-year Ave Runoff, mm***

Washington	7.3	3428	0.30	*	*
				*	*
New York	7.1	1145	0.56	0.32	404
				0.28	349
Georgia	16.3	1310	0.50	0.46	629
				0.43	600
South Dakota	8.6	398	0.77	0.15	68
				0.16	68
Washington II	10.5	1569	0.30	0.28	504
				0.07	124
Georgia II	15.5	1355	0.47	0.34	550
				0.32	465
Montana	7.1	450	0.57	0.36	178
				0.32	155
New Jersey	10.8	1220	0.55	0.14	176
				0.10	132
Maryland	13.7	1102	0.54	0.44	508
				0.37	432
Wyoming	7.4	388	0.67	0.22	94
				0.17	74
Iowa	9.7	901	0.69	0.54	589
				0.37	397

Table 2: The average runoff for the urban streams (top figures in the split rows) is consistently higher than the non-urban streams (lower figures). The runoff ratio is also higher in the urban stream compared to the non-urban stream (except South Dakota). * (Data currently unavailable from USGS)

Annual Precipitation -runoff relationships

Annual precipitation and annual runoff were determined for a 10-year time period for each watershed pair. A 10-year time period was selected for this comparison because land-use in urbanized watersheds changes over time. The 10-year average runoff for the urban and non-urban watersheds for all of the regions is shown in fig. 3. The individual year data for selected urban and non-urban streams are shown in fig. 4-7; the rest of these diagrams are in the appendix.



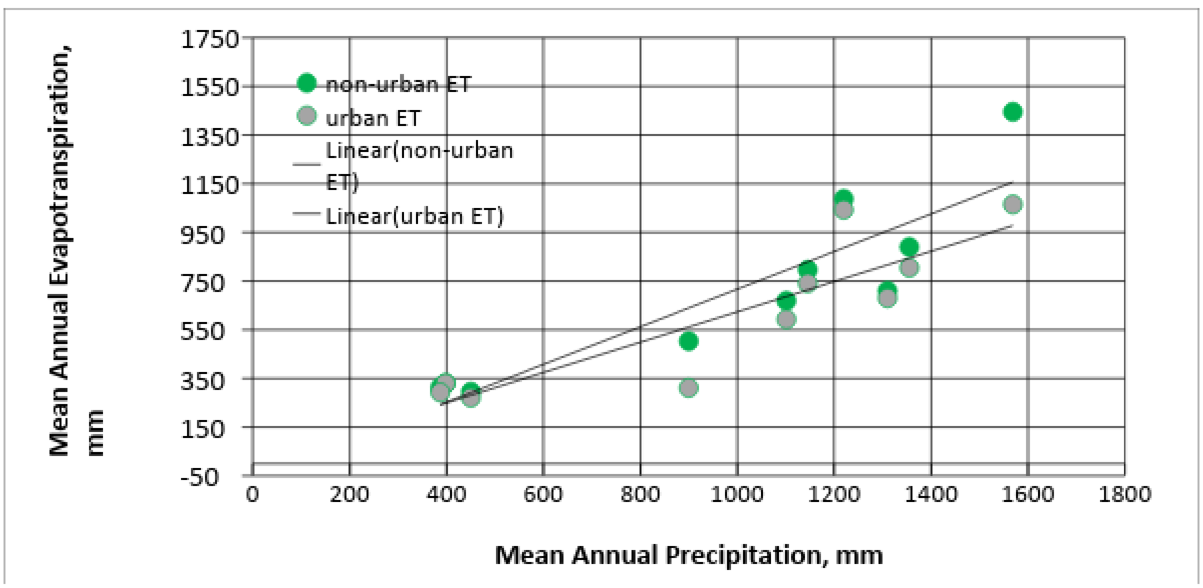


Figure 3a: Relationship of mean annual runoff to mean annual precipitation for urban and non-urban streams among the study sites. 3b: Relationship of mean annual ET for urban and non-urban streams. Urban runoff increases with mean annual precipitation (slope = 0 .37; R2 = 0.557); ET increases more strongly with precipitation (non-urban slope = 0.773, R2 = 0.806; urban slope = 0.623; R2 = 0.774).

Analysis of the runoff values between the urban and non-urban streams below show that the urban streams have higher runoff than the non-urban streams. However, the difference between the runoff values vary and the difference is more profound in the regions with higher mean annual precipitation and high levels of urbanization. Non-urban evapotranspiration (precipitation – runoff) is higher in the non-urban streams than in the urban streams for all regions. These data indicate that urbanization affects the water balance of the streams as well as the temporal distribution of stream discharges. The figures below show the runoff values of the urban and non-urban streams:

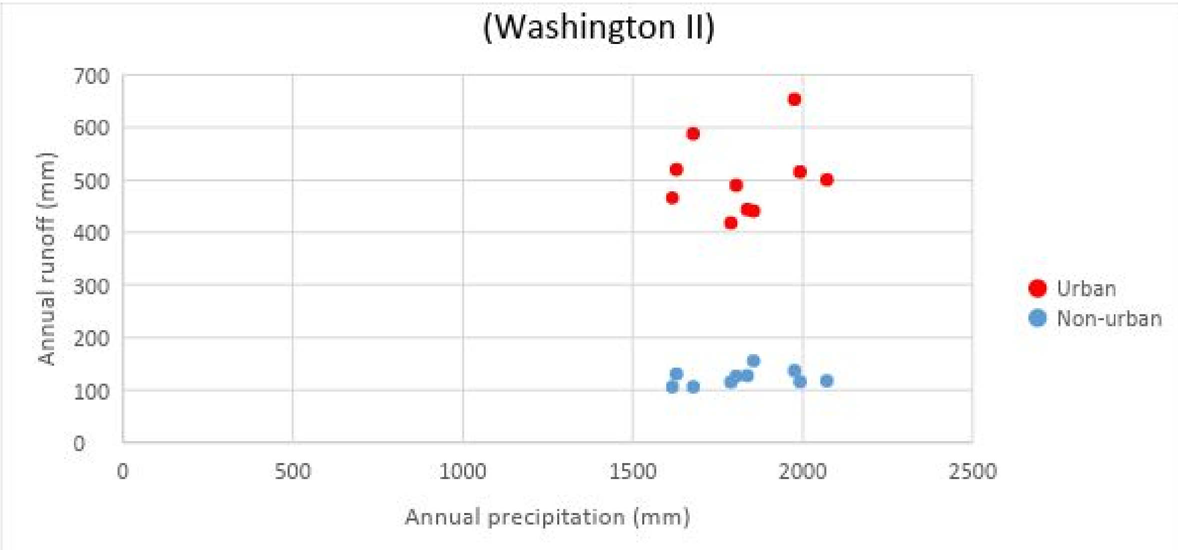


Figure 4: This set of paired watersheds is a region of cool season precipitation (precipitation ratio = 0.30), the impervious surface ratio of the paired watersheds is 3.0. Annual runoff is significantly higher for the urbanized watershed; it also shows an increase with annual precipitation, which is not observed in the non-urban watershed. The increase in precipitation is used for ET in the non-urban watershed

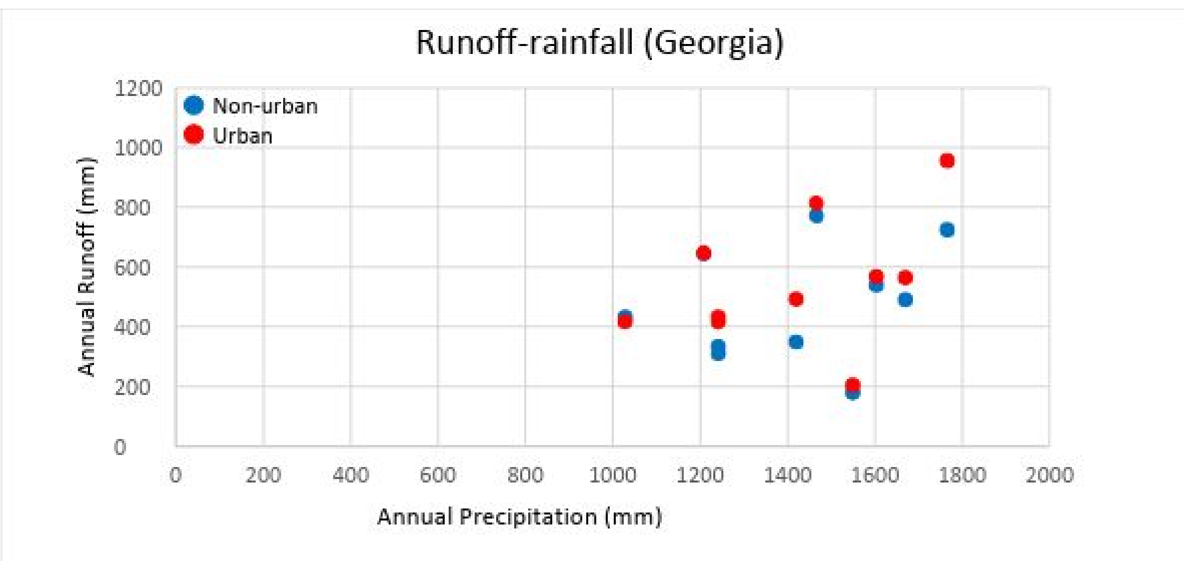


Figure 5: This set of paired watersheds is a region of low warm/cool season precipitation (precipitation ratio = 0.497), the impervious surface ratio of the paired watersheds is 2.17. Annual runoff is significantly higher for the urbanized watershed; it also shows an increase with annual precipitation, which is observed in the non-urban watershed

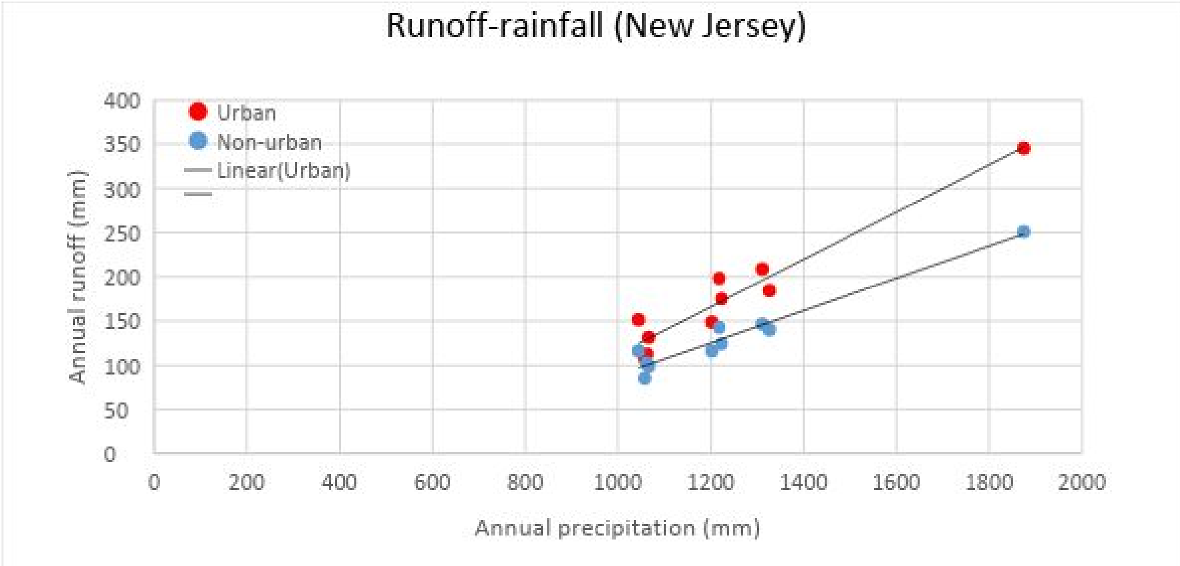


Figure 6: This set of paired watersheds is a region of warm season precipitation (precipitation ratio = 0.55), the impervious surface ratio of the paired watersheds is 2.14. Annual runoff is significantly higher for the urbanized watershed; it also shows an increase with annual precipitation, which is also observed in the non-urban watershed

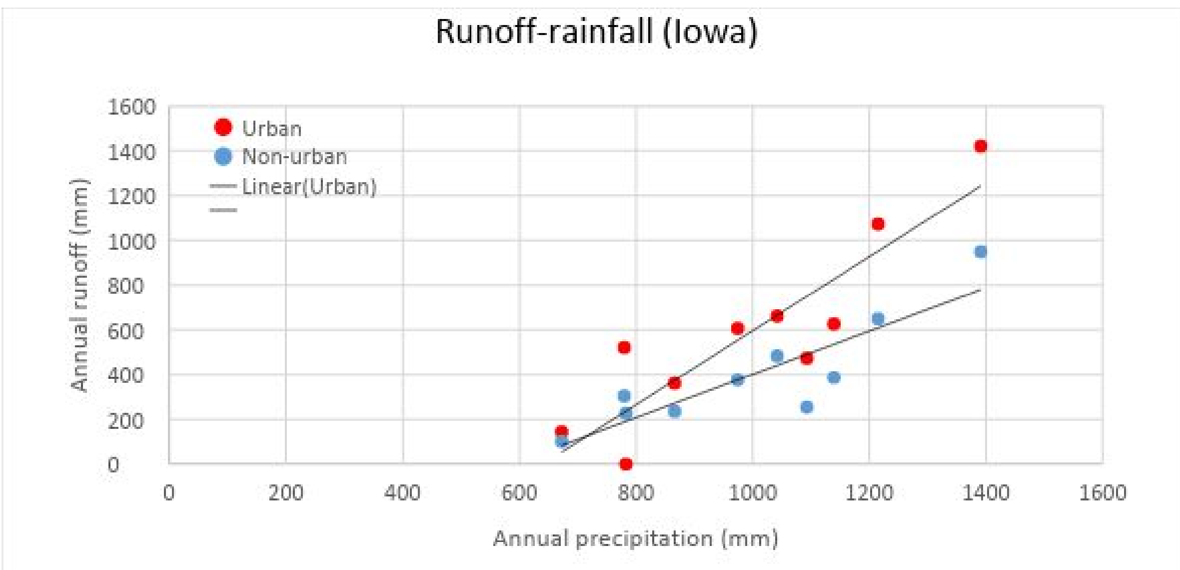


Figure 7: This set of paired watersheds is a region of significant warm season precipitation (precipitation ratio = 0.69), the impervious surface ratio of the paired watersheds is 1.78. Annual runoff is significantly higher for the urbanized watershed; it also shows an increase with annual precipitation, which is also observed in the non-urban watershed but shows less linearity in the non-urban watershed

The four graphs above (top to bottom) exhibit the inter-annual relationships between annual precipitation and mean annual runoff for the urban and non-urban streams from the Pacific Northwest (King County in Washington), Northeast (Fulton County in Georgia), Southeast (Passaic County in New Jersey), and Upper Midwest (Polk County in Iowa) respectively. In all of these regions, the annual runoff in the urban streams is higher than the annual runoff in the non-urban streams. In some regions with higher summer precipitation (e.g. New Jersey and Iowa), there is a general trend of increased runoff with increased rainfall in the region. In New Jersey and Iowa, the difference in runoff between the urban and non-urban watersheds increases during years with higher annual precipitation, which is reflected in the slope and R^2 values of the precipitation-runoff relationships (fig. 6.7).

Comparison of Precipitation Seasonality among regions

After selecting streams in different hydro-climatic regions, they are further distinguished by their precipitation seasonality. Precipitation seasonality could be reflected directly in the seasonal flow duration curves. Summer precipitation could be directly used by vegetation, limiting the water available for summer base flow discharge. Winter precipitation could be stored in non-urban watershed groundwater systems and used at a later date for evapotranspiration, which may also reduce summer streamflow in heavily forested regions. Below are the graphs showing the precipitation and temperature data for the same stream pairs shown above in the four regions.

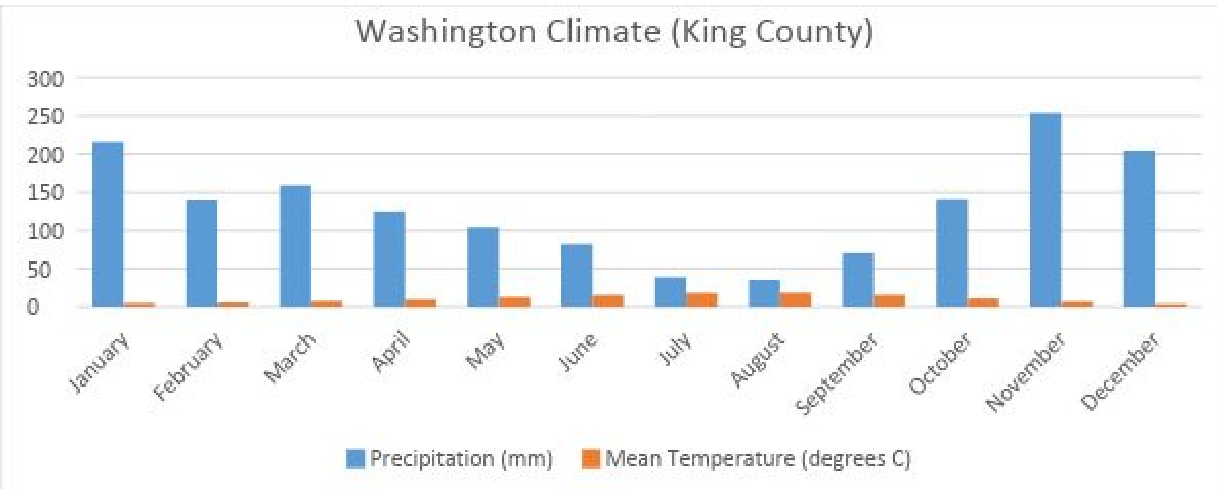


Figure 8a: Temperature and precipitation data for the stream pair in King County in *Washington. This region is characterized by mild temperatures and lower summer precipitation. The mean annual temperature is 10.5 and the mean annual precipitation is 1569.*

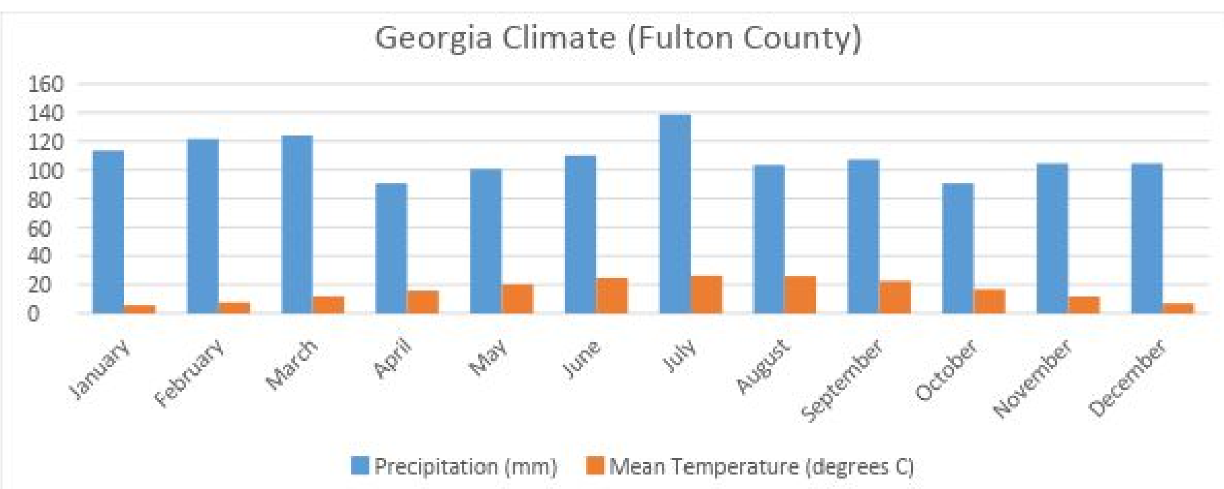


Figure 8b: Temperature and precipitation data for the stream pair in Fulton County in Georgia. Temperature ranges from 5.6 to 26.2. Summer (May-Oct) precipitation is only slightly less than Nov-April precipitation. The mean annual temperature is 16.3 and the mean annual precipitation is 1310.

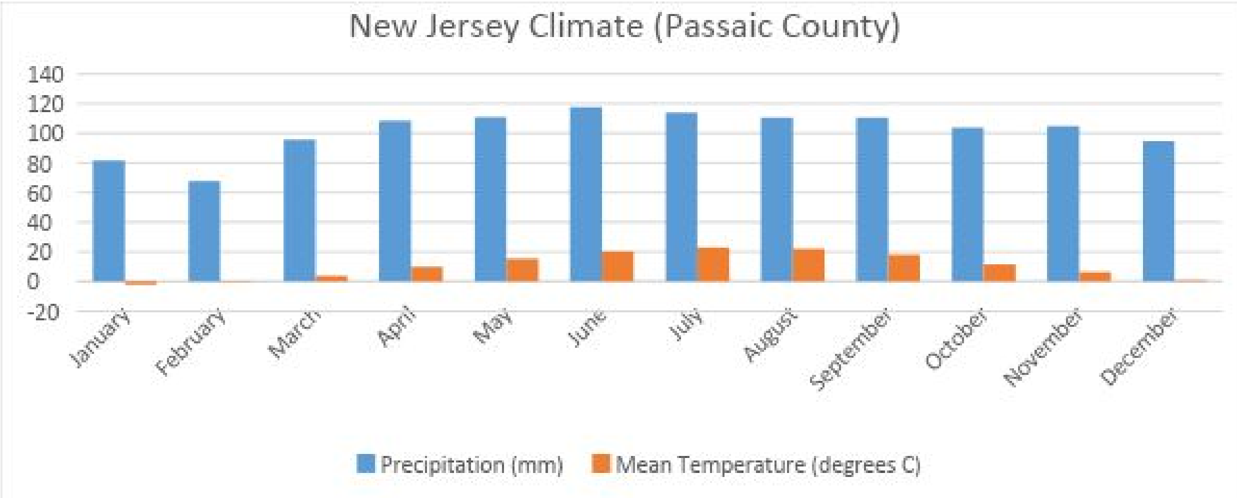


Figure 8c : Temperature and precipitation data for the stream pair in Passaic County in *New Jersey. This region is characterized by very high summer temperature and slightly more precipitation in the summer (May-Oct) than the cooler months (Nov-April). The mean annual temperature is 10.8 and the mean annual precipitation is 1220.*

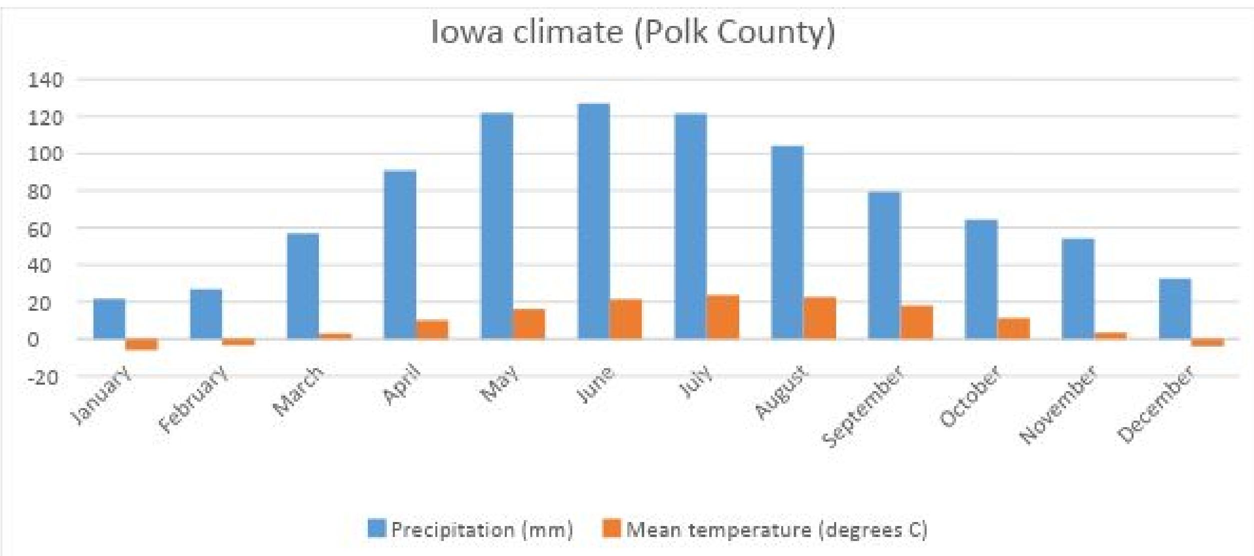


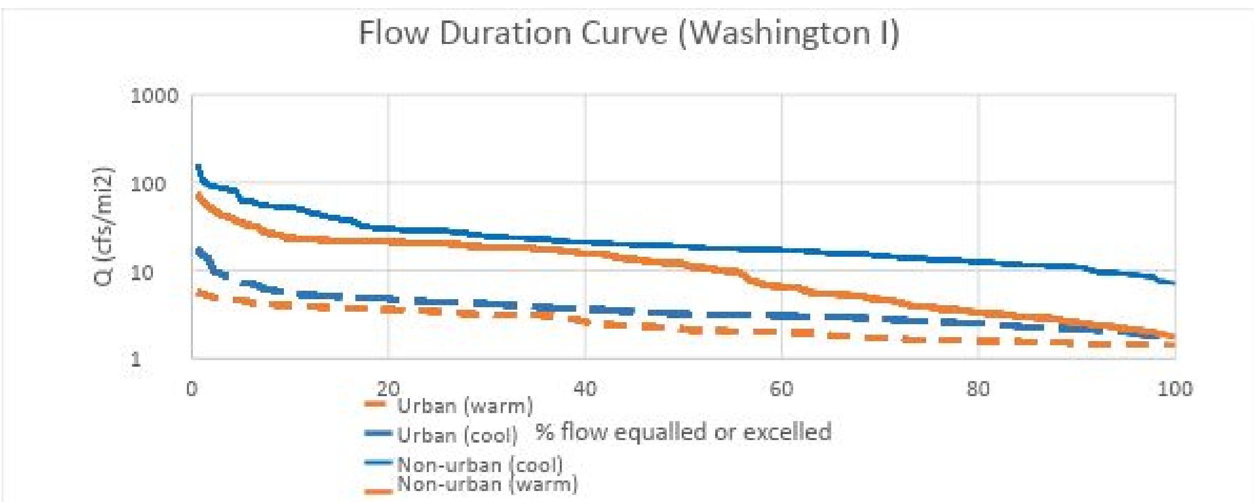
Figure 8d: Temperature and precipitation data for the stream pair in Polk County in *Iowa. Nov-April months in this region are characterized by very low temperature and precipitation. Warmer months (May-Oct) have significantly higher temperature and precipitation. The mean annual temperature is 9.7 and the mean annual precipitation is 901.*

The stream pair in the Pacific NW (King County) is characterized by mild temperatures all year round and a relatively wet winter period. The warmer months, May to October, have significantly less rainfall than the November-April months. Rainfall totals in this period are approximately double the values in the warmer months. The resulting summer precipitation seasonality in this region is well below 0.5. The stream pair in the Southeast region (Fulton County) has low precipitation variability. It is characterized by high temperatures, especially in the summer months and almost equal precipitation all year round. The summer precipitation in this region is only slightly less than the cooler months precipitation giving a summer precipitation seasonality of only slightly less than 0.5.

The stream pair in the Northeast (Passaic County) has low precipitation variability all year round. This region has a very cool winter and relatively mild summer. The warmer months, May to October, have slightly more rainfall compared to the November-April months. This region has a summer precipitation seasonality of slightly above 0.5. The stream pair in the Upper Midwest (Polk County) is characterized by extremely cool winter and very warm summer. There is significantly more rainfall in the May-October months than in the November-April months. The total rainfall in the summer are almost double the rainfall in the cooler months. This region has a summer precipitation seasonality much greater than 0.5.

Seasonally-separated Flow duration curves

Flow duration analysis of 10-years of seasonally-separated daily discharge data was conducted for warm and cool season discharge for each discharge pair. The stream pairs showed different trends in the flow duration curves in the same four regions being represented. The flow duration curves below have been seasonally separated and show the flows in the warmer (May to October) months and cooler November to April) months for both urban and non-urban stream. All flow duration analyses are expressed as unit discharges, which normalizes for the effects of slightly different basin areas in each watershed pair. The flow duration curves are presented for each hydroclimatic region, starting in the winter precipitation-dominated regions of the west coast, followed by the upper mid-west (summer precipitation), and followed by the East Coast (distributed precipitation).



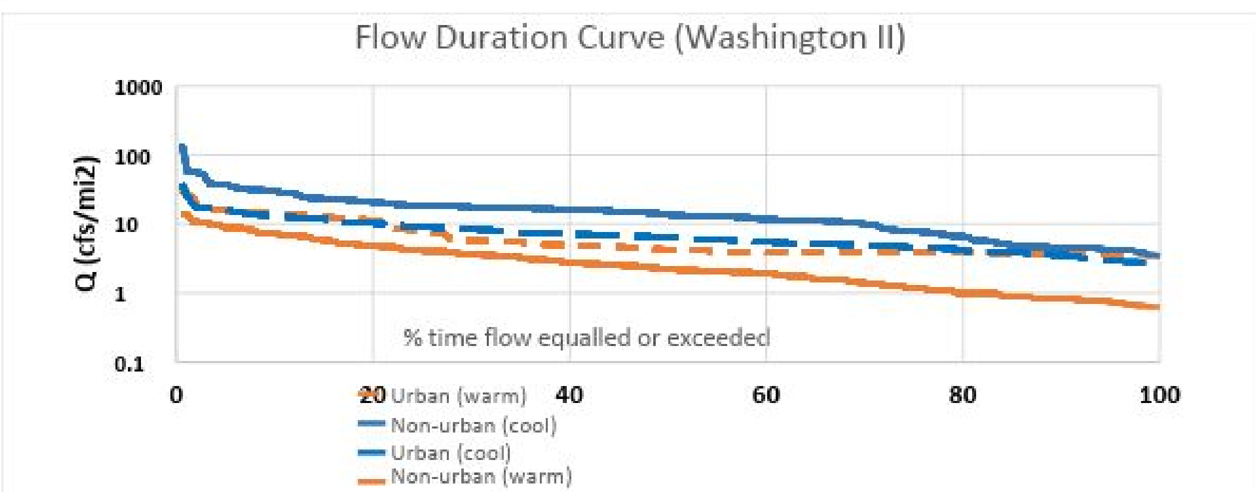
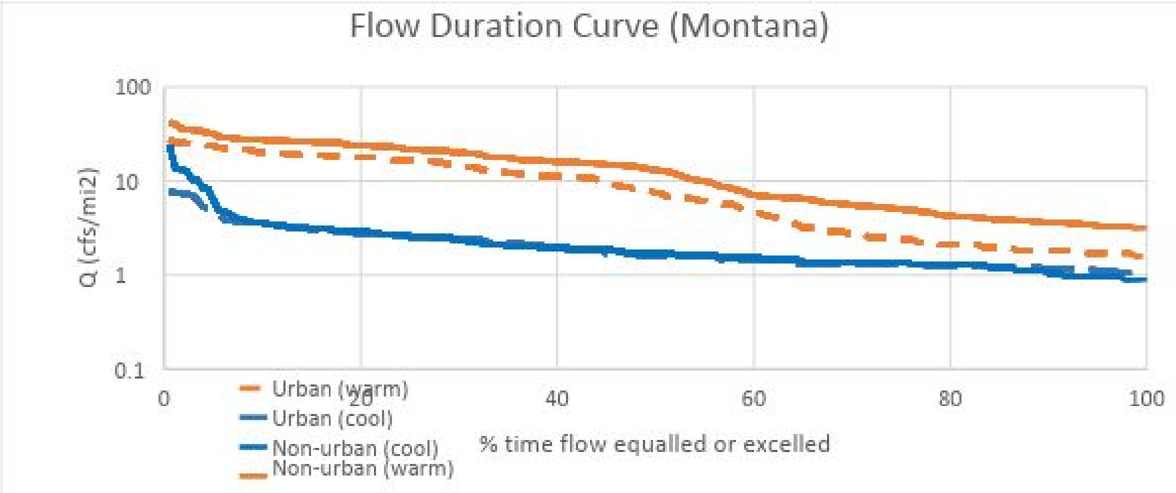
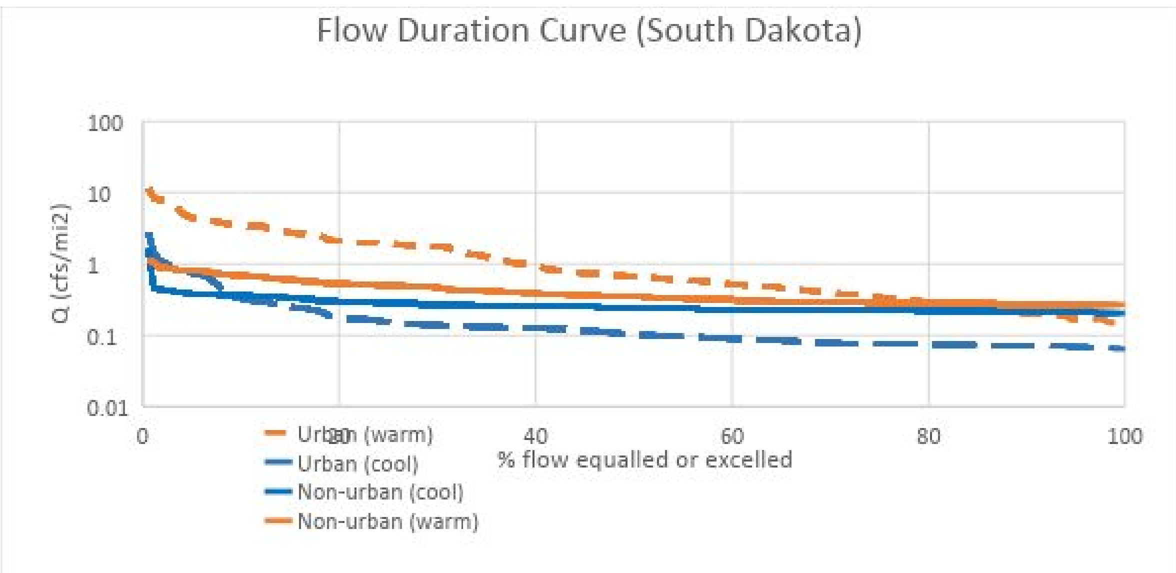
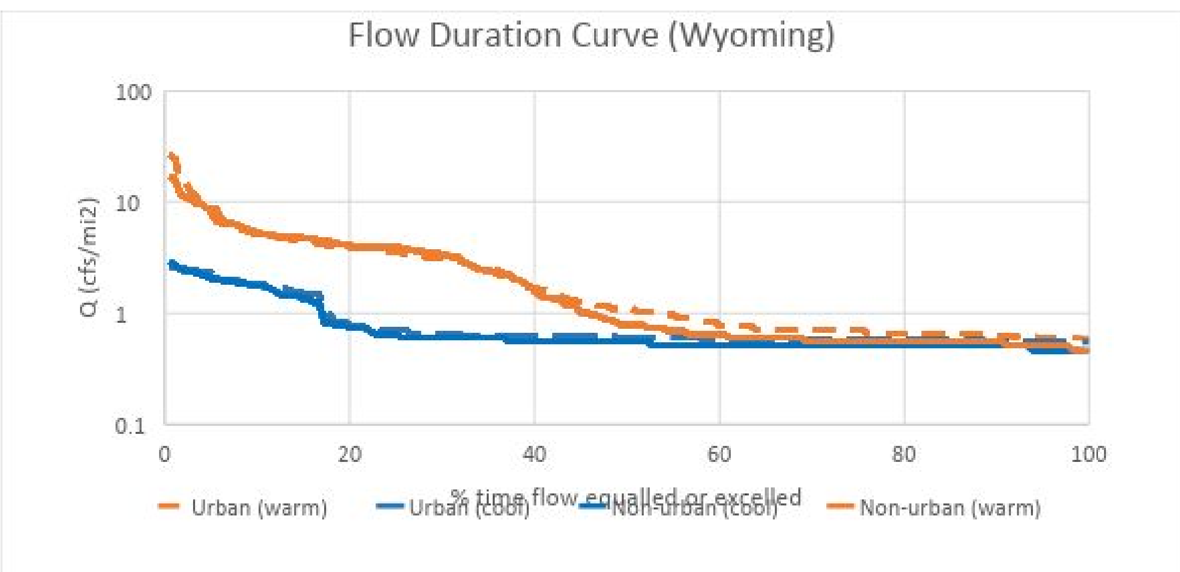


Figure 9a-b: Seasonally-separated flow duration curves for urban and non-urban paired streams in the winter-dominated precipitation region. Discharge is normalized (cfs/mi^2). The watersheds in the upper diagram have an impervious surface ratio of 1.73, the lower diagram of 3.00.


Flow Duration Curve (Montana)
Q (cfs/mi2)
100
10
1
0.1
0
20
40
60
80
100
% time flow equalled or excelled
Urban (warm)
Urban (cool)
Non-urban (cool)
Non-urban (warm)


Flow Duration Curve (South Dakota)
Q (cfs/mi2)
100
10
1
0.1
0.01
0
20
40
60
80
100
% flow equalled or excelled
Urban (warm)
Urban (cool)
Non-urban (cool)
Non-urban (warm)


Flow Duration Curve (Wyoming)
Q (cfs/mi2)
100
10
1
0.1
0
20
40
60
80
100
% time flow equalled or excelled
Urban (warm)
Urban (cool)
Non-urban (cool)
Non-urban (warm)

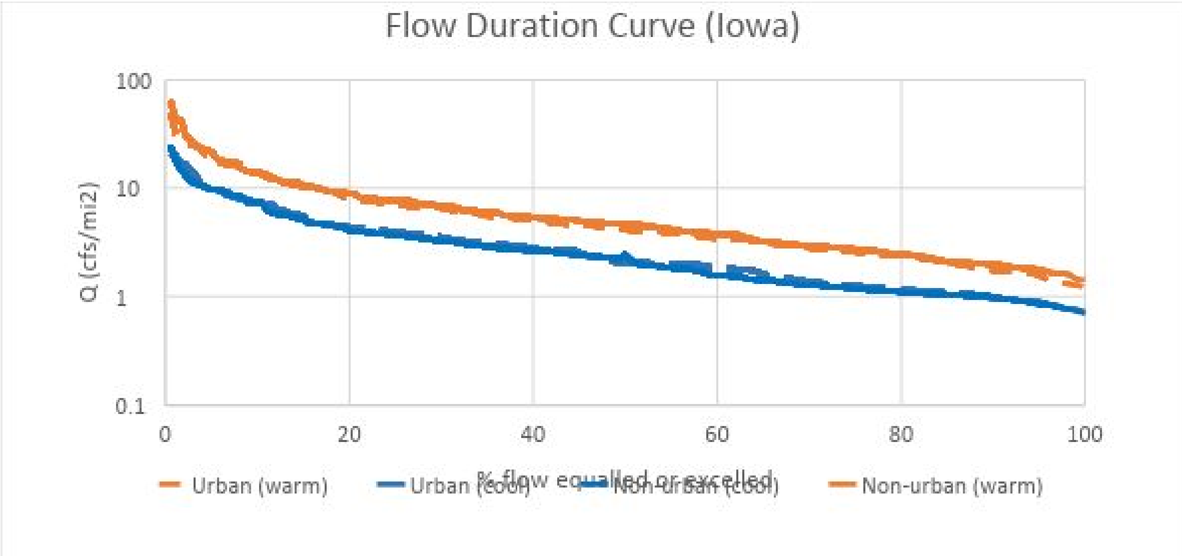
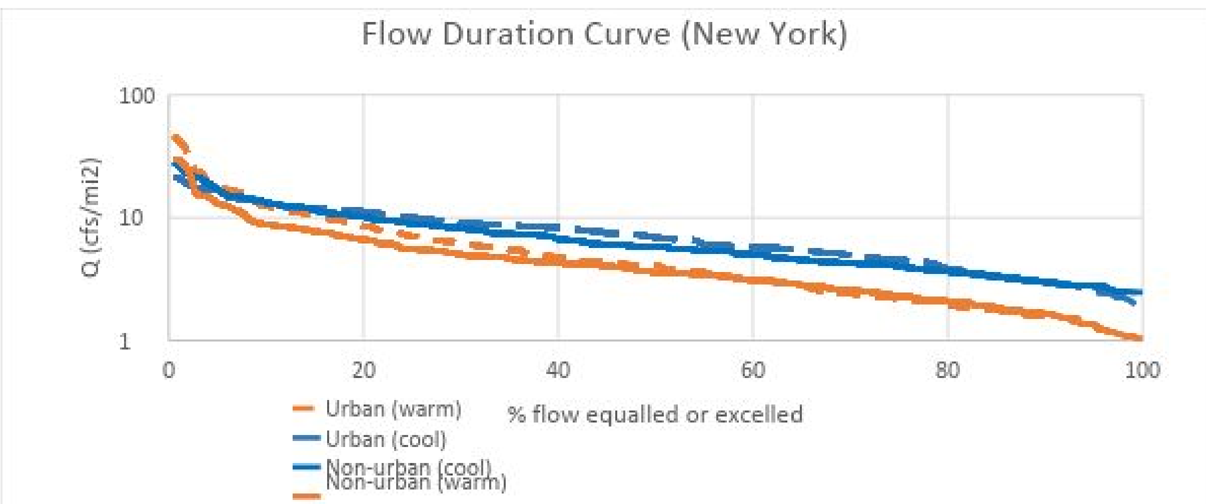
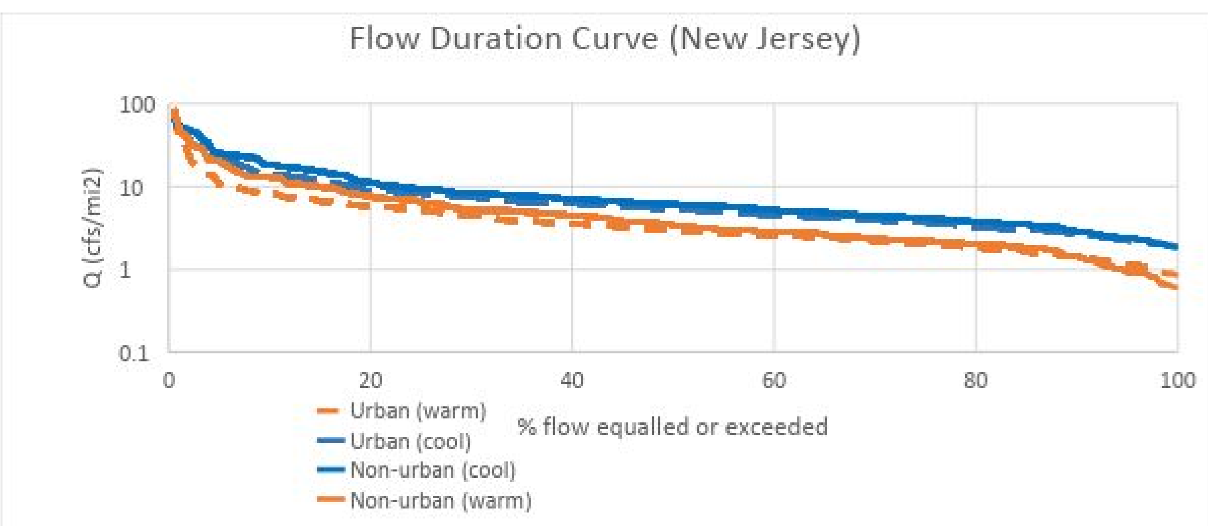
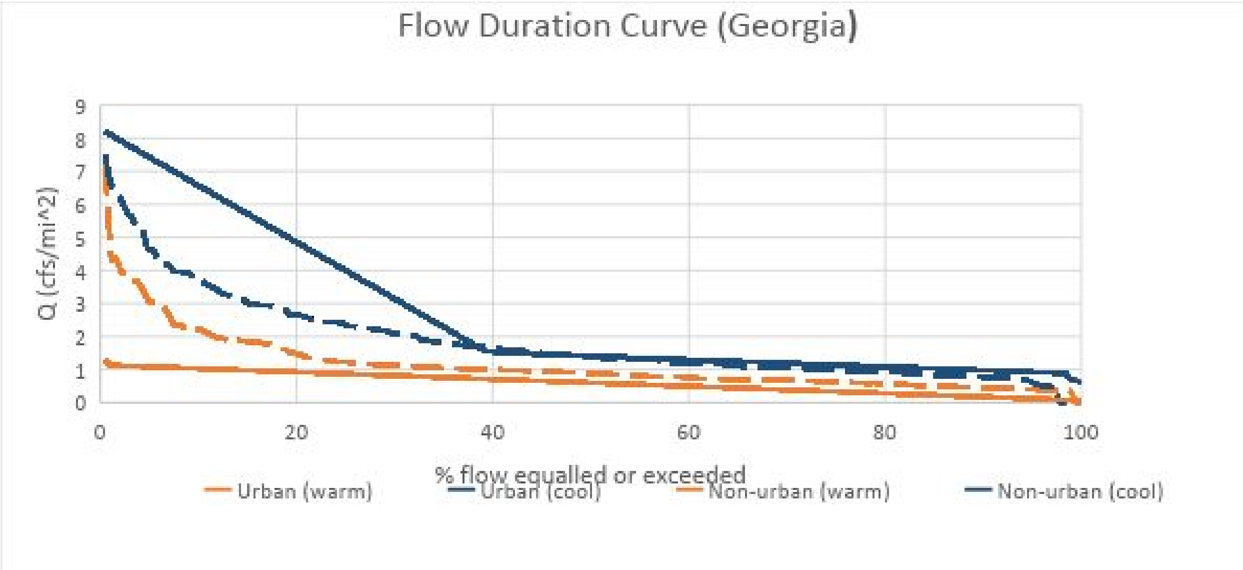


Figure 10a-10d: Seasonally separated flow duration analysis for regions with summer dominated precipitation and cold winters. This region also has the lowest MAP, and the lowest impervious surface ratio. The only stream pairs that show significant differences between the urban and non-urban runoff distribution are Montana and South Dakota pairs, which also have the highest impervious surface ratios.







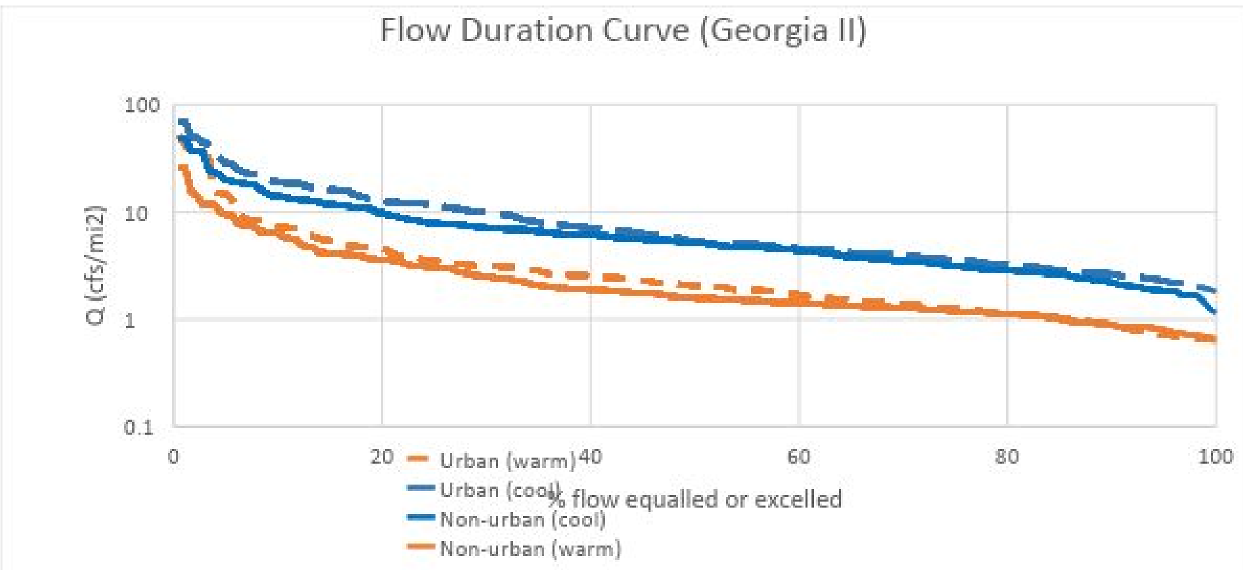


Figure 11a-11d: Seasonally separated flow duration analysis for regions with variable precipitation and temperature. This region has very warm summers and very cold winters. The impervious surface ratios range from 1.88 to 2.67.

The flow duration curves in the Pacific NW and Southeast depicted above show the urban stream has lower base flow in the cool months but higher base flow in the warm months. Overall, there is lower base flow in the warm months compared to the cool months as this region show a lower summer precipitation seasonality. In the Northeast region shown above, the urban stream has lower base flow in both warm and cool months. There is relatively lower variability in the warm and cool base flow but the warm base flow is lower. In the Upper Midwest region, the urban streams have lower base flow in both warm and cool seasons. However, the warm base flow is significantly higher than the cool base flow as the summer precipitation in this region is also significantly higher compared to the cool months.

Determination of Discharge Urbanization and Seasonality ratios for flow Quantiles

Below are the urbanization and seasonality ratios for all stream pairs in the 10th, 50th and 90th percentile. The 50th percentile is of most interest as it is the median of the flow which represents the base flow more accurately. For the urbanization ratios in the 50th percentile, the warm season has a higher ratio compared with the cool season. This indicates a possible trend in the decrease in ET for the non-urban stream compared to the urban stream during the warm season when more plants are being grown and water is being evaporated into the atmosphere due to less % impervious surface area. The following tables show the urbanization, seasonality and impervious cover ratios:

Flow Quantile **Urbanization ratios**				
Stream Pair	Season	10%	50%	90%
Washington I	Warm	0.17	0.18	0.58
	Cool	0.10	0.17	0.20
Washington II	Warm	1.97	2.01	4.51
	Cool	2.31	2.00	1.32
Georgia I	Warm	0.96	1.48	1.22
	Cool	1.06	0.98	1.72
Georgia II	Warm	1.13	1.29	0.96
	Cool	1.35	1.03	1.19
New York	Warm	1.42	1.18	1.42
	Cool	1.01	1.17	1.01
New Jersey	Warm	0.62	0.89	1.01
	Cool	0.75	0.86	0.91
Montana	Warm	0.74	0.56	0.51
	Cool	1.00	0.93	1.13
South Dakota	Warm	4.99	1.88	0.77
	Cool	0.89	0.43	0.33
Maryland	Warm	1.67	2.06	3.51
	Cool	1.43	1.10	0.84
Wyoming	Warm	1.02	1.41	1.14
	Cool	1.04	1.10	1.10
Iowa	Warm	1.03	0.88	0.88
	Cool	0.97	0.86	0.98

Table 4 : Urbanization ratios for the streams in the 10th, 50th, and 90th percentiles in the two seasons: warm and cool. The most important ratio for the base flow is the 50th percentile. In majority of the streams, the warm urbanization ratio is higher than the cool urbanization ratio.

For the seasonality ratios in the 50th percentile, the urban streams all show less seasonal variation compared to the non-urban streams.

Flow Quantile Seasonality ratios				
Stream pair	Stream Type	10%	50%	90%
Washington I	Urban	1.35	1.48	1.44
	Non-urban	2.21	1.57	4.25
Washington II	Urban	2.08	1.55	1.23
	Non-urban	1.77	3.04	4.2
Georgia I	Urban	1.69	1.55	1.73
	Non-urban	6.40	2.35	5.71
Georgia II	Urban	0.38	1.53	3.07
	Non-urban	0.45	3.24	2.48
New York	Urban	1.06	1.64	1.93
	Non-urban	1.49	1.65	1.80
New Jersey	Urban	0.58	1.74	1.81
	Non-urban	0.70	1.80	2.00
Montana	Urban	7.75	7.71	3.46
	Non-urban	5.74	4.67	1.75
South Dakota	Urban	0.09	0.15	0.35
	Non-urban	0.53	0.68	0.81
Maryland	Urban	0.74	1.07	1.64
	Non-urban	0.86	2.01	6.90
Wyoming	Urban	2.89	0.55	0.89
	Non-urban	2.95	0.71	0.92
Iowa	Urban	1.99	0.50	1.80
	Non-urban	1.89	0.70	1.99

Table 5: Seasonality ratios for the streams in the 10th, 50th, and 90th percentiles in the two stream types: Urban and non-urban. The most important ratio for the base flow is the 50th percentile

The table shows the impervious surface area ratio between the urban to the non-urban streams

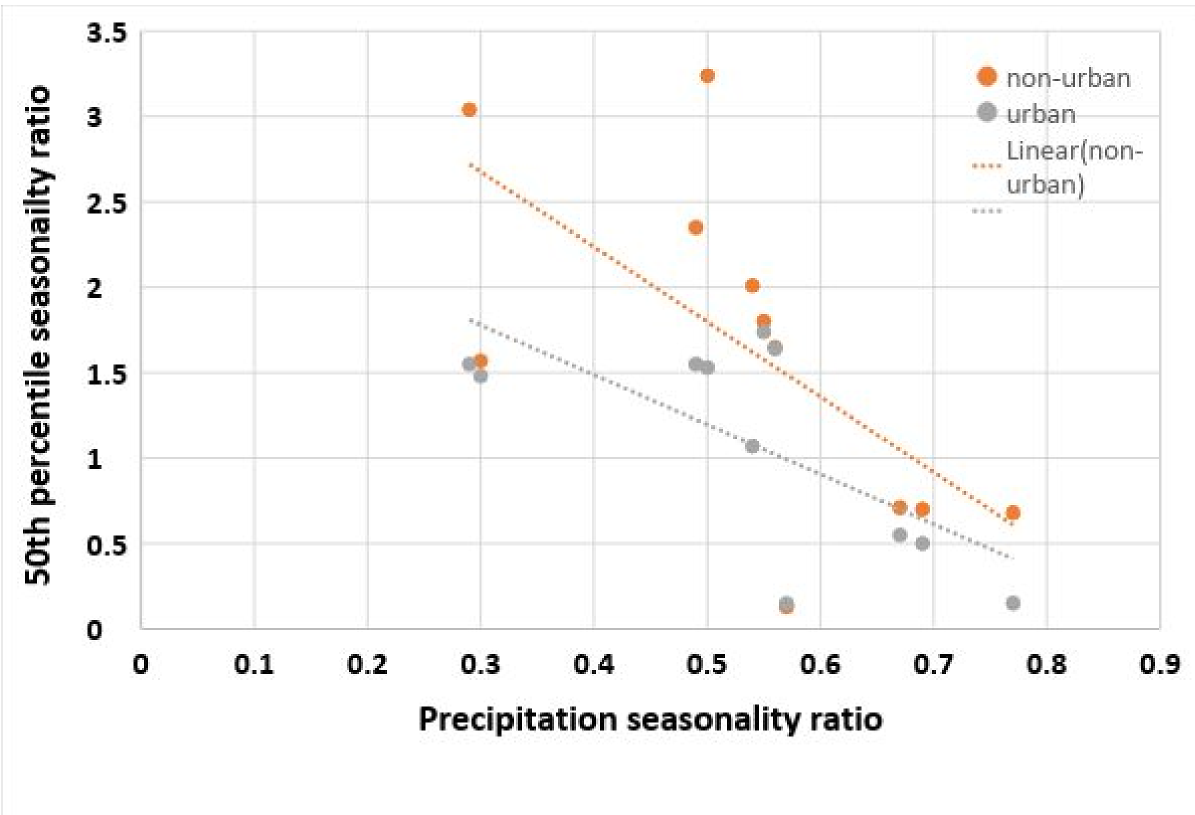
Stream pair	**Impervious surface area ratio**
Washington I	1.73
Washington II	2.67
Georgia I	2.17
Georgia II	2.50
New York	3.00
New Jersey	1.88
Montana	1.60
South Dakota	2.14
Maryland	3.83
Wyoming	2.11
Iowa	1.78

Table 6 : Impervious surface ratio for all stream pairs (Urban/non-urban).

ANOVA and Regression analyses of urbanization and seasonality effects on flow duration curves

Single factor Analysis of Variance was conducted on the discharge data for both urban and non-urban streams to test for the differences among the watershed types (urban and non-urban). The p-value from the ANOVA tests were all less than 0.05 leading to the conclusion that the data from the stream types are statistically different.

Linear regression analyses were conducted on the relationship between precipitation seasonality and flow duration curve seasonality (using the 10th, 50th, and 90th percentile seasonality ratios). Urban and non-urban streams were evaluated separately in this analysis. The linear regression analyses for the seasonality ratios is shown in fig. 12 below.



Figures 12: 50th percentile seasonality ratio vs precipitation seasonality ratio showing a negative linear trend.

The urbanization ratio is the ratio of urban Q to non-urban Q for the various flow quantiles (10%, 50%, and 90%). This was evaluated for both warm season and cool season discharge values and regressed against the impervious surface ratio values for each watershed pair. The analyses ere done for all the streams and also for the streams grouped by precipitation seasonality.

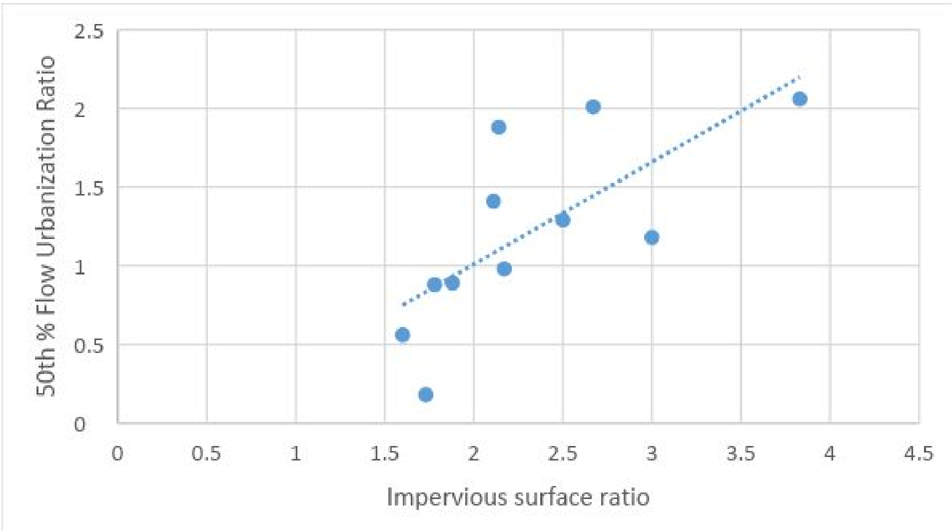
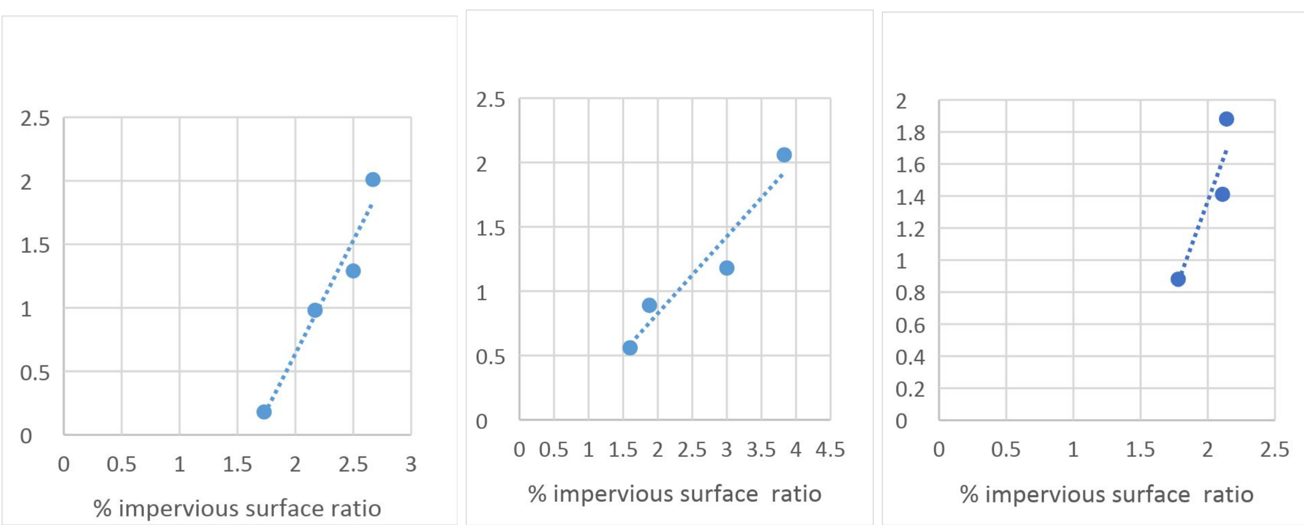


Figure 13: All warm season urbanization ratios (urban Q50/non-urban Q50) versus the impervious surface ratio for each watershed pair



Figures 13a-c: L-R- Warm season urbanization ratios versus the impervious surface ratio for streams separated by the precipitation seasonality index: <0.5 and streams around 0.5 and streams significantly above 0.5 precipitation seasonality. There is a stronger linear relationship between the variables when the streams are grouped by their various climatic characteristics

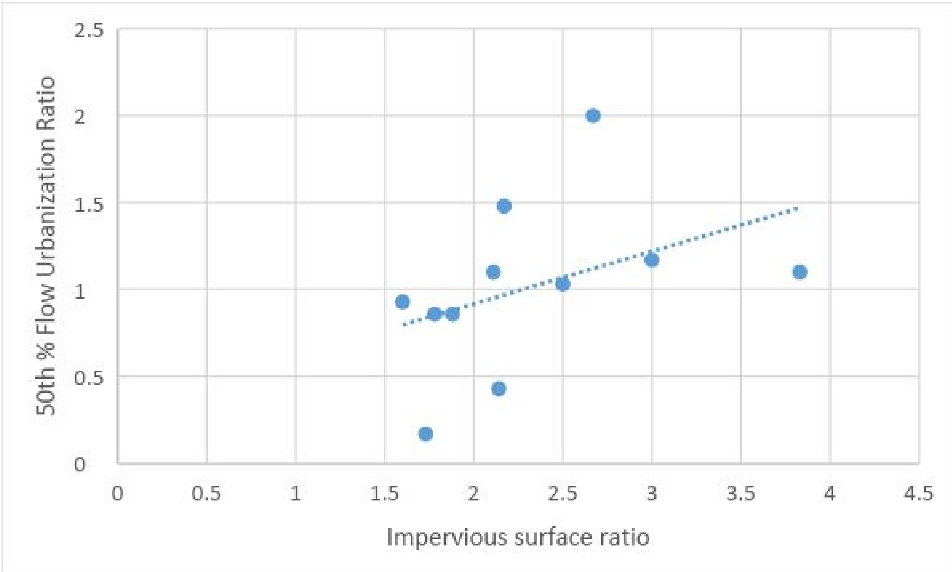
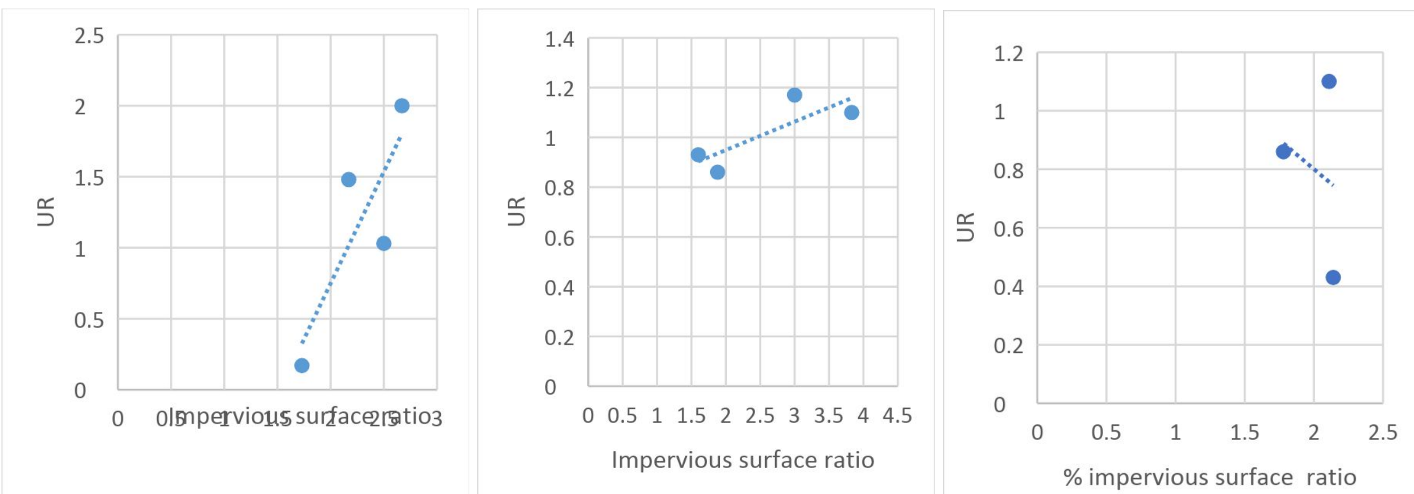


Figure 14: All cool season urbanization ratios (urban Q50/non-urban Q50) versus the impervious surface ratio for each watershed pair.



Figures 14a-c: L-R- Cool season urbanization ratios versus the impervious surface ratio for streams with precipitation seasonality less than 0.5, around 0.5 and significantly greater than 0.5. There is stronger linear relationship between the variables when they are separated into different climatic similarities except for the case where the summer precipitation is significantly higher.

Discussion

This study set out to understand and predict the flow processes of urban streams. Analyzing flow processes such as base flow and runoff in urban streams is important to understand how human activities and constructions can impact the watersheds around us and aid watershed management (Yao et al., 2016). Previous work showing this relationship have been done on smaller sized streams. I selected medium sized urban and non-urban streams in various hydro-climatic regions with distinct precipitation patterns to examine how urbanization affects watersheds. Streams from various geographic regions were grouped as distinct flow regimes based on their temperature and precipitation seasonality.

From the rainfall-runoff analyses, the urban streams consistently have higher runoff compared to the non-urban streams. Linear regressions showed significant linear relationship between the urbanization ratios and the % impervious surface ratio for the group of streams in their distinct flow regimes. In comparison, there was almost no linear relationship between these variables when the streams were analyzed together regardless of their geographic locations or flow regimes. The biggest factor that is shown to predict a linear trend is the precipitation pattern (% summer precipitation / total precipitation). Streams in the same geographic region but with significantly different precipitation seasonality show no or almost no relationship.

Evapotranspiration in the growing season seems to have a significant effect in most of the streams selected especially in regions with lower summer precipitation or little variation between summer and winter precipitation. Overall, the seasonality ratio in the urban case is lower while the urbanization ratio is consistently higher in the warm season compared to the cool season indicating less output (decreased ET) in the non-urban streams during the warm months.

Conclusion

Past studies have shown the effect of urbanization on the runoff and flow on some small streams. Urbanization decreases the base flow and increases the runoff of the small streams compared to non-urban streams (e.g. Leopold, 1968). This suggests changes in the temporal distribution in discharges during the year, but not necessarily changes in the water balance. Modifications of the water balance could affect bot the amount of runoff and the temporal distribution of runoff. In particular, evapotranspiration may decrease in urban watersheds, which may enhance warm season base flow discharge. In this study, I compared the runoff and discharge of various streams in a paired watershed approach to analyze the flow processes in 4 major regions (Pacific NW, Southeast, Northeast, and Upper Midwest) with different hydro-climatic characteristics. I used a seasonal separation of daily discharge values to evaluate the differences in the base flow in the flow duration curves, followed by extracting urbanization and seasonality ratios to evaluate and compare the interaction between the impervious cover area and the flow processes analyzed for each stream pair.

The following were observed:

1. The flow duration curve urbanization ratio (UR) for 50th percentile are consistently higher in the warm UR compared to the cool UR. This shows a decrease in water output (Evapotranspiration) in the streams during the warm season in the urban streams.
2. The flow duration curve seasonality ratio (SR) for the median flow are consistently lower in the urban SR compared to the non-urban SR. This shows that the urban streams have lower variability in the warm and cool seasons compared to the non-urban stream. The urban stream has more impervious cover and therefore, less ET going out during the summer as stated in the hypotheses.

3. All urban streams have significantly greater runoff (compared to the rainfall as shown in the runoff-rainfall relationships) than the non-urban streams. The urban streams have higher impervious surfaces and were therefore expected to have higher runoff.
4. There is some linear relationship between the urbanization ratios and the impervious cover ratio. The urbanization ratio tends to increase with increasing impervious cover ratio especially when the streams are grouped into more similar precipitation seasonality. This relationship is more evident in the warm season compared to the cool season.
5. Regions with significantly high summer precipitation seasonality have higher warm season base flow on the flow duration curves (e.g. South Dakota, Iowa)
6. The stream base flow in the urban streams have lower seasonal variation due to decreased evapotranspiration as stated in the hypotheses (Except Montana).

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Appendix I – precipitation data

Washington climate data

Date	Precipitation (cm)	Mean temperature (°C)			
January	48.157	0.8	4.8157	-1.8	3.4
February	32.686	1.7	3.2686	-1.9	5.3
March	35.852	3.5	3.5852	-0.7	7.7
April	24.972	5.9	2.4972	0.9	11
May	21.422	9.1	2.1422	3.8	14.3
June	14.465	12	1.4465	6.8	17.2
July	7.77	15.2	0.777	9.5	21
August	7.021	15.5	0.7021	9.8	21.3
September	16.929	12.8	1.6929	7.3	18.2
October	34.777	7.9	3.4777	3.5	12.2
November	58.124	2.9	5.8124	0.2	5.7
December	40.599	0.3	4.0599	-2.2	2.8

Georgia climate data

Date	Precipitation (mm)	Mean temperature (°C)	Precipitation (cm)	Minimum T	Maximum T
January	11.368	5.6	1.1368	-0.1	11.2
February	12.141	7.6	1.2141	1.6	13.6
March	12.407	11.6	1.2407	5.2	18.1
April	9.065	15.8	0.9065	9.2	22.5
May	10.073	20.4	1.0073	14.5	26.4
June	11	24.6	1.1	19.1	30
July	13.874	26.2	1.3874	20.9	31.6
August	10.345	25.8	1.0345	20.5	31.1

September	10.732	22.5	1.0732	16.9	28.1
October	9.064	16.7	0.9064	10.5	22.9
November	10.439	11.5	1.0439	5.2	17.8
December	10.449	6.9	1.0449	1.4	12.5
Annual	1309.57	16.3			

New York climate data

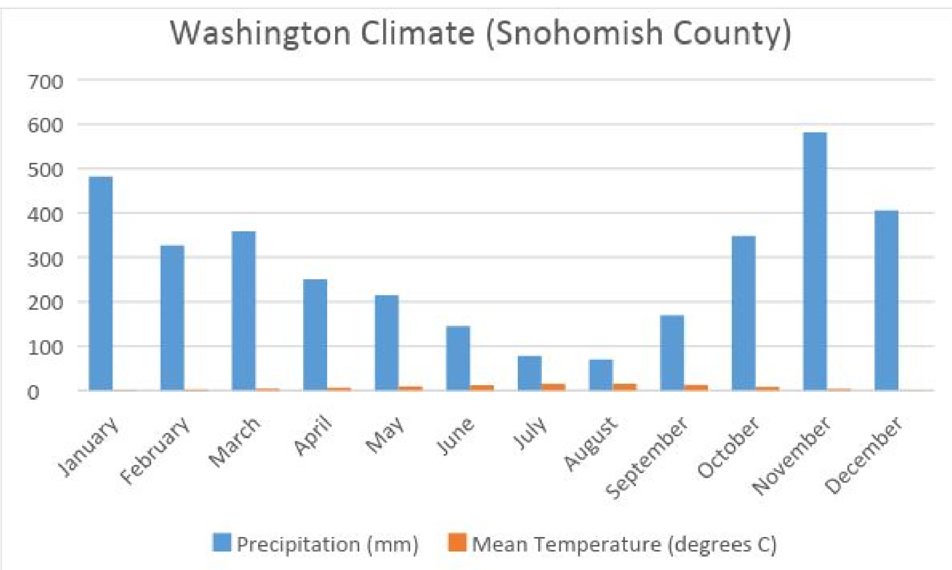
Date	Precipitation (mm)	Mean temperature (°C)	Precipitation (cm)	Min Temp	Max Temp
January	7.523	-6.2	0.7523	-11.7	-0.7
February	6.167	-4.8	0.6167	-10.6	1.1
March	8.423	-0.3	0.8423	-6.4	5.8
April	9.53	6.3	0.953	-0.3	12.8
May	11.01	12	1.101	4.7	19.2
June	11.42	16.9	1.142	10.1	23.7
July	10.86	19.2	1.086	12.4	26.1
August	9.681	18.6	0.9681	11.9	25.3
September	11.201	14.6	1.1201	7.9	21.3
October	10.387	8.5	1.0387	2	14.9
November	9.778	2.9	0.9778	-2.1	8
December	8.49	-3.1	0.849	-7.9	1.6
Annual	1144.7	7.1			

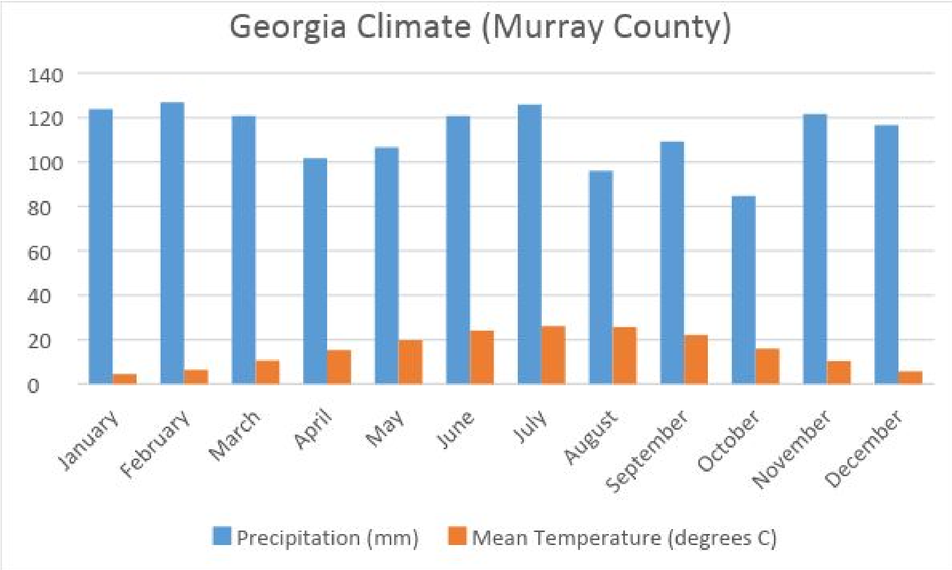
South Dakota climate data

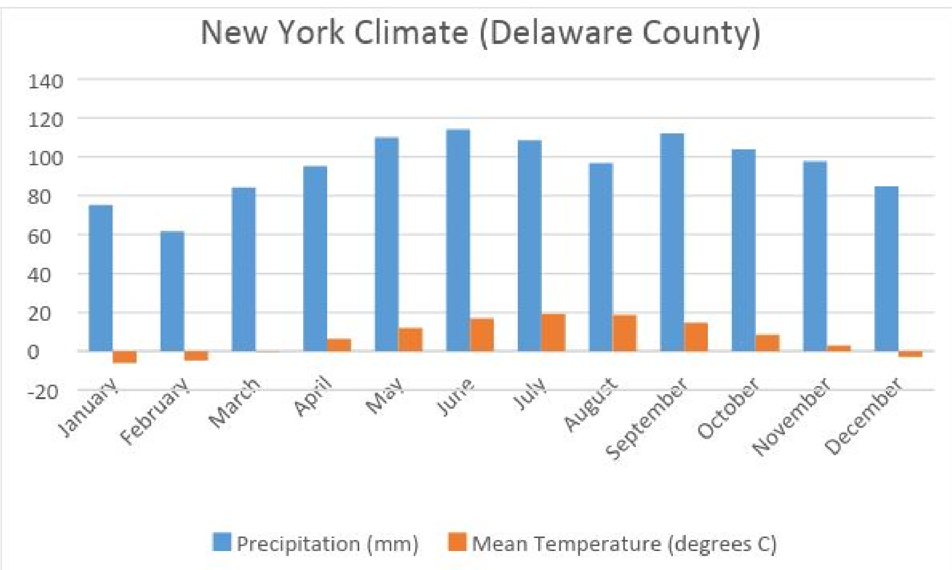
Date	Precipitation (cm)	Mean temperature (°C)	tmax (degrees C)	tmin (degrees C)	ppt (mm)
January	0.564	-4.2	2.2	-10.5	5.64
February	0.841	-2.5	3.8	-8.9	8.41
March	1.974	1.7	8.4	-5	19.74

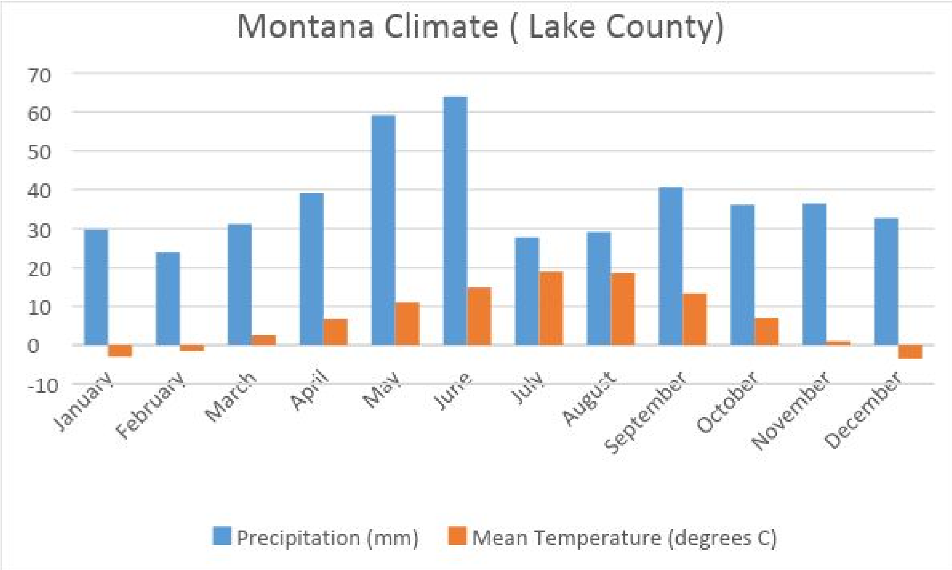
April	4.132	7.4	14.4	0.4	41.32
May	8.329	13	19.7	6.2	83.29
June	6.47	18.5	25.3	11.6	64.7
July	4.967	22.9	30.4	15.4	49.67
August	4.34	22.4	30.2	14.5	43.4
September	3.136	16.4	24.2	8.6	31.36
October	3.279	9.2	16.3	2	32.79
November	1.126	1.8	8.3	-4.7	11.26
December	0.614	-3.7	2.4	-9.9	6.14
Annual		8.6	15.5	1.7	397.72

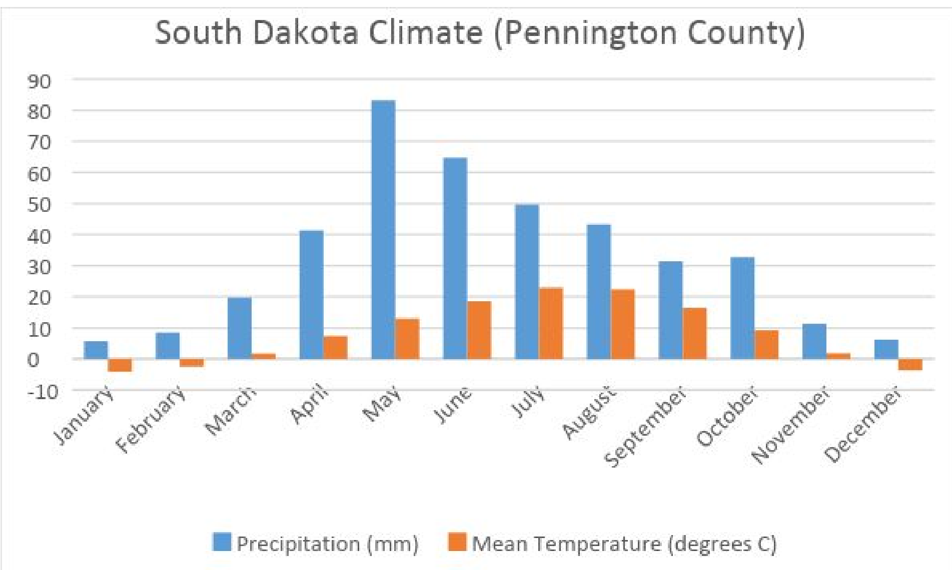
Monthly Precipitation Data:

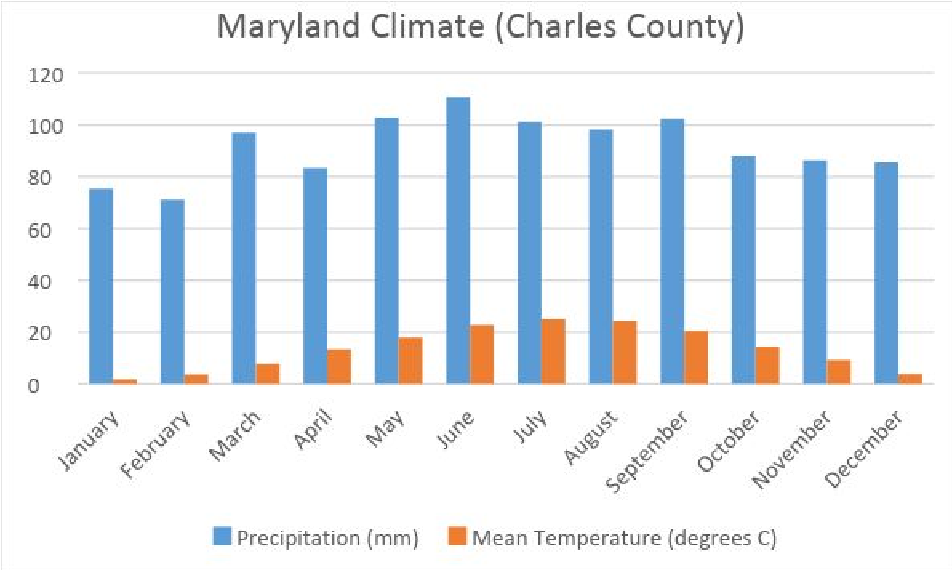


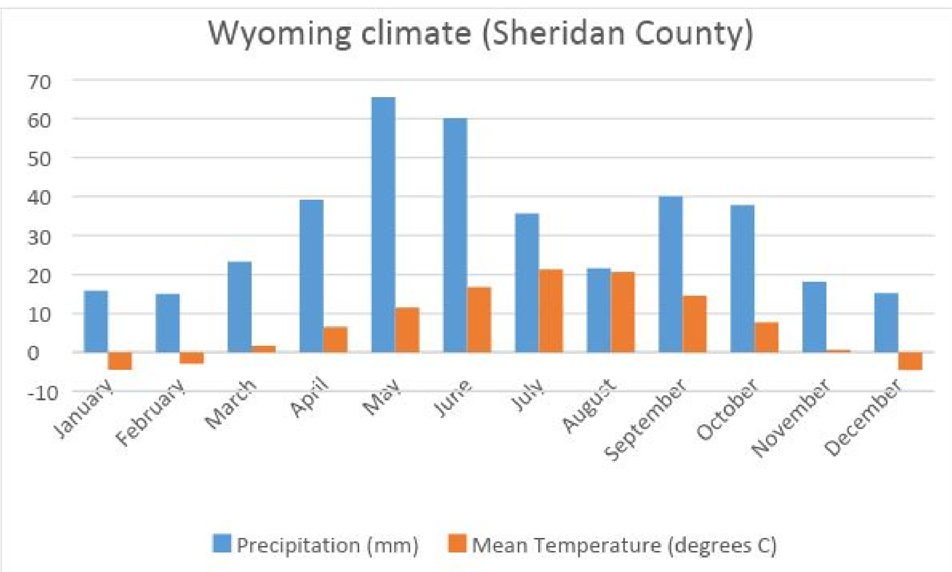

Georgia Climate (Murray County)
140
120
100
80
60
40
20
0
January
February
March
April
May
June
July
August
September
October
November
December
Precipitation (mm)
Mean Temperature (degrees C)


New York Climate (Delaware County)
140
120
100
80
60
40
20
0
-20
January
February
March
April
May
June
July
August
September
October
November
December
Precipitation (mm)
Mean Temperature (degrees C)

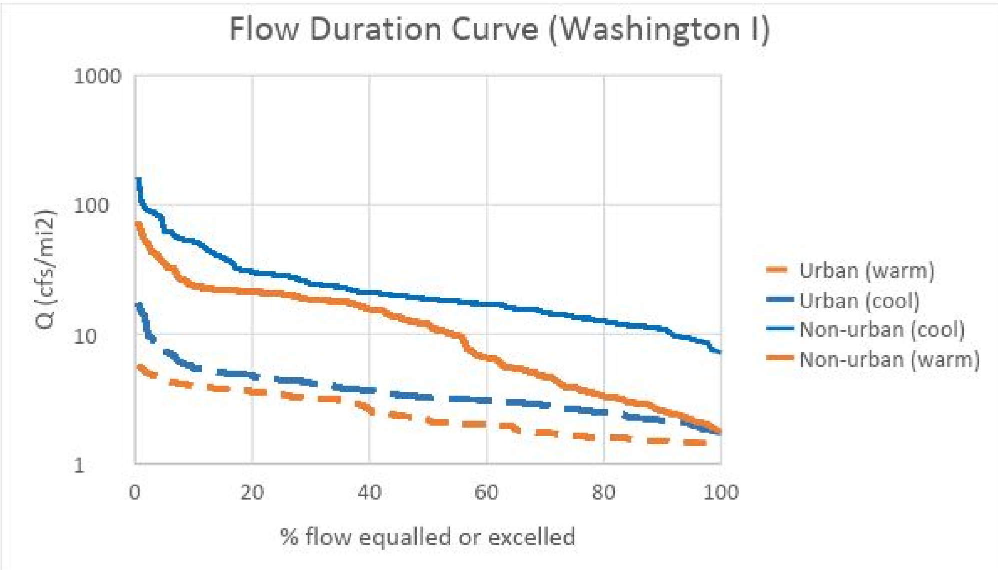

Montana Climate (Lake County)
70
60
50
40
30
20
10
0
-10
January
February
March
April
May
June
July
August
September
October
November
December
Precipitation (mm)
Mean Temperature (degrees C)

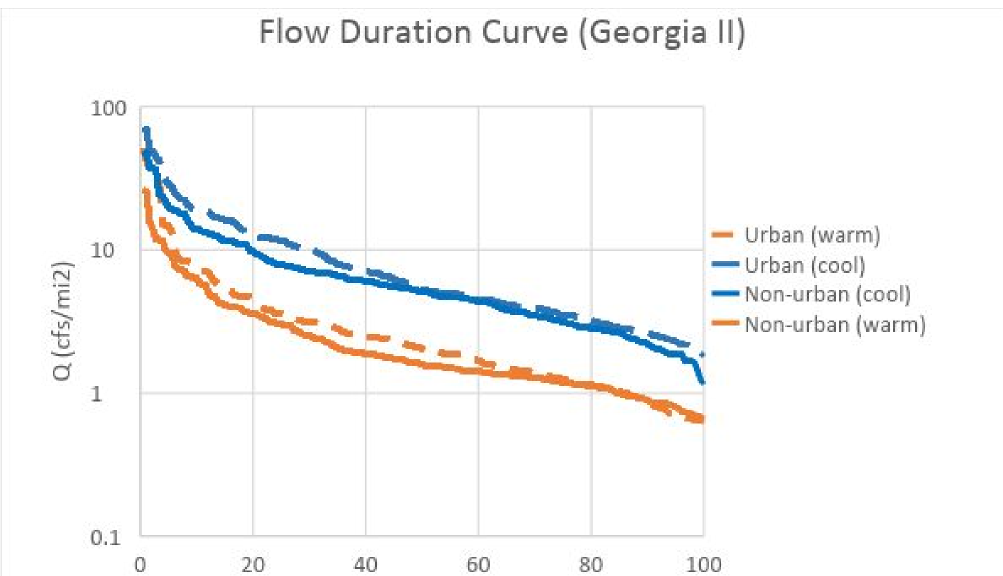

South Dakota Climate (Pennington County)
90
80
70
60
50
40
30
20
10
0
-10
January
February
March
April
May
June
July
August
September
October
November
December
Precipitation (mm)
Mean Temperature (degrees C)

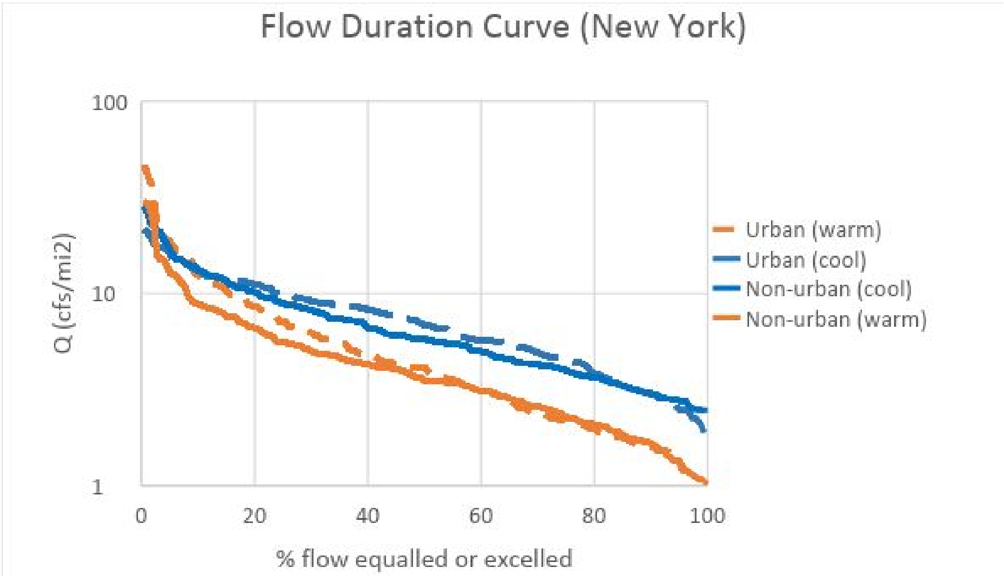

Maryland Climate (Charles County)
120
100
80
60
40
20
0
January
February
March
April
May
June
July
August
September
October
November
December
Precipitation (mm)
Mean Temperature (degrees C)

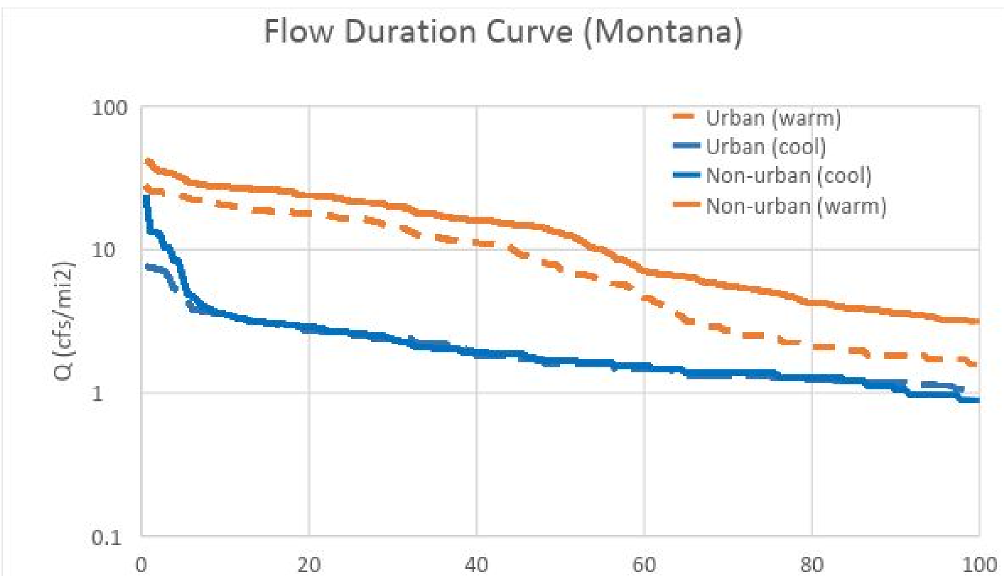

Wyoming climate (Sheridan County)
70
60
50
40
30
20
10
0
-10
January
February
March
April
May
June
July
August
September
October
November
December
Precipitation (mm)
Mean Temperature (degrees C)

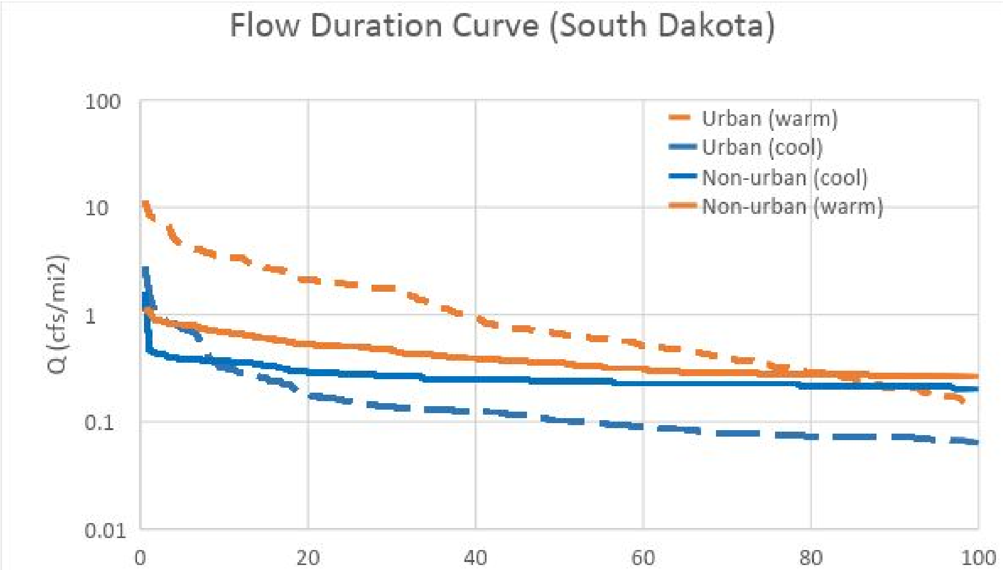
Appendix II – Base flow data

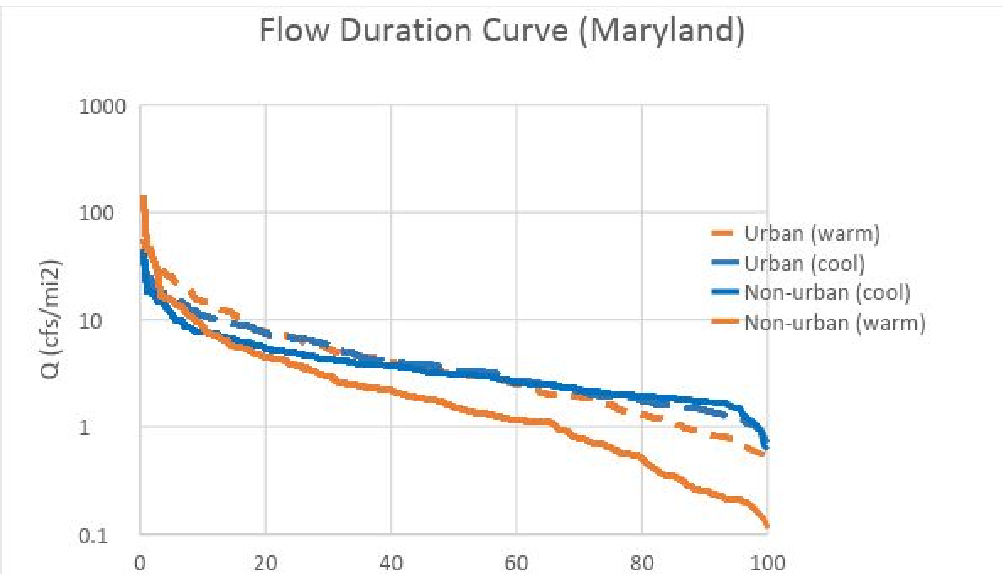


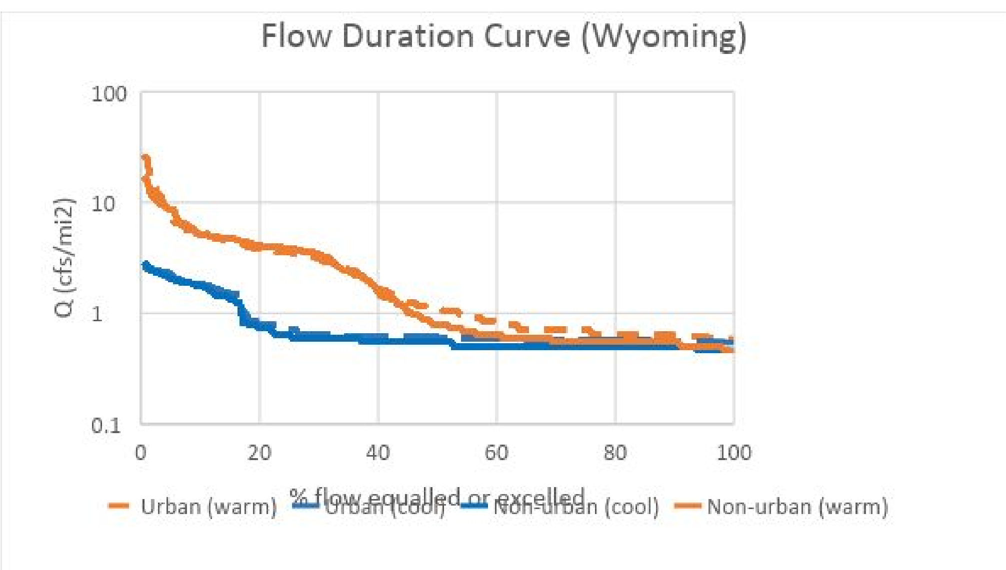



Flow Duration Curve (New York)
100
10
1
Q (cfs/mi2)
0
20
40
60
80
100
% flow equalled or excelled
Urban (warm)
Urban (cool)
Non-urban (cool)
Non-urban (warm)


Flow Duration Curve (Montana)
100
10
1
0.1
Q (cfs/mi2)
0
20
40
60
80
100
Urban (warm)
Urban (cool)
Non-urban (cool)
Non-urban (warm)


Flow Duration Curve (South Dakota)
Q (cfs/mi2)
100
10
1
0.1
0.01
0
20
40
60
80
100
Urban (warm)
Urban (cool)
Non-urban (cool)
Non-urban (warm)


Flow Duration Curve (Maryland)
Q (cfs/mi2)
1000
100
10
1
0.1
0
20
40
60
80
100
Urban (warm)
Urban (cool)
Non-urban (cool)
Non-urban (warm)


Flow Duration Curve (Wyoming)
Q (cfs/mi2)
100
10
1
0.1
0
20
40
60
80
100
% flow equalled or excelled
Urban (warm)
Non-urban (cool)
Non-urban (warm)

Appendix III – Runoff data

Annual Rainfall (mm)	Average Annual Runoff (mm)	State
1228.8	403.77	New York
1228.8	348.71	New York
1459.89	629.49	Georgia
1459.89	600.01	Georgia
439.94	67.85	South Dakota
439.94	67.79	South Dakota
1824.7	503.64	Washington
1824.7	123.71	Washington
1419.21	549.52	Georgia
1419.21	464.81	Georgia
495.95	178.29	Montana
495.95	154.54	Montana
1238.56	176.49	New Jersey
1238.56	132.43	New Jersey
1173.5	507.72	Maryland
1173.5	431.96	Maryland
432.97	93.53	Wyoming
432.97	73.63	Wyoming
995.5	588.86	Iowa
995.5	396.88	Iowa

Appendix IV – ANOVA
Washington

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	837.7012	179	4.679895	5.569804	8.4E-28	1.279589
Columns	144.2355	1	144.2355	171.6628	6.17E-28	3.893934
Error	150.4005	179	0.840226			
Total	1132.337	359				

Georgia

SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	181	103649	572.6464	197291.6		
Column 2	184	63501	345.1141	179746.8		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4723779	1	4723779	25.06692	8.66E-07	3.867203
Within Groups	68406150	363	188446.7			
Total	73129929	364				

UR vs Impervious cover ratio (warm):

SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	11	25.41	2.31	0.4347		
Column 2	11	13.32	1.210909	0.360629		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6.644005	1	6.644005	16.70756	0.000573	4.351244
Within Groups	7.953291	20	0.397665			
Total	14.5973	21				

UR vs Impervious cover area (cool):

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	11	25.41	2.31	0.4347		
Column 2	11	11.13	1.011818	0.233656		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*

Between Groups	9.269018	1	9.269018	27.73675	3.74E-05	4.351244
Within Groups	6.683564	20	0.334178			
Total	15.95258	21				