Urban and Non-Urban Stream Channel Dynamics and Morphology for Chesapeake Bay Tributaries

The Influence of Urbanization on the Velocity of Water in the Channel Component of Lag Time

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ABSTRACT

For millions of years the power of water has shaped some of the most famous features found on continents throughout the world. The Grand Canyon in the state of Arizona is one example of how water has shaped the identity of the United States. As people migrated to the United States population centers grew along the country's first highway of waterways.. Today water is a finite resource and increasing threat with drought, rising sea levels, flooding, and powerful hurricanes capable of producing higher storm surges for longer durations. Designing a future that leaves enough water to use as a resource while also providing safe management of river flow in population centers is an Anthropogenic challenge facing engineers, hydrologists, environmental scientists, and geologists. Channelization and urbanization affect the peak discharges and peak velocities of streams. Urbanization and channelization both increase peak discharges and peak velocities. The research work of Arnold and Gibbons (Arnold and Gibbons, 1996) raised awareness for integrating impervious cover into community goals, policies, and regulations. The common practices to managing excess runoff from impervious surfaces included directing or draining water off these impermeable surfaces as quickly and efficiently as possible (Arnold & Gibbons, 1996). Examples of these storm water management practices can be observed in many local tributaries within the Baltimore Washington metropolitan area. The channelization of the stream channel may have more effect on peak discharge and velocity for the larger storms. In this study lag times for both urban and non-urban watersheds have been measured using rise time from hydrographs created using United States Geological Survey real time stream gauging data. Storms of different magnitude and duration were investigated on streams with similar basin areas with differences in the amount of urbanization. In this research study lag time for urban and non-urban stream drainage basins were analyzed utilizing real time water data for a nation United States Geological Survey website. Sixteen research sites in the Chesapeake Bay Watershed in Maryland, Virginia, and Washington DC were identified for analysis. These sites are found in the coastal plain and piedmont provenance of Maryland. This research area provides a location that is developed and has many stream gage locations monitored by the United States Geological Survey USGS. Nine of the research sites are in urban watersheds and seven of the research sites are in non-urban watersheds. The research study duration was March 2019 through December 2019. During this time five storm events were chosen for analysis with three storm events normalized. The amount of urbanization is defined in this study as the percent of impervious cover in the watershed. (Leopold, 1991) showed that the degree of development or sewerage is a measure of the degree of urbanization in the watershed. Results from the study support that the storms with longer duration and more precipitation have a similar lag time but greater volume and discharge when comparing the size of the drainage basin area with amount of urbanization.

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INTRODUCTION

STATEMENT OF THE PROBLEM

Water is a finite resource and increasing threat with environmental changes drought, rising sea levels, flooding, and frequent powerful storms. Rivers erode and deposit sediment as they shape the landscape over time. In the study of the Earth's physical surface features and relationship to geologic structures, landforms created through the interaction of surface processes with river hydrologic processes are of engineering and geoscientific significance when it comes to controlling river processes for water resource and flood management practices. Understanding hydrological river processes that contribute to floodplain and channel formation is important to protecting the environment while also ensuring the large amount of people living in the floodplain of major rivers are protected from flooding during storm events.

Rivers and streams have the power to transform the drainage basins they flow through. For millions of years vast canyons, hillslopes, and other geologic features have constantly experienced erosion and deposition from flowing water traveling to the ocean in the hydrologic cycle. The drainage basin is defined as the amount of area that contributes to the flow of a stream or river. The volume of water required to produce this flow comes from precipitation falling in the stream drainage basin. Precipitation that falls in a drainage basin with more permeable surface features will experience infiltration into the subsurface. Once the precipitation reaches the subsurface, the water becomes groundwater that travels to the stream channel underground. However, precipitation that falls in a drainage basin with more impervious surface features will not be able to distribute the travel time of total precipitation in the drainage basin between the slower groundwater flow and faster overland surface flow.

The travel time of water produced during individual storm events that collects and can't reach the subsurface is known as overland surface flow. Overland flow further decreases travel time when a storm sewer connects directly to a stream. The impervious surface on the bottom of the storm sewer prevents infiltration while also increasing the velocity of the water moving towards the channel. The increase in velocity and direct route to the stream channel contributes to the decrease in travel time to the channel. The amount of storm sewers and the percentage of drainage basin area impervious provide two quantifiable characteristics commonly used in research studies to define urban and non-urban streams. No perfect criterion exists for defining urban or non-urban streams but comparing the amount of channelization and impervious surface cover in the drainage basin is one way to quantify drainage basins as urban or non-urban taking into effect the influence impervious surface has on the travel time component of the velocity equation. The overland travel time to the stream channel is one parameter to consider when researching the influence of urbanization in a watered. The amount of the basin area urbanized was used in this research study to characterize the streams as urban or non-urban.

Figure 1 shows three different relationships between basin area and lag time that influences travel time. The black line on the top is a natural non-urban unaltered single channel stream system. This type of stream system I would expect to experience the highest rise time and

lowest velocity or stream travel time. Below the non-urban unaltered single channel stream system is the hypothesized urban stream system (red) with unaltered stream channels.
The urban stream system that hasn't been channelized would be influenced by an increase in impervious cover in the watershed decreasing the travel time to the stream channel but inside the stream channel I don't expect to see the high stream travel time values expected in the third and final case of the urban single channel channelized stream system. This stream system would be called flashy as the rise time will be short and velocity fast in the channel. There will not be as much time for storage of rainfall excess from the storm events causing the responses leaving these stream systems the most influenced by urbanization.

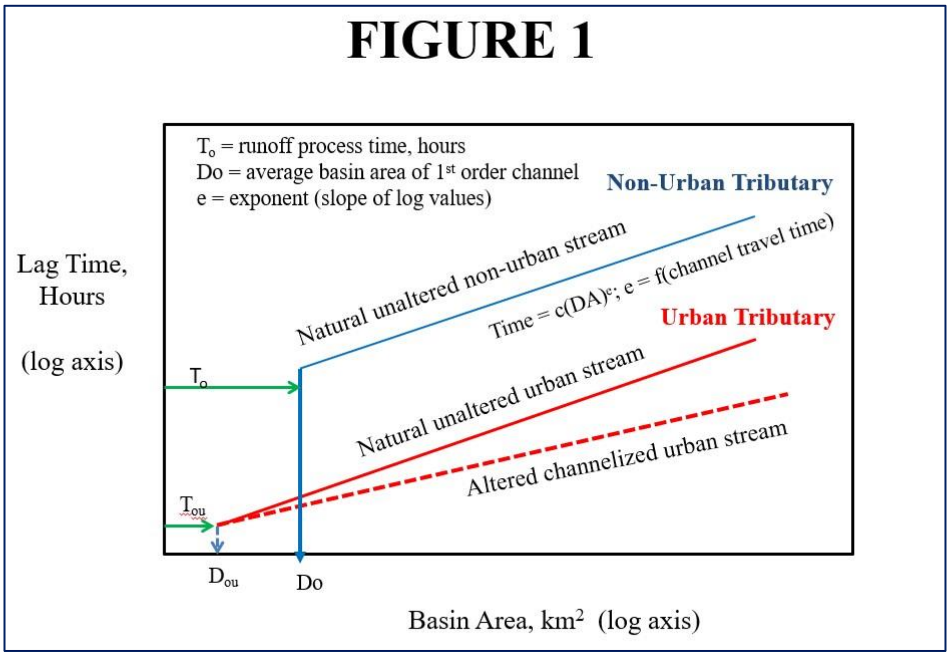


Figure 1: The projected lag time versus basin area response to urbanization in the Chesapeake Bay drainage basin.

Another way to characterize a stream as urban or non-urban is to monitor the response a stream provides for an individual storm event. The response to an individual storm event in a non-urban and urban stream can be quantified through measuring discharge versus elapsed time. An example of a response is pictured in figure 2. During a storm event total precipitation in inches is recorded at a precipitation gage located close to the stream gage. The time it takes for the water that falls as precipitation to flow past the stream gage is known as lag time.

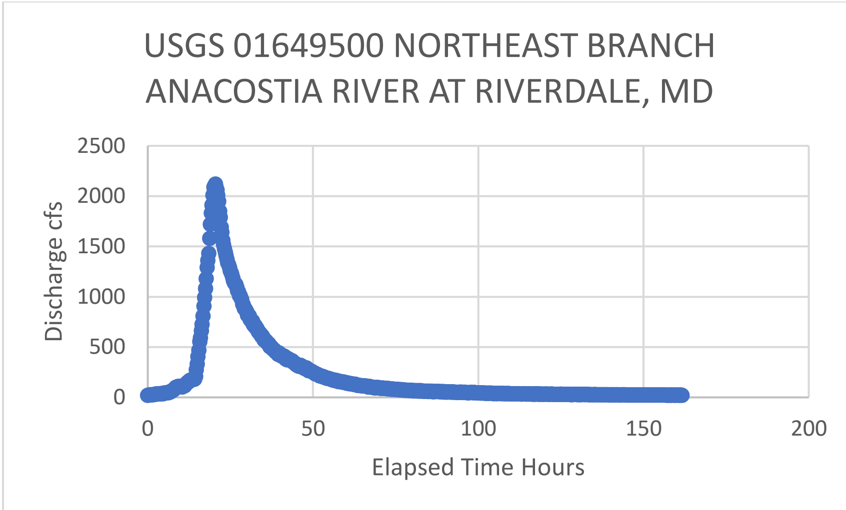


Figure 2: A response to a storm event is when a sudden rise in discharge from baseflow to a peak flow occurs in response to an amount of precipitation falling in a stream drainage basin. hydrograph is a tool for analyzing the relationship between parameters that characterize the response to the storm event.

Figure 2 is also A characteristic hydrograph that includes different parts. The first part includes the steep climb from baseflow to the peak flow. The steepness of this curve is a representative of the time it takes for the discharge to rise from baseflow to peak flow. For the purpose of this research study the elapsed time to reach the peak flow from baseflow is known as time to peak, or ttp. Time to peak is measured in hours. Lag time is another name commonly used for time to peak; however, lag time has different meanings depending on the application during the research study.

Peak discharge, or Q peak, is measured in cubic feet per second. The parameter Q peak is measured from the hydrograph by reading the peak value form the y axis at the hydrograph's apex. At this point on the hydrograph the time to peak in hours can also be recorded.

The problem isn't that runoff to the channel isn't important when measuring the response to an individual storm event. Channelization and urbanization both affect peak discharge and peak velocities, but the effect of channelization may have a more significant effect on larger storms.

BACKGROUND

Rivers provide a source of transportation, drinking water, and recreational benefit for much of the population living among them. However, they are also dangerous when their flow velocity and height rapidly changes due to natural and anthropogenic changes to their environments. Anthropogenic changes include alterations to the channel, width, depth, and floodplain that influence the natural hydrology of the stream. Baseflow conditions are the stream conditions before there is a sudden rise or decrease in discharge followed by a return to previous condition. Baseflow contributes to the stream flow as the shallow subsurface flow not to be mistaken for groundwater. For the purpose of this research study baseflow was the flow in the stream between individual storm events.

Water continuously moves below the surface, above the surface, and in the atmosphere of the Earth through the hydrologic cycle. Evaporation, transpiration, precipitation, condensation and runoff are influential processes for the continuous movement of water cycling through the Earth's water storage reservoirs. These reservoirs include bodies of water with visible flowing water, reservoirs of frozen water, and reservoirs of water contained underground. Lakes, streams, and rivers are surface water storage reservoirs important towards the growth of urban development. Engineers have designed and built dams, created lake reservoirs, removed river meanders, added concrete bedded channels, and built berms attempting to control flooding in the floodplain of urban streams and rivers.

For example, engineering projects allow the city of New Orleans, L.A. and other cities along rivers to share the floodplain with powerful rivers. Engineers have influenced the growth of New Orleans, L.A. through building levees to restrict the flow of the Mississippi River with both success but also extreme consequences for structure failure when underestimating the response to storm events.

Underground water storage reservoirs include soils and groundwater. When precipitation falls on the continental surface water accumulates at areas of convergence. The gradient, change in elevation over a specified distance, influences the runoff processes towards convergence. If where the water accumulates has a permeable surface layer water will begin to infiltrate through the surface into the groundwater reservoir where storage in a confined aquifer or subsurface ground water flow to the stream channel can occur. One important characteristic of groundwater flow for this research study is the long travel time compared to surface flow. The time a water molecule arriving in a drainage basin in the form of precipitation from an individual storm event takes to travels to an observation point downstream is the travel time.

TRAVEL TIME

RUNOFF PROCESSES TO THE CHANNEL

Runoff response times of stream channels are related to the rates of two different processes. One process is related to the pathway that water takes from hillslopes to stream channels, which is known as hillslope runoff processes (Dunne & D. Black, 1970).

Runoff process rate refers to how long it takes for water to move from the hillslope to the first order channel. Urbanization influences this travel time of water with increased impervious cover in a watershed that causes excess overland flow. A common storm water management practice in urban areas includes funneling this excess overland flow into storm sewers that carry the water to the stream channel quicker than natural processes. Urbanization also decreases travel time in the stream through channelization, which decreases channel flow resistance and keeps high velocity discharge within the channel. Restricting high-velocity discharge in the channel minimizes floodplain dissipation of kinetic energy.

TRAVEL TIME IN THE CHANNEL

In non-urban watersheds, another process that controls the timing of the hydrological response is the time it takes for water to move down the stream channel. The rate of downstream travel of water is related to the flow resistance of the channel and the channel length. In general, channel flow velocities are two components that affect lag time. Urbanization has an influence on both components of lag time.

This pathway is known as a hillslope process. In non-urban watersheds where urbanization hasn't increased travel time to the stream channel through an increase in impervious cover, travel time in the channel controls the timing of the hydrological response. The rate of downstream travel of water is related to the flow resistance and the channel length. Channelization is a form of urbanization that decreases flow resistance and length when the new channel has been straitened. Channelization increases flow velocities in the stream and therefore channelized urban streams should have a shorter lag time than non-urban unaltered stream channels.

Travel time to the channel is related to the pathway that water takes from hillslopes to stream channels. This pathway is known as a hillslope process. In non-urban watersheds where urbanization hasn't increased travel time to the stream channel through an increase in impervious cover, travel time in the channel controls the timing of the hydrological response. The rate of downstream travel of water is related to the flow resistance and the channel length. Channelization is a form of urbanization that decreases flow resistance and length when the new channel has been straitened. Channelization increases flow velocities in the stream and therefore channelized urban streams should have a shorter lag time than non-urban unaltered stream channels.

HYDROGRAPHS

Hydrographs are an important diagram for analyzing and modeling hydrologic effects on streams. Peak rates can be used to show the hydrologic effects of existing or proposed watershed projects and land use changes. Storm hydrographs allow us to investigate the relationship between a rainfall event and discharge. They cover a relatively short period of time, commonly hours or days. The unit hydrograph is the characteristic shape of a streamflow hydrograph at a given gauge site for a storm of a set duration. Using lag time relationships, the construction of hydrographs shows the effect of urbanization on peak discharge from a storm of given intensity (Leopold, 1991). Variances in the characteristic shape of a hydrograph for storm events demonstrate the effect of urbanization on lag time. Measuring the time from the start of the hydrograph to the peak flow provides a way to measure the difference in lag time for urban and non-urban watersheds during similar storm events without needing to calculate the center of mass of rainfall.

LAG TIME

Rainfall and stream flow observations in the drainage basin are used to identify lag time. Lag time is defined as the burst of rainfall and the resulting hydrograph (Leopold, 1991). In most studies lag time is defined as time between center of mass of rainfall and the peak of the runoff event (Leopold, 1991). In small watersheds, one rain gauge may describe the rainfall distribution effectively. In larger watersheds, spatially distributed precipitation data may not be available so rise time can be used as a similar variable.

Simple observations of rainfall and stream flow in drainage basins can be used to determine the lag time between rainfall and resultant runoff (Leopold, 1991).

BASIN AREA

The larger the basin area the higher the lag time.

STREAM FLOW

Streamflow contributes to sediment transport, deposition, erosion, and flooding. Investigating how different parameters contribute to changes in flow allows engineers to design infrastructure for flood management, transportation, and restoration projects. After the piedmont coastal plain boundary at Great Falls Park, the Potomac River begins to accumulate flow from urbanized tributaries throughout the Washington DC metropolitan area. Both non-urban and urban tributaries exist in the metropolitan area, but most non-urban streams are found in areas of set aside park land where the natural floodplain is protected from urban development.

Streamflow: Determined by amount of rainfall excess.
Infiltration Capacity: rate at which water will be absorbed by a soil.

THEORY

Measurement of Streamflow

$$Q = AV$$

Q, discharge, is the volume of water passing through a cross sectional area at a time interval recorded in the unit cubic meters per second (cms).

A is the cross-sectional area.

V is the mean velocity.

DOWNSTREAM HYDROLOGIC GEOMETRY

Downstream Hydrologic Geometry (Leopold Maddock)

Non-Urban
Urban – Channelized
Urban – Non-channelized

Using the basis of the power equation three different treatments were explored for this research study.

HYPOTHESIS

Channelization and urbanization both affect peak discharge and peak velocities, but the effect of channelization may have a more significant effect on larger storms.

H1: The rise time of urban streams (impervious surface area more than 10%) will be lower than non-urban streams with similar basin area.

H2: Stream channelization and other modifications common in urban watersheds tend to decrease stream flow resistance. Therefore, peak flow velocities will be higher in urban streams than for non-urban streams.

H3: The total hydrograph volume will increase with peak discharge and will be higher for urban streams than for non-urban streams.

METHODOLOGY

Collection of Total Precipitation and Stream Data for Storm Events

Real time water data for a nation website:

https://waterdata.usgs.gov/nwis/rt

One method for studying the effects of urbanization on stream systems includes analyzing real time stream data from the United States Geological Survey (USGS) water data for a nation website. Stream data is available for free access to researchers on the website provided in the Appendix. Stream data recorded by the USGS of interest for this research study include discharge, elapsed time, and historical channel measurement data. Many other parameters are collected and available for download from the USGS for studying urbanization and anthropogenic effects on streams; however, discharge and elapsed time over the duration of individual storm events are the focus parameters for data collection in this study of stream responses in the Potomac River's tributaries.

These tributaries form a network of streams that branch out through the already urbanized and growing population center found in the Potomac River's drainage basin as the river crosses the fall line at the piedmont coastal plain province boundary. The tributaries within the Washington DC metropolitan area provide ideal locations for investigation into urbanization influences on streams from storm events with many of these tributaries encompassing the large network of stream gage sites with data available for access in the Chesapeake Bay Watershed. The Chesapeake Bay is one of many large coastal ecosystems that have large population centers influencing the drainage network. All research sties selected for analysis are found within the Washington DC metropolitan area concentrated in the Maryland counties of Montgomery County, Prince Georges County, St Mary's County, and Charles County. One research site is found in Alexandria, Virginia; however, this research site is a tributary that enters the Potomac

River on the Virginia bank side across from the Charles County and St Mary's County stream gage locations.

SELECTION OF RESEARCH SITES

Research sites were selected in both the Patuxent River and Lower Potomac drainage basins. Both the Patuxent River and Potomac River are

To test effects of urbanization on lag time urban and non-urban stream gauge sites have been selected. This study will focus on streams in Maryland, DC, and Virginia, with basin areas between 6 and 100 mi^2. Urban streams are defined here as being within watersheds that contain more than ten percent impervious cover.

Sixteen research sites were selected for the study across Maryland, Virginia, and Washington D.C. Most of the research sites are tributaries of the Potomac River in the Chesapeake Bay Watershed. There are nine urban stream research site locations and seven non-urban research site locations. For this research study the stream sites selected for analysis are found in the Coastal Plain and Piedmont Physiographic Provinces of Maryland.

LOWER POTOMAC DRAINAGE BASIN STREAMS

PATUXENT RIVER DRAINAGE BASIN STREAMS

TABLE 1: URBAN RESEARCH SITE LOCATIONS

RESEARCH SITE	USGS STREAM GAGE #	LOCATION	PROVINCE	BASIN AREA km^2	% IMP
Accotink Creek	01654000	Annandale, VA	Coastal Plain	135.20	27
Piscataway Creek	01653600	Piscataway, MD	Coastal Plain	102.70	44
NE Branch Anacostia	01649500	Riverdale, MD	Coastal Plain	189.28	35
St. Marys River	01661500	Great Mills, MD	Coastal Plain	62.40	12
Fourmile Run	01652500	Alexandria, VA	Coastal Plain	32.76	15

Rock Creek	01648000	Washington, DC	Piedmont	161.72	21
Seneca Creek	01645000	Dawsonville, MD	Piedmont	262.60	12
Sligo Creek	01650800	Tacoma Park, MD	Piedmont	16.77	33.6
NW Branch Anacostia	01650500	Colesville, MD	Piedmont	139.10	19

TABLE 1: Urban research site locations. Impervious cover estimates from (McCandless, 2003)

TABLE 2: NON-URBAN RESEARCH SITE LOCATIONS

RESEARCH SITE	USGS STREAM GAGE #	LOCATION	PROVINCE	BASIN AREA km^2	% IMP
Zekiah Swamp Run	01660920	Newton, MD	Coastal Plain	207.74	5.9
Mattawoman Creek	01658000	Pomonkey, MD	Coastal Plain	142.48	9.7
St. Clements Creek	01661050	Clements, MD	Coastal Plain	48.10	3.4
Hawlings River	01591700	Sandy Spring, MD	Piedmont	70.20	6.86
Bennet Creek	01643500	Park Mills, MD	Piedmont	163.28	1.2
Tenmile Creek	01644390	Boyds, MD	Piedmont	11.65	5
Tenmile Creek	01644388	Clarksburg, MD	Piedmont	8.76	6

SELECTION OF STORM EVENTS

This research study started in March 2019 and is ongoing through November 2019. Storm events of various duration and intensities were selected. Table 1 shows the storm events selected in order of lowest amount of total precipitation to the largest amount total precipitation. This total precipitation represents the amount of rainfall that falls in a stream drainage basin that influences a streams response to the storm. The total precipitation data used for this research study was collected at the United States Geological Survey's Four Mile Run weighing cell precipitation gage in Alexandria, Va. This precipitation gage location is found in proximity to many of the stream gage locations collecting discharge data over the duration of this study. The total precipitation for the duration of the study at Four Mile Run's precipitation gage is provided in Figure 2. The large storms capable of producing measurable stream responses to individual storm events were targeted for analysis during the research study.

FIGURE 2 USGS 01652500 ALEXANDRIA, VA

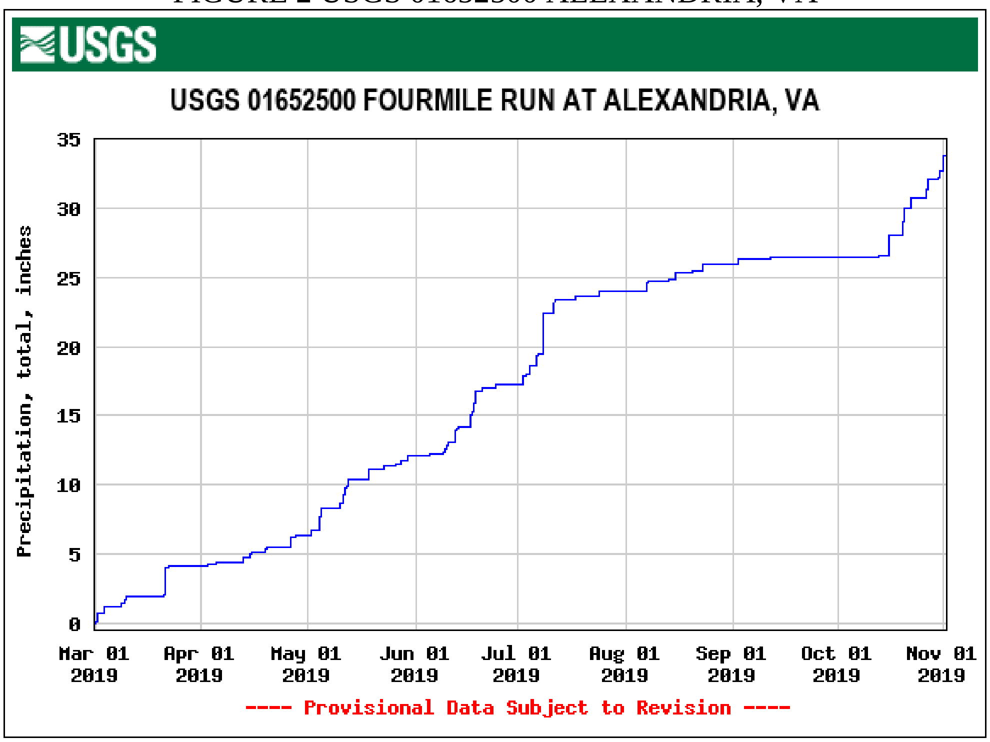


Figure 2: Precipitation gage data over the duration of the research study March 2019 – November 2019 at Four Mile Run at Alexandria, VA. In this figure precipitation in total inches versus elapsed time in months during f the 2019 year is displayed.

To identify the large storms capable of producing a measurable response to storm events total precipitation in inches versus elapsed time is graphed in figure 2. In this figure the total precipitation data for the entire duration of the study is reported. Beginning in March 2019 after each storm event in the Chesapeake Bay Watershed precipitation data was accessed and downloaded for analysis from the United States Geological Survey. The United States Geological Survey provides real time precipitation data for free access to researchers on their real time water data for a nation website. Figure 2 shows a graphical representation of the total precipitation for Four Mile Run in Alexandria, VA for the duration of the research study. The total precipitation data used for categorizing the intensity of the storm events in this research study was from the Four Mile Run precipitation gage site.

Another precipitation gage found in Slidell, MD was also used to collect precipitation data during the study for the piedmont research stream site locations in Montgomery County, MD. Figure 3 provides the total precipitation for the duration of the study at the Ten Mile Creek precipitation gage. From the figure you can see that the difference in amount of total precipitation for the duration of the study doesn't vary significantly.

TABLE 3 presents the storm event data organized from the storm event with the least amount of total precipitation to the most.

FIGURE 3 Ten Mile Creek Precipitation Gage Data

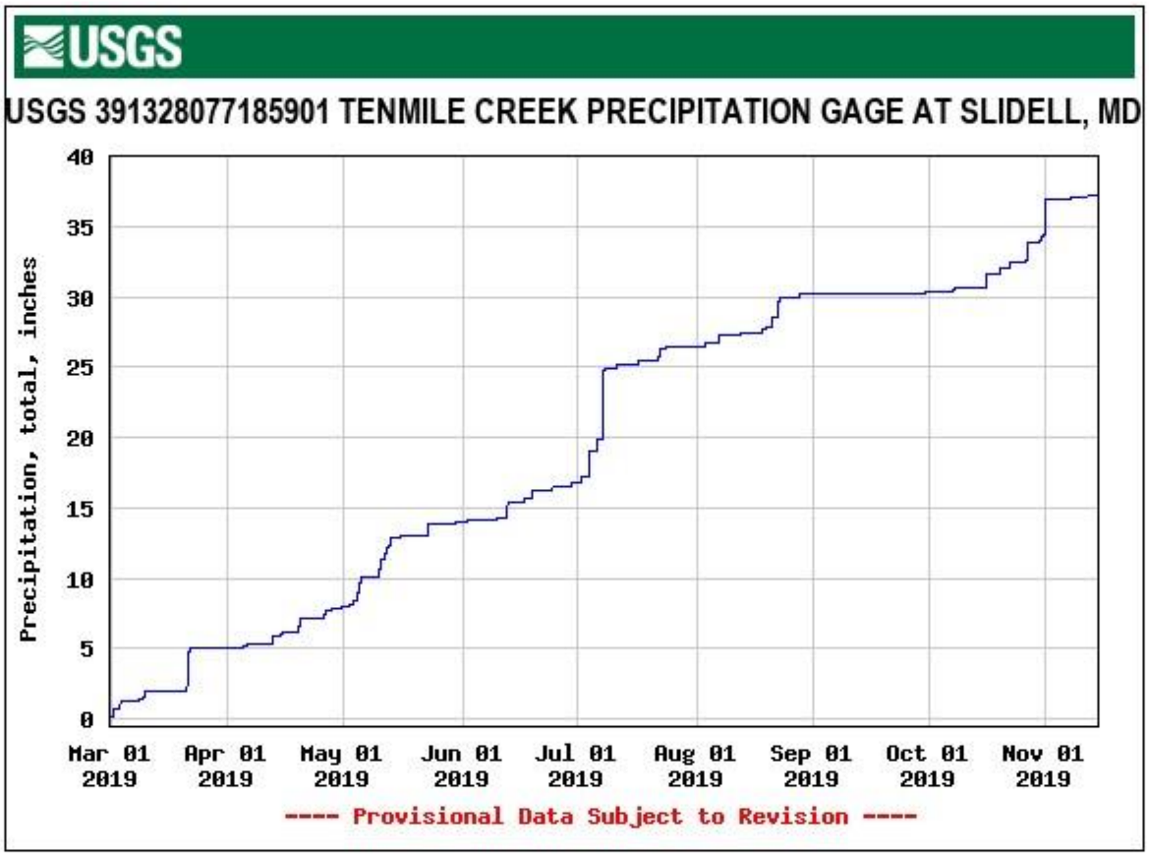


Figure 3: Precipitation gage data over the duration of the research study March 2019 – November 2019 at Tenmile Creek at Slidell, Md. In this figure precipitation in total inches versus elapsed time in months during 2019 is displayed.

TABLE 3 PRESENTATION OF STORM EVENT DATA

Storm Event	Date	Duration	Total Precipitation
Storm Event 1	March 10, 2019	02 hours	0.50 inches
Storm Event 2	October 27, 2019	9.2 hours	1.44 inches
Storm Event 3	October 18, 2019	40 hours	1.97 inches
Storm Event 5	October 31, 2019	29 hours	3.07 inches
Storm Event 5	July 8, 2019	14 hours	4.98 inches

TABLE 3: Table of storm events selected for research organized by lowest to highest amount of total precipitation in inches. Storm duration is represented in hours.

HYDROGRAPHS

Hydrographs are one way to analyze the response of a watershed to a rainfall event. The time between a burst of rainfall and the resulting hydrograph downstream is referred to as lag time (Leopold, 1991). In most studies lag time is defined as time between center of mass of rainfall and the peak of the runoff event (Leopold, 1991). In small watersheds, one rain gauge may describe the rainfall distribution effectively; however, spatially distributed precipitation data may not be available in larger watersheds so risetime can be used as a similar variable.

Acquisition of Storm hydrograph data

A hydrograph of discharge in feet per second versus elapsed time in hours can be created from real time United States Geological Survey water data for a nation.

Use the October 18, 2019 storm event data since it will be excluded later in the study due to the similarity to another storms total precipitation but has a longer duration.

Creating a Hydrograph of Discharge Versus Elapsed Time

A hydrograph of discharge in feet per second versus elapsed time in hours can be created from real time United States Geological Survey water data for a nation.

Determination of Peak Discharge

Calculating Peak Discharge

Peak discharge in the stream channel can be calculated from real time measurements taken in the stream at United States Geological Survey (USGS) stream gaging stations. USGS provides a database of available stream gages that provide data for research in stream drainage basins throughout the United States. This free data is available for access on USGS current water data for a nation website (Appendix).

From a hydrograph of discharge in feet per second versus elapsed time in hours peak discharge can be calculated at the apex of the hydrograph curve. The value can be recorded directly from the hydrograph.

Peak discharge in the stream channel can be calculated from real time measurements taken in the stream at United States Geological Survey (USGS) stream gaging stations. USGS provides a database of available stream gages that provide data for research in stream drainage basins throughout the United States. This free data is available for access on USGS current water data for a nation website (Appendix).

From a hydrograph peak discharge can be determined from the 15 or 30 minute interval records of streamflow.

<u>Calculating Rise time of peak discharge</u>

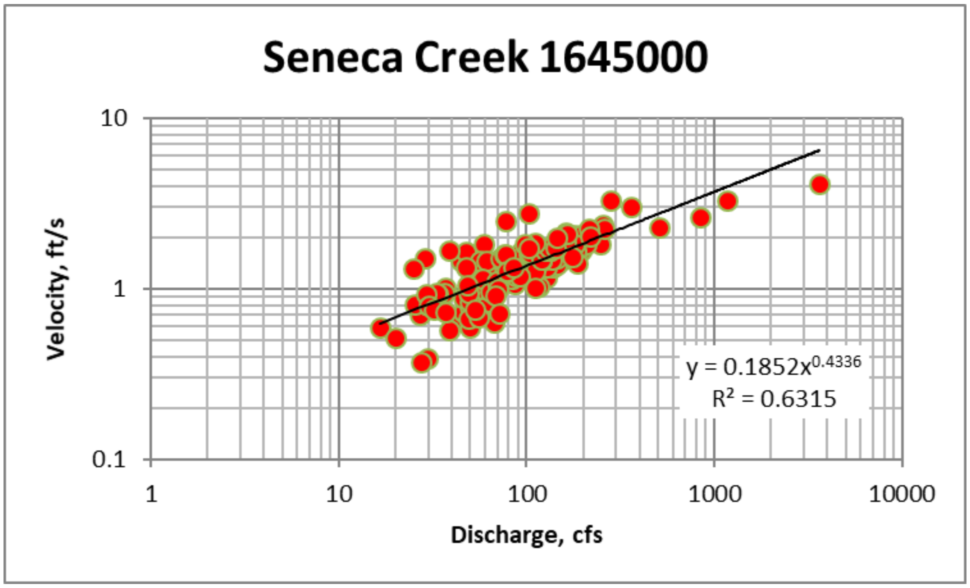
From a hydrograph of discharge in feet per second versus elapsed time in hours the time to peak discharge can be determined directly from the hydrograph. Rise time (explain).

<u>Calculating the stream velocity in the channel</u>

AT-A-STATION GEOMETRY

Velocity Equations

From channel measurements the relationship between stream velocity and discharge in the channel can be determined. This relationship, one of the hydraulic geometry equations, is usually a power function relationship between discharge and velocity (fig. x). .



Channel Velocity in ft/s Versus Discharge in cfs.

Storm events cause an increase in streamflow or discharge q. From field observations a trend is observed that as discharge increases over time height of the stream flow above a datum also increases to a peak value at the peak discharge. The peak discharge will be defined as q peak in this study and stage is the value of the stream gauge height above a datum. A change in stream flow characteristics is known as a response. Figure 1 shows a response to a storm event for the Paint Branch Tributary near Colesville, MD.

NORMALIZED DATA

Normalized data is used to compare data based on a common parameter.
Rise Time versus Drainage basin area graph
Q peak / Basin Area versus Drainage basin area graph
Rise Time versus Q Peak/ Drainage Basin Area

Normalized data is used to compare based on a common parameter.

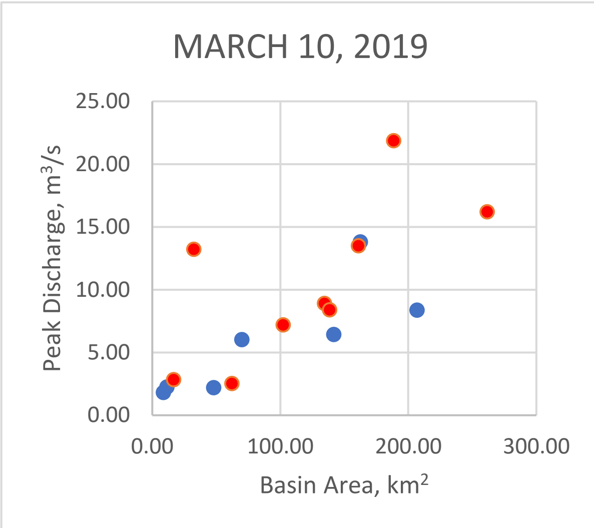
PRESENTATION OF RESULTS

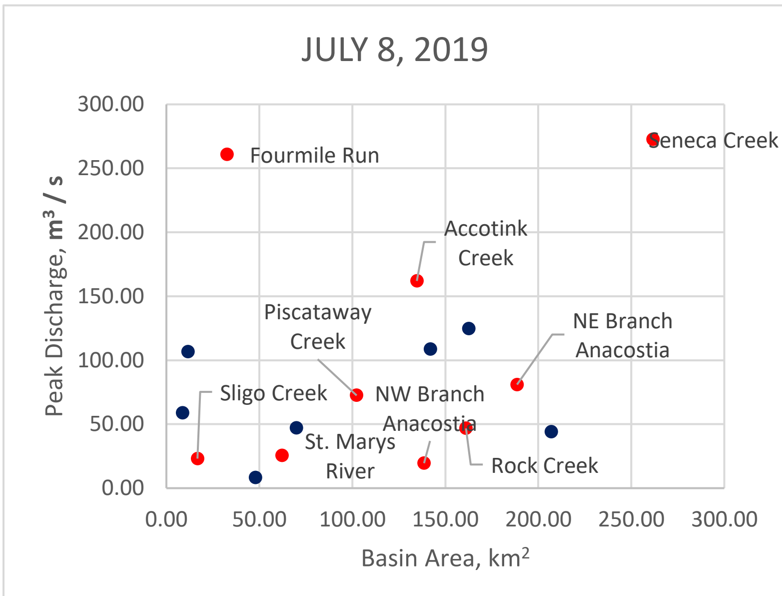
Five storm events of different intensities and durations were chosen for analysis during this research study; however, the similarity in total precipitation between the October 27, 2019 storm event and the October 18, 2019 storm event. For the sixteen research sites each storm event was analyzed separately. The response to March 10, 2019 storm event is presented in TABLE 4. TABLE 4 provides the basin area, baseflow, peak discharge, lag time, and velocity for the urban research sties included in the study. TABLE 5 provides the same information for the non-urban research sites. The results for each individual storm event were separated into either an urban research site table or non-urban table. The response results from the various storm events will be presented from smallest to largest storm by total precipitation.

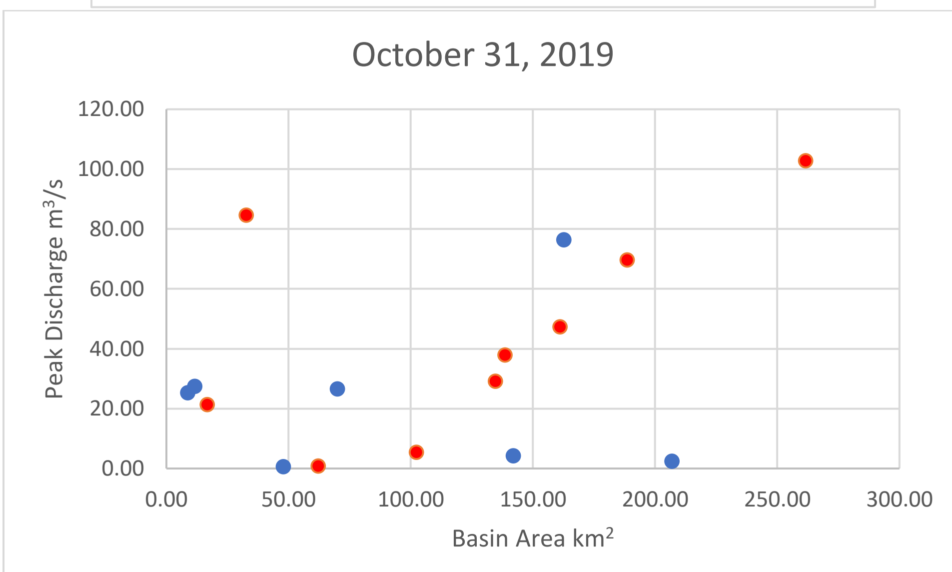
TABLE 4: MARCH 10, 2019 STORM EVENT RESPONSE

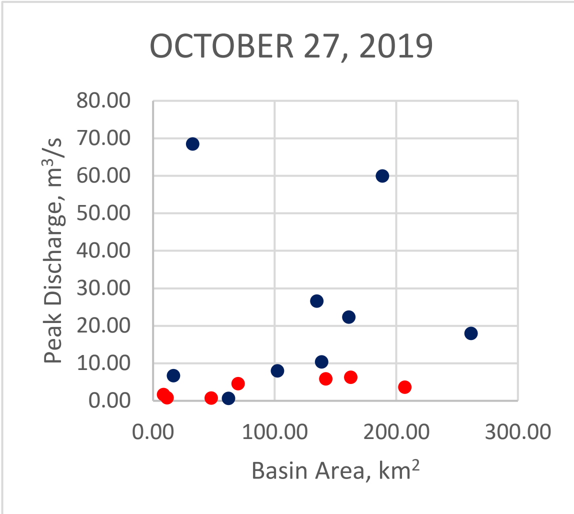
		km^2	m^3/s	m^3/s	hrs	m^2/s
Research Sites	**Imp %**	**Basin Area**	**Q Baseflow cms**	**Q Peak cms**	**ttp hours**	**Velocity**
Accotink Creek	27.00	134.68	0.61	8.89	5.75	0.76
Piscataway Creek	44.00	102.30	2.27	7.19	9.00	0.49
NE Branch Anacostia	35.00	188.55	2.82	21.86	4.50	0.45
St. Marys River	12.00	62.16	1.59	2.53	4.00	0.39
Fourmile Run	15.00	32.63	0.87	13.20	3.00	0.38
Rock Creek	21.00	161.10	3.14	13.48	5.75	0.24
Seneca Creek	12.00	261.59	7.14	16.20	7.92	0.62
Sligo Creek	33.60	16.71	0.24	2.82	3.33	0.16
NW Branch Anacostia	19.00	138.56	1.25	8.38	4.75	0.79
Zekiah Swamp Run	5.90	206.94	6.99	8.35	16.75	0.18
Mattawoman Creek	9.70	141.93	3.99	6.43	13.00	0.46
St. Clements Creek	3.40	47.91	1.18	2.19	5.25	0.20
Hawlings River	6.86	69.93	1.78	6.00	6.50	0.29
Bennet Creek	1.20	162.65	4.19	13.79	5.25	0.59
Tenmile Creek Boyds	5.00	11.60	0.29	2.23	2.00	0.36
Tenmile Creek Clarksburg	6.00	8.73	0.35	1.80	2.25	0.35

TABLE 4: March 10, 2019 response for a storm event of 0.5 inches and a storm duration of 2 hours. Urban streams are colored in red and non-urban streams are colored in blue.

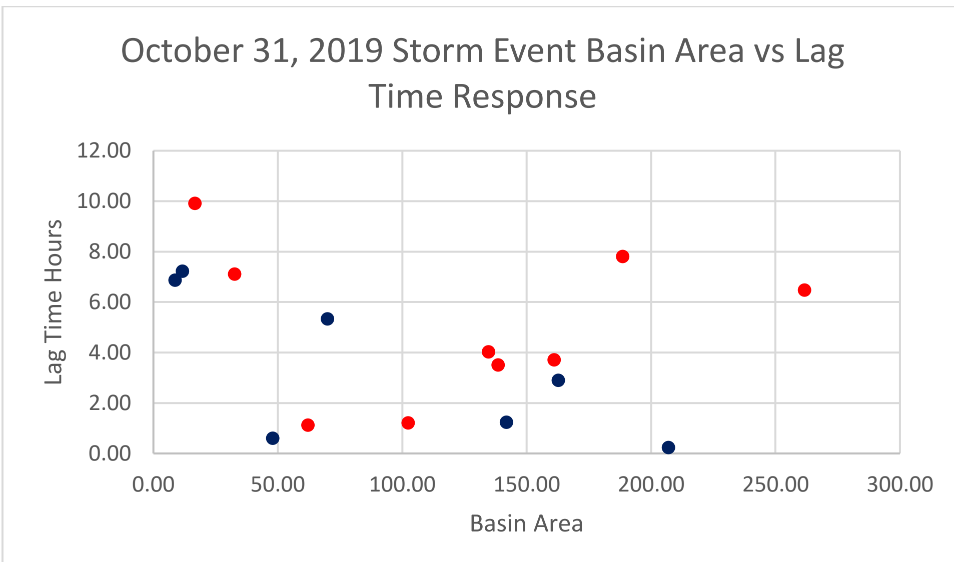

MARCH 10, 2019
25.00
20.00
15.00
10.00
5.00
0.00
Peak Discharge, m³/s
0.00
100.00
200.00
300.00
Basin Area, km²

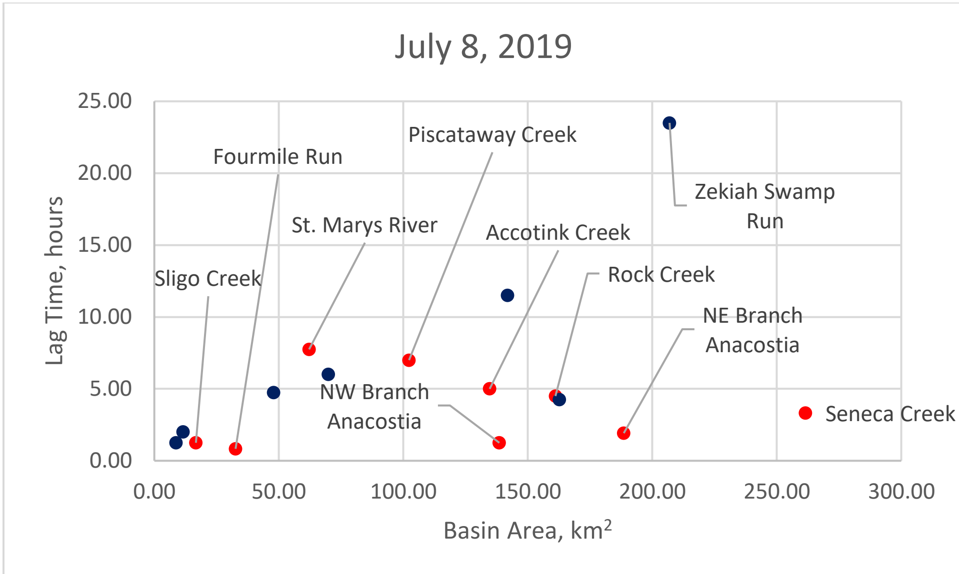

JULY 8, 2019
Peak Discharge, m³ / s
Basin Area, km²
300.00
250.00
200.00
150.00
100.00
50.00
0.00
0.00
50.00
100.00
150.00
200.00
250.00
300.00
Fourmile Run
Seneca Creek
Accotink Creek
Piscataway Creek
NE Branch Anacostia
Sligo Creek
NW Branch Anacostia
St. Marys River
Rock Creek

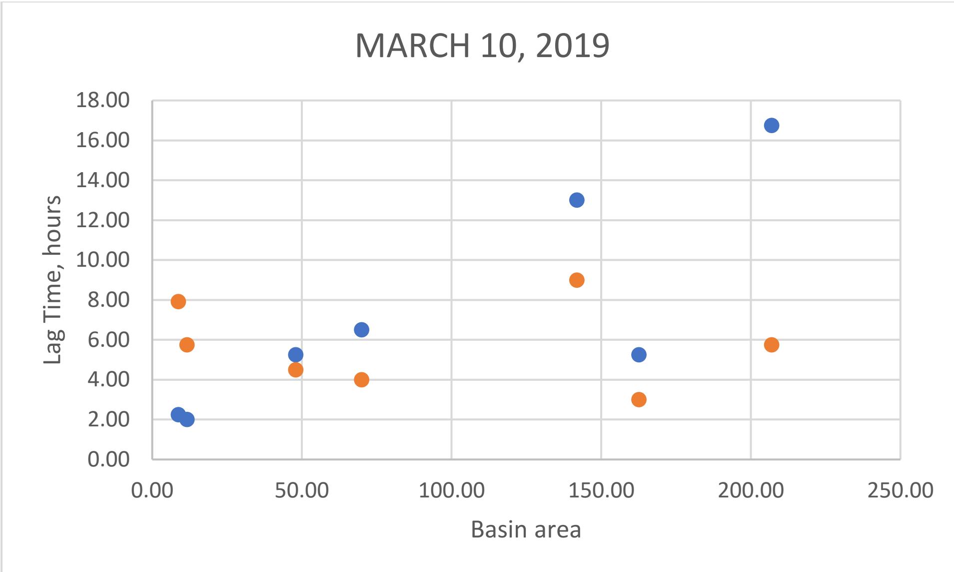

October 31, 2019
Peak Discharge m³/s
Basin Area km²
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0.00
50.00
100.00
150.00
200.00
250.00
300.00

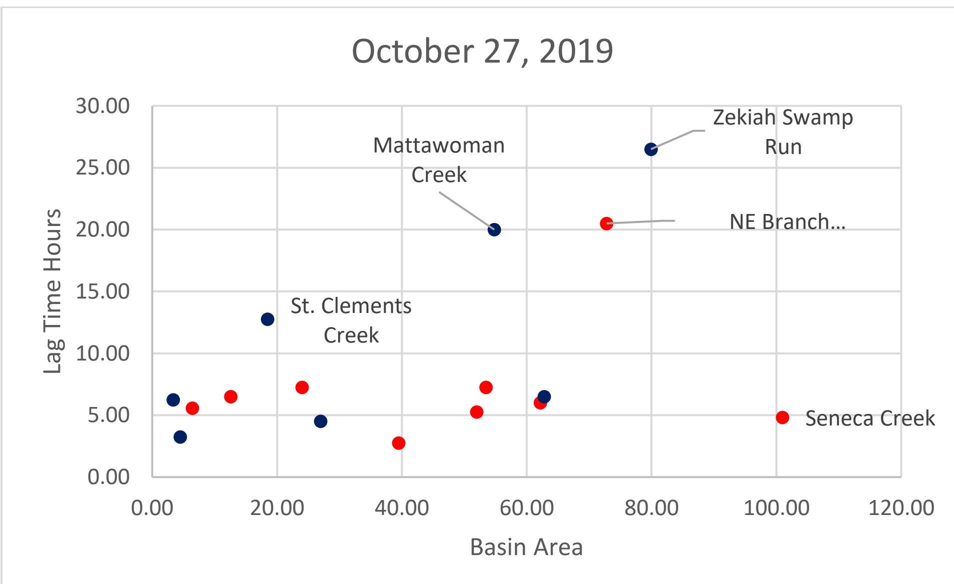

OCTOBER 27, 2019
Peak Discharge, m³/s
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0.00
100.00
200.00
300.00
Basin Area, km²

LAG TIME

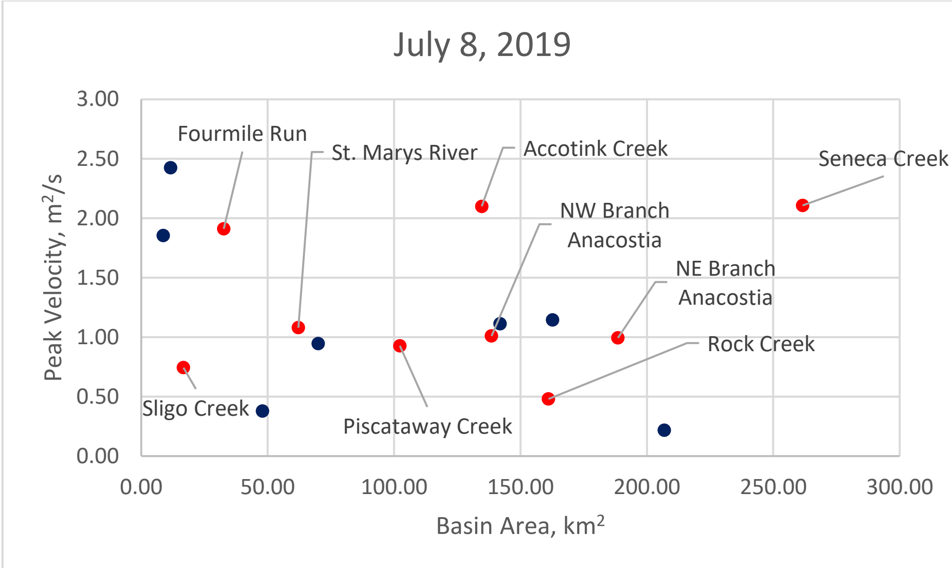

October 31, 2019 Storm Event Basin Area vs Lag Time Response
Lag Time Hours
12.00
10.00
8.00
6.00
4.00
2.00
0.00
0.00
50.00
100.00
150.00
200.00
250.00
300.00
Basin Area

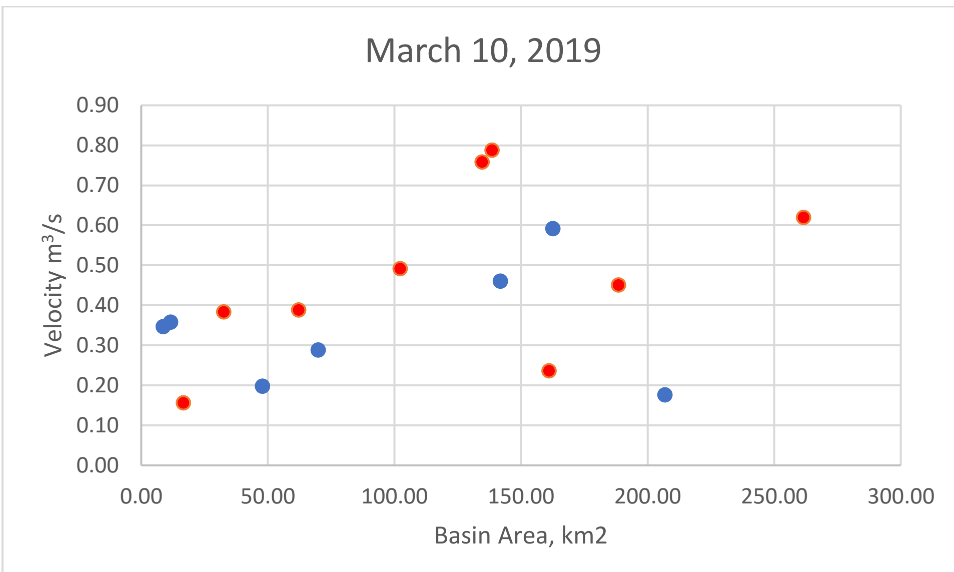

July 8, 2019
Lag Time, hours
Basin Area, km2
25.00
20.00
15.00
10.00
5.00
0.00
0.00
50.00
100.00
150.00
200.00
250.00
300.00
Fourmile Run
Piscataway Creek
St. Marys River
Accotink Creek
Zekiah Swamp Run
Sligo Creek
Rock Creek
NE Branch Anacostia
NW Branch Anacostia
Seneca Creek

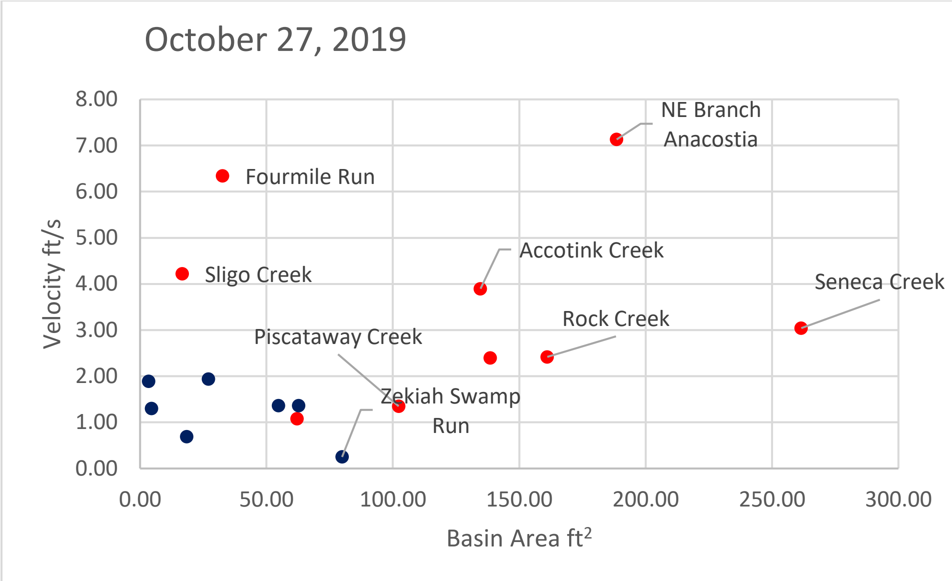


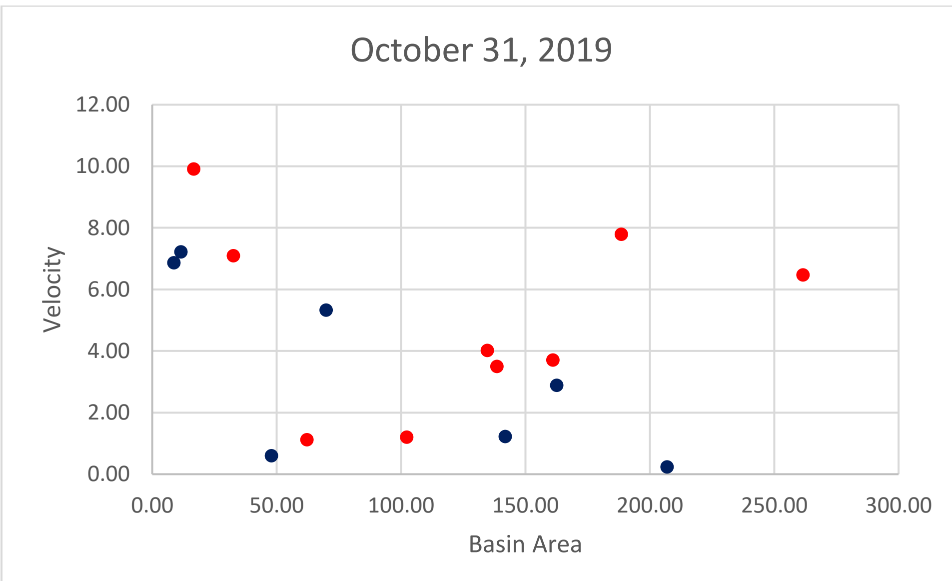


PEAK VELOCITY


July 8, 2019
Peak Velocity, m²/s
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Fourmile Run
St. Marys River
Accotink Creek
Seneca Creek
NW Branch
Anacostia
NE Branch
Anacostia
Rock Creek
Sligo Creek
Piscataway Creek
0.00
50.00
100.00
150.00
200.00
250.00
300.00
Basin Area, km²

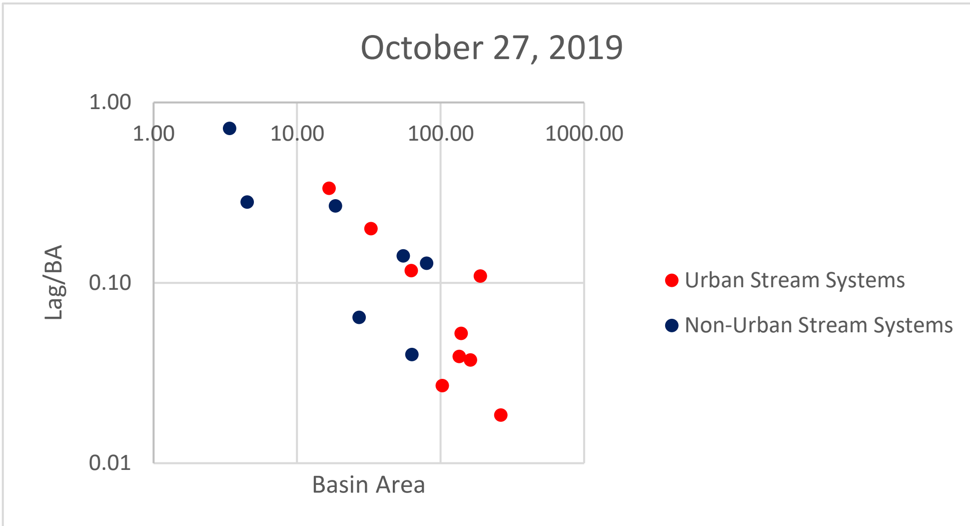

March 10, 2019
Velocity m³/s
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00
50.00
100.00
150.00
200.00
250.00
300.00
Basin Area, km2

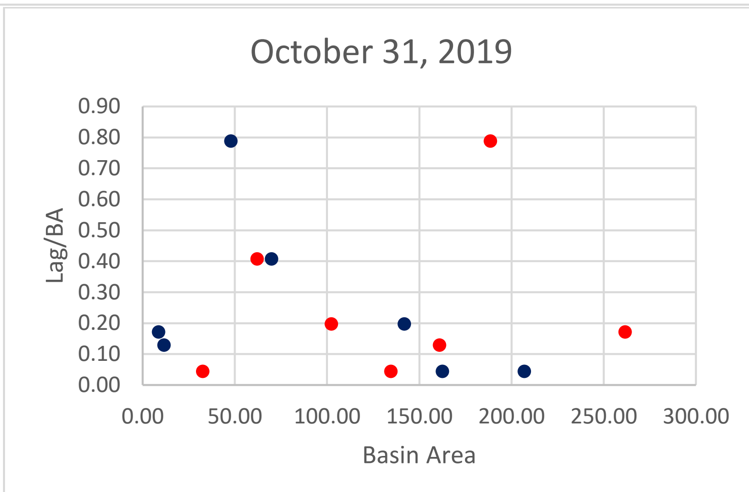

October 27, 2019
Velocity ft/s
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.00
50.00
100.00
150.00
200.00
250.00
300.00
Basin Area ft2
NE Branch Anacostia
Fourmile Run
Accotink Creek
Sligo Creek
Seneca Creek
Rock Creek
Piscataway Creek
Zekiah Swamp Run

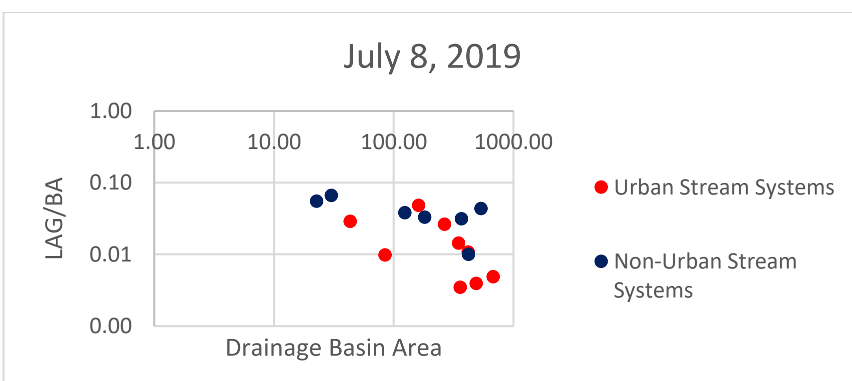

October 31, 2019
Velocity
12.00
10.00
8.00
6.00
4.00
2.00
0.00
0.00
50.00
100.00
150.00
200.00
250.00
300.00
Basin Area

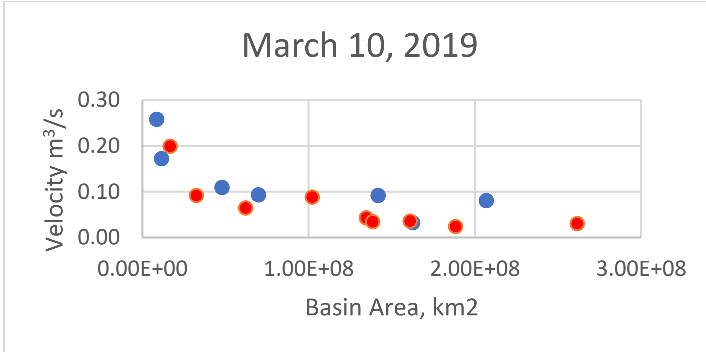
NORMALIZED DATA

LAG TIME VERSUS DRAINAGE BASIN AREA

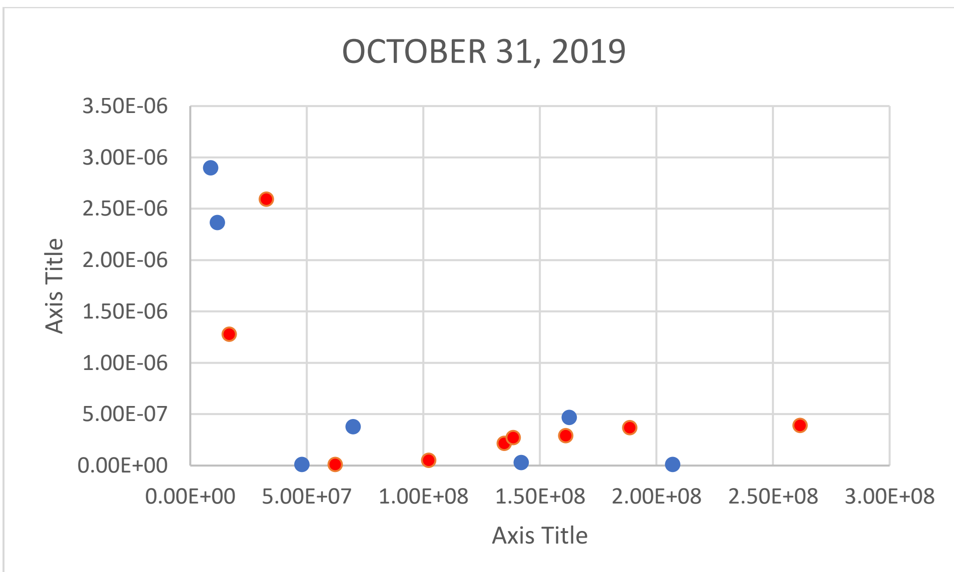


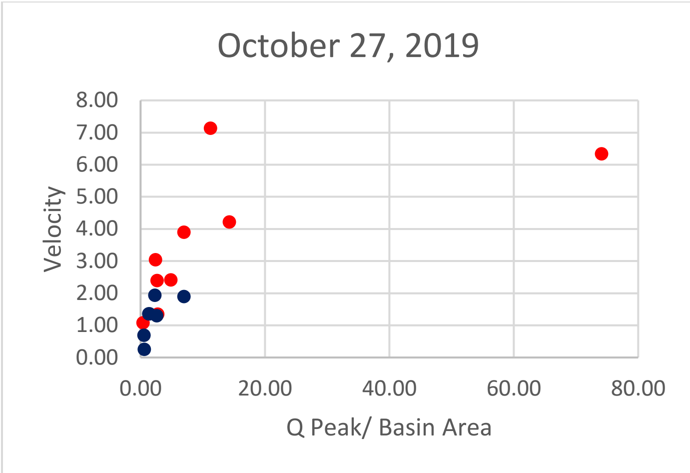


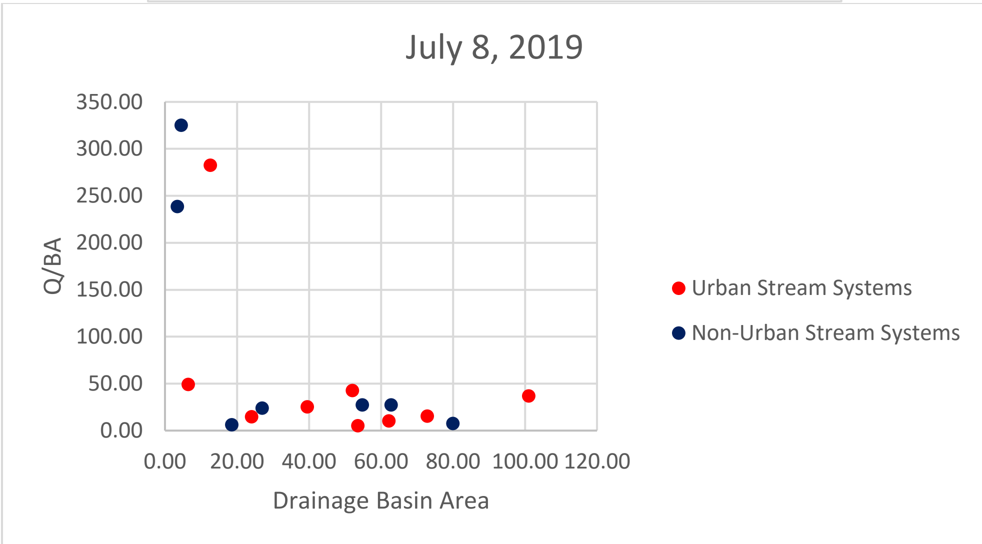


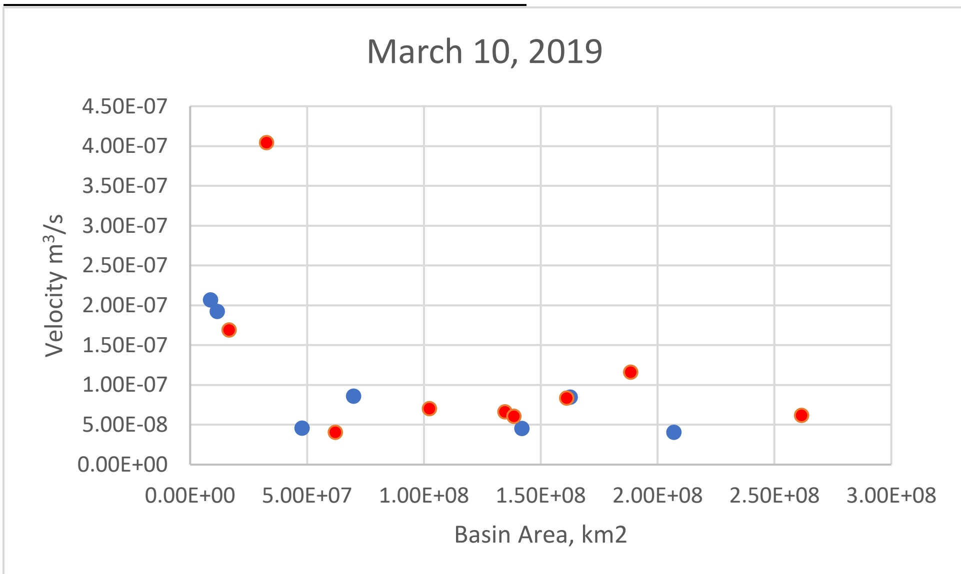


Q PEAK / BASIN AREA VERSUS DRAINAGE BASIN AREA

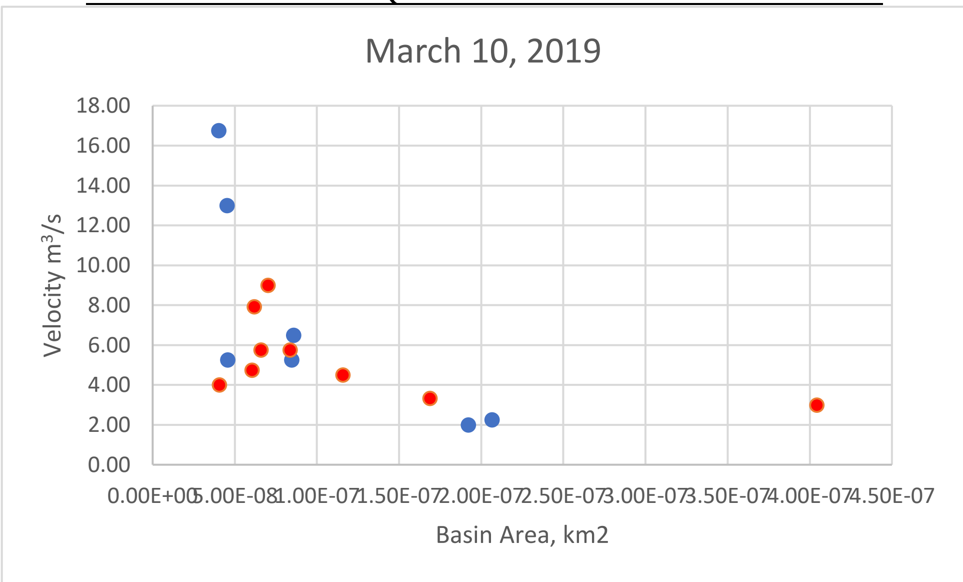


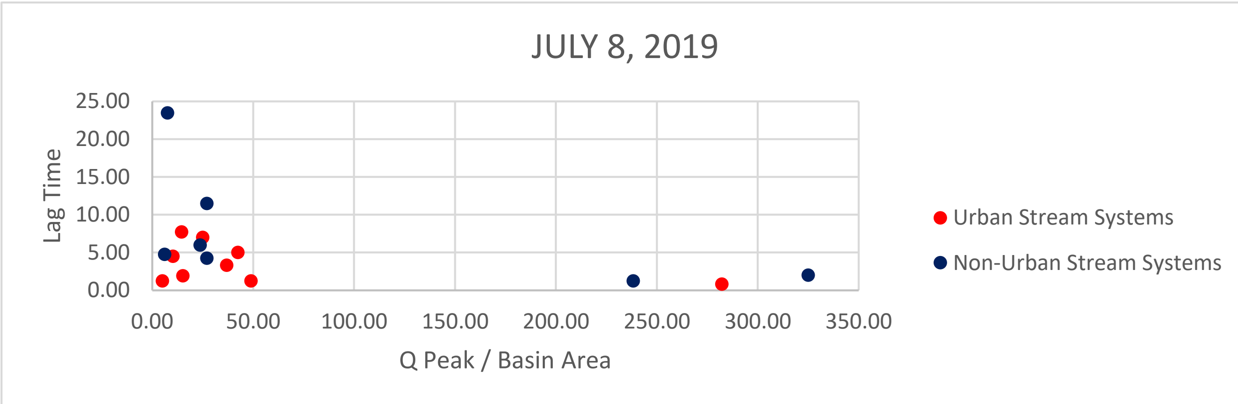

October 27, 2019
Velocity
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.00
20.00
40.00
60.00
80.00
Q Peak/ Basin Area

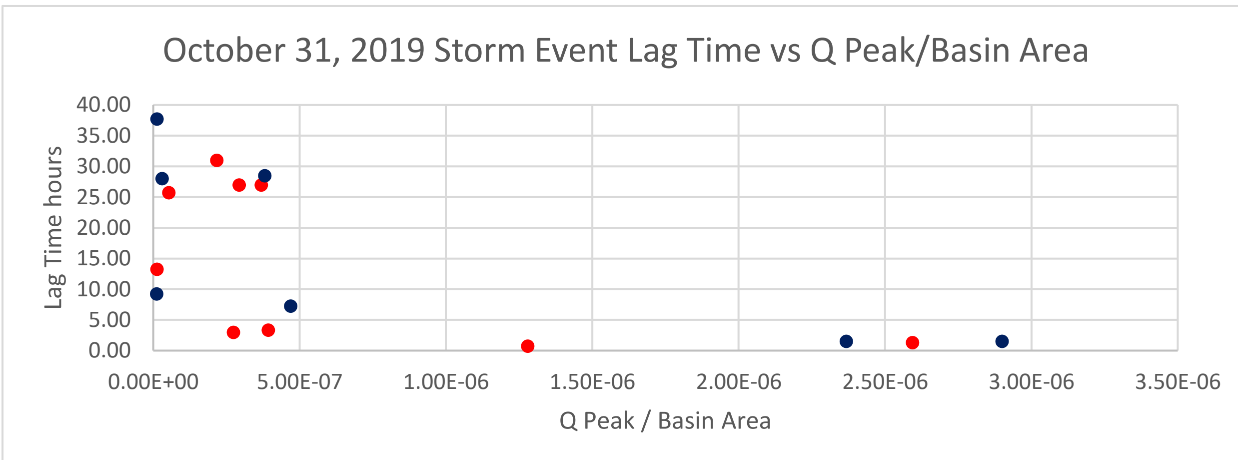

July 8, 2019
Q/BA
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
Drainage Basin Area
Urban Stream Systems
Non-Urban Stream Systems


March 10, 2019
Velocity m³/s
4.50E-07
4.00E-07
3.50E-07
3.00E-07
2.50E-07
2.00E-07
1.50E-07
1.00E-07
5.00E-08
0.00E+00
0.00E+00
5.00E+07
1.00E+08
1.50E+08
2.00E+08
2.50E+08
3.00E+08
Basin Area, km2

LAG TIME VERSUS Q PEAK / DRAINAGE BASIN AREA




JULY 8, 2019
Lag Time
25.00
20.00
15.00
10.00
5.00
0.00
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
Q Peak / Basin Area
Urban Stream Systems
Non-Urban Stream Systems


October 31, 2019 Storm Event Lag Time vs Q Peak/Basin Area
Lag Time hours
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0.00E+00
5.00E-07
1.00E-06
1.50E-06
2.00E-06
2.50E-06
3.00E-06
3.50E-06
Q Peak / Basin Area

OCTOBER 27, 2019

MARCH 10, 2019

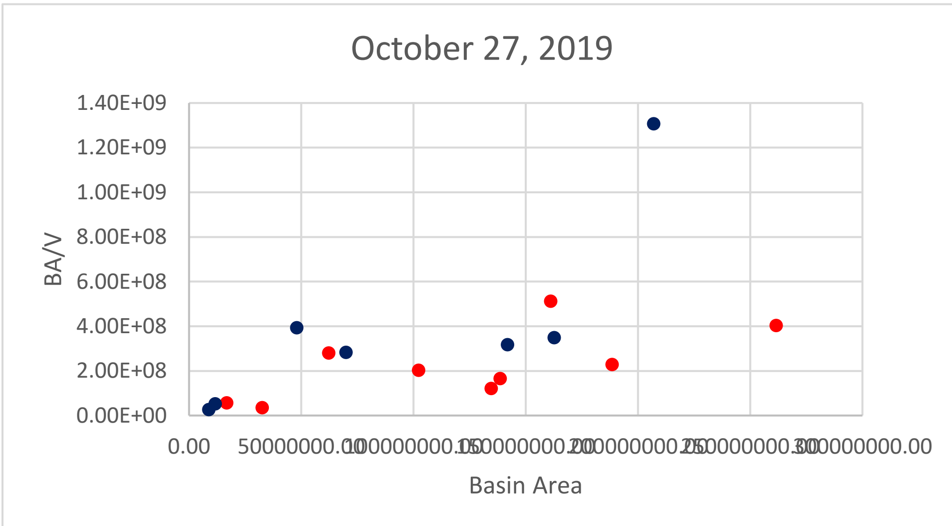


TABLE 5: JULY 8, 2019 STORM EVENT

		km^2	m^2	m^3 / s	m^3/s	hrs	m^2/s
Research Sites	**Imp %**	**Basin Area**	**Basin Area**	**Q Baseflow cms**	**Q Peak cms**	**ttp hours**	**vel**
Accotink Creek	27.00	134.68	1.35E+08	0.20	161.97	5.00	2.10

Piscataway Creek	44.00	102.30	1.02E+08	0.40	72.49	7.00	0.93
NE Branch Anacostia	35.00	188.55	1.89E+08	1.80	80.99	1.92	0.99
St. Marys River	12.00	62.16	6.22E+07	2.46	25.54	7.75	1.08
Fourmile Run	15.00	32.63	3.26E+07	1.22	260.80	0.83	1.91
Rock Creek	21.00	161.10	1.61E+08	4.11	46.72	4.50	0.48
Seneca Creek	12.00	261.59	2.62E+08	5.47	272.69	3.33	2.11
Sligo Creek	33.60	16.71	1.67E+07	0.12	23.11	1.25	0.74
NW Branch Anacostia	19.00	138.56	1.39E+08	0.31	19.51	1.25	1.01
Zekiah Swamp Run	5.90	206.94	2.07E+08	2.71	44.17	23.50	0.22
Mattawoman Creek	9.70	141.93	1.42E+08	3.03	108.74	11.50	1.11
St. Clements Creek	3.40	47.91	4.79E+07	1.03	8.35	4.75	0.38
Hawlings River	6.86	69.93	6.99E+07	0.80	47.01	6.00	0.95
Bennet Creek	1.20	162.65	1.63E+08	2.75	124.59	4.25	1.15
Tenmile Creek Boyds	5.00	11.60	1.16E+07	0.13	106.75	2.00	2.42
Tenmile Creek Clarksburg	6.00	8.73	8.73E+06	0.08	58.90	1.25	1.86

Table 5: July 8, 2019 storm event. This is the largest storm event during the research study.

TABLE 6: OCTOBER 18, 2019 STORM EVENT NORMALIZED RESULTS

	km^2	**m^3 / s**	**m^3/s**	**hrs**	**m^2/s**	**m/s**	**hrs/km^2**	**m - s**
Research Sites	**Basin Area**	**Q Baseflow cms**	**Q Peak cms**	**ttp hours**	**vel**	**Q/BA**	**Lag/BA**	**BA/V**

Accotink Creek	134.67	2.03E+00	18.69	10.25	0.98	1.39E-07	0.08	1.37E+08
Piscataway Creek	102.30	1.66E+01	6.06	7.75	0.47	5.92E-02	0.08	2.18E+08
NE Branch Anacostia	188.54	3.84E+01	33.70	8.30	0.59	1.79E-01	0.04	3.22E+08
St. Marys River	62.16	2.62E+01	6.88	5.25	0.60	1.11E-01	0.08	1.03E+08
Fourmile Run	32.63	6.15E+01	26.31	22.50	0.56	8.06E-01	0.69	5.87E+07
Rock Creek	161.09	3.16E+01	21.97	8.50	0.31	1.36E-01	0.05	5.16E+08
Seneca Creek	261.58	7.48E+01	6.48	27.25	0.42	2.48E-02	0.10	6.28E+08
Sligo Creek	16.70	9.69E+00	4.79	16.00	0.23	2.86E-01	0.96	7.24E+07
NW Branch Anacostia	138.56	1.02E+01	9.00	7.25	0.80	6.50E-02	0.05	1.72E+08
Zekiah Swamp Run	206.93	8.57E+00	0.33	10.50	0.12	1.60E-03	0.05	1.78E+09
Mattawoman Creek	141.93	0.00E+00	3.37	11.75	0.38	2.37E-02	0.08	3.77E+08
St. Clements Creek	47.91	2.00E+01	2.45	4.00	0.21	5.11E-02	0.08	2.29E+08
Hawlings River	69.93	1.41E+01	2.60	5.75	0.18	3.72E-02	0.08	3.94E+08
Bennet Creek	162.65	1.96E+01	0.71	5.00	0.24	4.37E-03	0.03	6.70E+08
Tenmile Creek Boyds	11.60	5.50E-01	0.16	5.00	0.10	1.35E-02	0.43	1.21E+08
Tenmile Creek Clarksburg	8.73	2.80E-01	0.22	3.10	0.13	2.58E-02	0.36	68546991.54

Table 6: October 18, 2019 storm event normalized data.

URBAN STREAM RESPONSE

PEAK DISCHARGE

FIGURE URBAN PEAK DISCHARGE VS BASIN AREA 03/10/2019

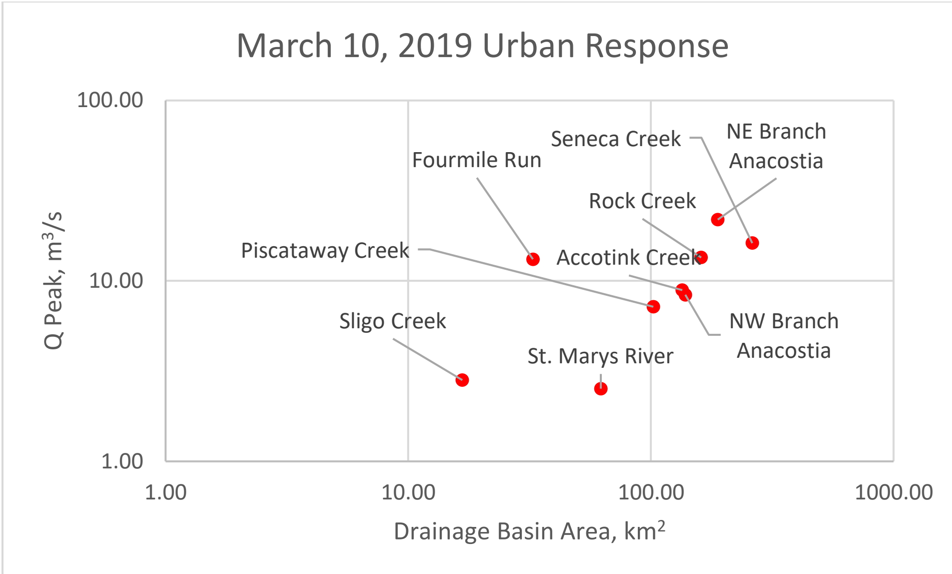


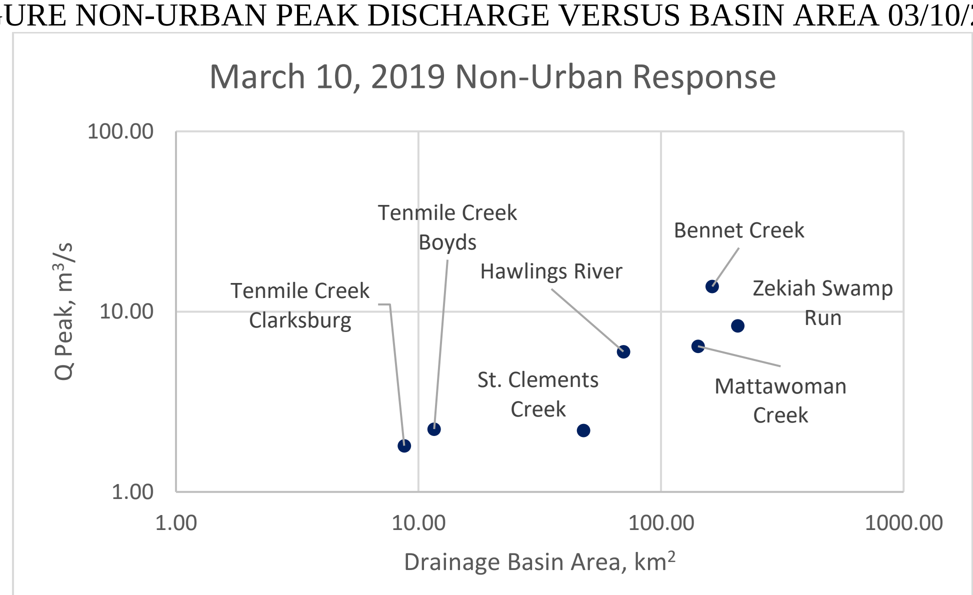
Figure: March 10, 2019 storm event stream response of peak discharge in cubic meters per second.

<u>LAG TIME</u>
<u>VELOCITY</u>

NON-URBAN STREAM RESPONSE

<u>PEAK DISCHARGE</u>

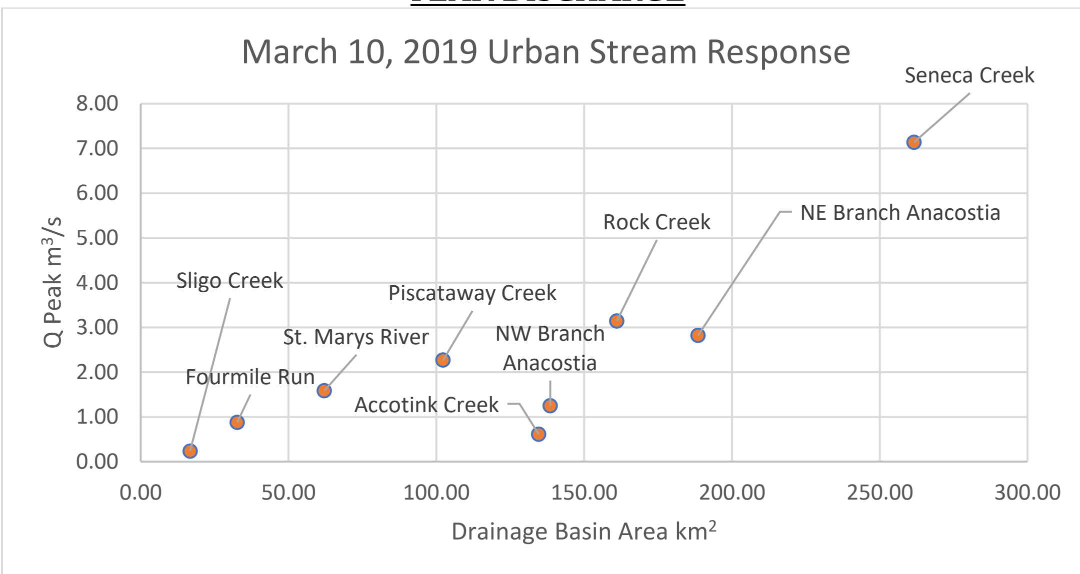
FIGURE NON-URBAN PEAK DISCHARGE VERSUS BASIN AREA 03/10/2019



Urban stream system results of Q peak in cubic feet per second, time to peak ttp in hours, velocity in feet squared per second, peak discharge divided by basin area in feet per second, time to peak divided by basin area in hours per feet squared, and basin area divided by velocity in feet seconds for March 10 storm event. The March 10, 2019 storm event had a total precipitation of 0.5 inches and 2 hours of total duration.

OCTOBER 27, 2019 STORM EVENT

PEAK DISCHARGE



ANALYSIS OF UNCERTAINTY

Selection of Storm Events

Amount of Actual Precipitation Captured in the Drainage Basin Area

To account for variance in the amount of actual precipitation captured in the drainage basin area for each storm event total rain precipitation data was collected at two available recording gages across the research site focus area. One stream gage is located in Montgomery County, Maryland while the second stream gage is located closer to the majority of research sites in Alexandria, Virginia. Figure 3 and figure 2 show a relatively event distribution of rainfall over the course of the study for the research sties.

FIGURE 2 Ten Mile Creek Precipitation Gage

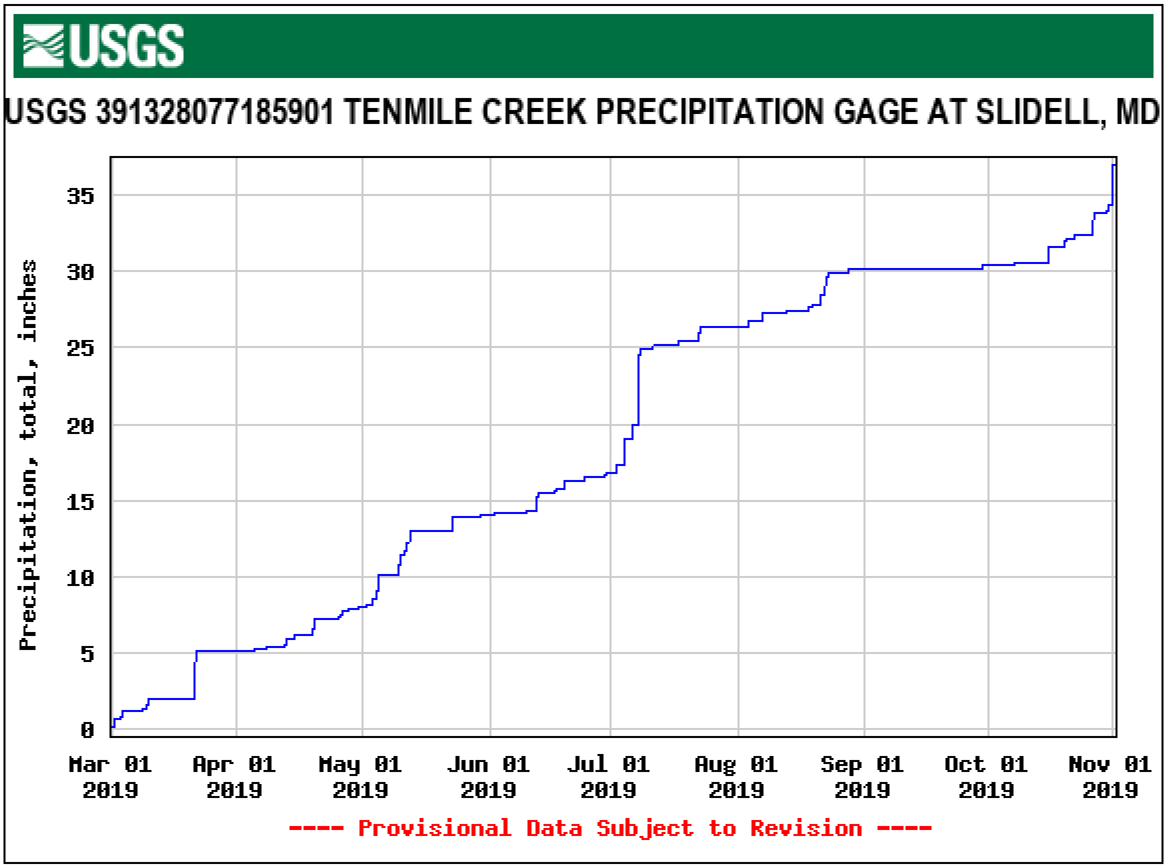


Figure 2: Precipitation gage data over the duration of the research study March 2019 – November 2019 at Tenmile Creek at Slidell, Md. In this figure precipitation in total inches versus elapsed time in months during the 2019 is displayed.

DISCUSSION OF RESULTS

LAG TIME

Lag time varies in watersheds. This can be observed through hydrographs from gauging stations in the same watershed. Peak flow was introduced in a study by Simas and Hawkins (1998) as a hydrologic variable to explain variation of lag time values within a watershed. The maximum flow rate in a hydrograph is characterized as peak flow (Simas and Hawkins 1998). Lag time was determined to be variable throughout watersheds in this study; however, bigger storms had closer values to a constant.

STREAMFLOW

In the coastal plain streams have low gradients. In Maryland the streams on the western coastal plain have slightly more fall than the streams on the erosion coastal plain (July 2003 Maryland Stream Survey)

CONCLUSIONS

Both urbanization and channelization can affect peak discharge and peak velocities, but the effect of channelization may have the most significant effects on larger storms as seen in figure 1.

Today water is a finite resource and increasing threat with drought, rising sea levels, flooding, and powerful hurricanes capable of producing higher storm surges for longer durations. Rivers erode and deposit sediment as they shape the landscape over time. In the study of the Earth's physical surface features and relationship to geologic structures, landforms created through the interaction of surface processes with river hydrologic processes are of geoscientific significance and engineering significance when it comes to controlling river processes for water resource and flood management practices. Understanding hydrological river processes that contribute to floodplain and channel formation is important to protecting the environment while also ensuring the large amount of people living in the floodplain of major rivers are protected from flooding from storm events. One way scientists monitor a river for flooding is through measuring streamflow.

The response to a storm event is important for water management, hazard management, environmental research, and infrastructure design.

There was not enough information available for non-urban altered single and multiple channel stream systems. Human influenced multiple channel stream systems are not readily identifiable in the research area as well.

THE INFLUENCE OF URBANIZATION ON STREAMS IN THE LOWER POTOMAC & PATUXENT RIVER DRAINAGE BASINS.

URBANIZATION IN THE DRAINAGE BASIN
Increase in Impervious Surface

URBANIZATION IN THE STREAM CHANNEL
Alteration of the Stream Channel

THE INFLUENCE OF THE STORM CHARACTERISTICS ON STREAMS

NON-URBAN & URBAN RESEARCH SITE STREAMFLOW DISCUSSION

- THE INFLUENCE OF BASIN AREA ON STREAMFLOW
- THE INFLUENCE OF BASEFLOW ON STREAMFLOW
- THE INFLUENCE OF URBANIZATION ON STREAMFLOW

NON-URBAN & URBAN RESEARCH SITE LAG TIME DISCUSSION

- THE INFLUENCE OF BASIN AREA ON LAG TIME

- THE INFLUENCE OF URBANIZATION ON LAG TIME

NON-URBAN & URBAN RESEARCH SITE PEAK VELOCITY DISCUSSION
- THE INFLUENCE OF BASIN AREA ON VELOCITY
- THE INFLUENCE OF PEAK DISCHARGE ON VELOCITY
- THE INFLUENCE OF URBANIZATION ON PEAK VELOCITY

THE RESUTLS OF THIS YEAR LONG STUDY INTO LOWER POTOMAC AND PATUXENT RIVER TRIBUTARIES IDENTIFIED THE POSSIBLE NATURAL STREAM CHANNEL CHARACFTERISTICS FOR THE STREAMAS IN THE BALTIMORE WASHINGTON METROPOLITION AREA.

In this study lag times for both urban and non-urban watersheds will be measured using rise time from hydrographs created using United States Geological Survey real time stream gauging data. Storms of different magnitude and duration will be investigated on streams with similar basin areas with differences in the amount of urbanization defined in this study by percent of impervious cover in the watershed. The preliminary results from this study support an interpretation that for a given watershed the characteristic hydrograph shape is similar for variations in storm intensity and duration. Storms with longer duration and more precipitation have a similar rise time but greater volume and discharge.

Normalized Data Results
Evapotranspiration
Manning Equation
Sediment Transport
Power functions at a station hydrologic geometry
Channel forming discharge

THE FUTURE FOR ANTHROPOGENIC STREAMS
THE INFLUENCE OF URBANIZATION ON ANTRHOPOGENIC STREAMS

The **hydrologic cycle attempts** to **model** the **storage** and **movement** of **water between** the **biosphere**, **atmosphere**, **lithosphere**, and the **hydrosphere** (**Figure 5c-1**). **Water** on this **planet can** be **stored** in **any one** of the **following reservoirs**: **atmosphere**, **oceans**, **lakes**, **rivers**, **soils**, **glaciers**, **snowfields**, and **groundwater**

Low impact development (LID) means an approach to stormwater management that mimics a site's natural hydrology as the landscape is developed.

Low impact development principles complement, and sometimes replace, traditional stormwater management systems, which historically emphasized moving stormwater off-site with curbs, pipes, ditches and ponds.
Green infrastructure is an approach to wet weather management that is cost-effective, sustainable, and environmentally friendly. Green infrastructure management approaches and technologies infiltrate, evapotranspire, capture and reuse stormwater to maintain or restore natural hydrologies. The terms "low impact development" and "green infrastructure" are used interchangeably.

<u>BROADER IMPLICATIONS</u>

ANTHROPOGENIC INFLUENCE ON THE HYDROLOGIC CYCLE

Designing a future that leaves enough water to use as a resource while also providing safe management of river flow in population centers is an Anthropogenic challenge facing engineers, hydrologists, environmental scientists, and geologists.

CLIMATE SHIFTING TOWARDS A WARMER CLIMATE

Increase in Total Precipitation

(Yearly total rainfall totals)
(100 year storms occur more frequently)

Influence of Urbanization on Evapotranspiration in Maryland Watersheds

LONG TERM PREPARATIONS FOR FLOOD MANAGEMENT

Restricting the Floodplain

Returning Drainage Basin Area to the River

New Legislation for agriculture next to rivers.

Land management practices

BROADER IMPLICATIONS FOR SEDIMENT TRANSPORT

Natural streams have heterogeneous mixtures of sediments. This affects when and how particles can move. Streams with a range of sizes of surface particles experience the onset of bedload motion when the large particles, ie D_{84} particles begin to move. This movement allows other surface particles to move. When surface particles move, finer subsurface material can also be transported.

Sediment Transport Equation

Sediment transport equations are mostly threshold exceedance equations used to describe the transport of particles once a threshold shear stress or stream power is reached and exceeded: Cities are found along major waterways.

MULTIPLE CHANNEL SYSTEM FOUND IN MARYLAND COASTAL PLAIN
Search for the natural channel system for Maryland.
Investigations into the storage properties of the floodplain for urban drainage basins.

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APPENDIX

TABLE A1: OCTOBER 18, 2019 URBAN STORM EVENT RESPONSE

Research Sites	Basin Area Km^2	Q Base-Flow m^3/s	Q Peak m^3/s	ttp hours	Velocity m^2/s
Accotink Creek	134.68	2.03	18.69	10.25	0.98
Piscataway Creek	102.30	16.60	6.06	7.75	0.47
NE Branch Anacostia	188.55	38.40	33.70	8.30	0.59
St. Marys River	62.16	26.20	6.88	5.25	0.60
Fourmile Run	32.63	61.50	26.31	22.50	0.56
Rock Creek	161.10	31.60	21.97	8.50	0.31
Seneca Creek	261.59	74.80	6.48	27.25	0.42
Sligo Creek	16.71	9.69	4.79	16.00	0.23
NW Branch Anacostia	138.56	10.20	9.00	7.25	0.80

TABLE A1: October 18, 2019 urban response to a storm event producing 1.97 inches of total precipitation in a storm duration of 40 hours.

TABLE A2: OCTOBER 18, 2019 NON-URBAN STORM EVENT RESPONSE

Research Sites	Basin Area Km^2	Q Base-Flow m^3/s	Q Peak m^3/s	ttp hours	Velocity m^2/s
Zekiah Swamp Run	8.57	0.33	10.50	0.12	8.57
Mattawoman Creek	0.00	3.37	11.75	0.38	0.00
St. Clements Creek	20.00	2.45	4.00	0.21	20.00
Hawlings River	14.10	2.60	5.75	0.18	14.10
Bennet Creek	19.60	0.71	5.00	0.24	19.60
Tenmile Creek Boyds	0.55	0.16	5.00	0.10	0.55
Tenmile Creek Clarksburg	0.28	0.22	3.10	0.13	0.28

TABLE A2: October 18, 2019 non-urban response to a storm event producing 1.97 inches of total precipitation in a storm duration of 40 hours.

TABLE A3: OCTOBER 27, 2019 URBAN STORM EVENT RESPONSE

Research Sites	**Basin Area Km^2**	**Q Base-Flow m^3/s**	**Q Peak m^3/s**	**ttp hours**	**Velocity m^2/s**
Accotink Creek	134.68	0.16	26.65	5.25	1.11
Piscataway Creek	102.30	0.26	8.04	2.75	0.51
NE Branch Anacostia	188.55	0.57	60.03	20.50	0.83
St. Marys River	62.16	0.26	0.72	7.25	0.22
Fourmile Run	32.63	0.20	68.53	6.50	0.93
Rock Creek	161.10	1.18	22.34	6.00	0.31
Seneca Creek	261.59	2.76	18.01	4.83	0.65
Sligo Creek	16.71	0.13	6.77	5.58	0.30
NW Branch Anacostia	138.56	0.23	10.42	7.25	0.84

TABLE A4: OCTOBER 27, 2019 NON-URBAN STORM EVENT RESPONSE

Research Sites	**Basin Area Km^2**	**Q Baseflow m^3/s**	**Q Peak m^3/s**	**ttp hours**	**Velocity m^2/s**
Zekiah Swamp Run	206.94	1.24	2.42	9.25	0.15
Mattawoman Creek	141.93	0.79	4.25	28.00	0.40
St. Clements Creek	47.91	0.35	0.61	37.75	0.11
Hawlings River	69.93	0.61	26.62	28.50	0.68
Bennet Creek	162.65	1.14	76.46	7.25	0.99
Tenmile Creek Boyds	11.60	0.04	27.47	1.50	1.24
Tenmile Creek Clarksburg	8.73	0.03	25.32	1.50	1.24

TABLE A5: October 31, 2019 URBAN STORM EVENT RESPONSE

Research Sites	**Basin Area Km^2**	**Q Base-Flow m^3/s**	**Q Peak m^3/s**	**ttp hours**	**Velocity m^2/s**
Accotink Creek	134.68	0.12	29.17	31.00	1.15
Piscataway Creek	102.30	0.32	5.41	25.75	0.45
NE Branch Anacostia	188.55	0.65	69.66	27.00	0.91
St. Marys River	62.16	0.24	0.79	13.25	0.23
Fourmile Run	32.63	0.37	84.67	1.33	1.04
Rock Creek	161.10	2.52	47.29	27.00	0.48
Seneca Creek	261.59	11.58	102.79	3.33	1.38
Sligo Creek	16.71	0.11	21.38	0.75	0.70
NW Branch Anacostia	138.56	0.75	37.94	3.00	1.23

TABLE A6: OCTOBER 31, 2019 NON-URBAN STORM EVENT RESPONSE

Research Sites	Basin Area Km^2	Q Baseflow m^3/s	Q Peak m^3/s	ttp hours	Velocity m^2/s
Zekiah Swamp Run	8.57	0.33	10.50	0.12	8.57
Mattawoman Creek	0.00	3.37	11.75	0.38	0.00
St. Clements Creek	20.00	2.45	4.00	0.21	20.00
Hawlings River	14.10	2.60	5.75	0.18	14.10
Bennet Creek	19.60	0.71	5.00	0.24	19.60
Tenmile Creek Boyds	0.55	0.16	5.00	0.10	0.55
Tenmile Creek Clarksburg	0.28	0.22	3.10	0.13	0.28

TABLE A7: July 8, 2019 URBAN STORM EVENT RESPONSE

Research Sites	Basin Area Km^2	Q Base-Flow m^3/s	Q Peak m^3/s	ttp hours	Velocity m^2/s
Accotink Creek	134.68	0.20	161.97	5.00	2.10
Piscataway Creek	102.30	0.40	72.49	7.00	0.93
NE Branch Anacostia	188.55	1.80	80.99	1.92	0.99
St. Marys River	62.16	2.46	25.54	7.75	1.08
Fourmile Run	32.63	1.22	260.80	0.83	1.91
Rock Creek	161.10	4.11	46.72	4.50	0.48
Seneca Creek	261.59	5.47	272.69	3.33	2.11
Sligo Creek	16.71	0.12	23.11	1.25	0.74
NW Branch Anacostia	138.56	0.31	19.51	1.25	1.01

TABLE A8: July 8, 2019 NON-URBAN STORM EVEN RESPONSE

Research Sites	Basin Area Km^2	Q Baseflow m^3/s	Q Peak m^3/s	ttp hours	Velocity m^2/s
Zekiah Swamp Run	206.94	2.71	44.17	23.50	0.22
Mattawoman Creek	141.93	3.03	108.74	11.50	1.11
St. Clements Creek	47.91	1.03	8.35	4.75	0.38
Hawlings River	69.93	0.80	47.01	6.00	0.95
Bennet Creek	162.65	2.75	124.59	4.25	1.15
Tenmile Creek Boyds	11.60	0.13	106.75	2.00	2.42
Tenmile Creek Clarksburg	8.73	0.08	58.90	1.25	1.86

TABLE A9: OCTOBER 27, 2019 STORM EVENT NORMALIZED RESULTS

	km^2	**m^3 / s**	**m^3/s**	**hrs**	**m^2/s**	**m/s**	**hrs/km^2**	**m - s**
Research Sites	**Basin Area**	**Q Baseflow cms**	**Q Peak cms**	**ttp hours**	**vel**	**Q/BA**	**Lag/BA**	**BA/V**
Accotink Creek	134.67	0.16	26.65	5.25	1.11	1.98E-07	0.04	1.21E+08
Piscataway Creek	102.30	0.26	8.04	2.75	0.51	7.86E-08	0.03	2.02E+08
NE Branch Anacostia	188.54	0.57	60.03	20.50	0.83	3.18E-07	0.11	2.27E+08
St. Marys River	62.16	0.26	0.72	7.25	0.22	1.16E-08	0.12	2.80E+08
Fourmile Run	32.63	0.20	68.53	6.50	0.93	2.10E-06	0.20	3.50E+07
Rock Creek	161.09	1.18	22.34	6.00	0.31	1.39E-07	0.04	5.11E+08
Seneca Creek	261.58	2.76	18.01	4.83	0.65	6.88E-08	0.02	4.03E+08
Sligo Creek	16.70	0.13	6.77	5.58	0.30	4.05E-07	0.33	5.60E+07
NW Branch Anacostia	138.56	0.23	10.42	7.25	0.84	7.52E-08	0.05	1.65E+08
Zekiah Swamp Run	206.93	1.50	3.68	26.50	0.16	1.78E-08	0.13	1.31E+09
Mattawoman Creek	141.93	1.23	5.89	20.00	0.45	4.15E-08	0.14	3.17E+08
St. Clements Creek	47.91	0.29	0.81	12.75	0.12	1.68E-08	0.27	3.93E+08
Hawlings River	69.93	0.42	4.62	4.50	0.25	6.60E-08	0.06	2.83E+08
Bennet Creek	162.65	0.65	6.29	6.50	0.47	3.87E-08	0.04	3.48E+08
Tenmile Creek Boyds	11.60	0.03	0.86	3.25	0.22	7.42E-08	0.28	5.20E+07
Tenmile Creek Clarksburg	8.73	0.01	1.74	6.25	0.34	1.99E-07	0.72	2.56E+07

TABLE A9: Urban stream systems are colored in red and non-urban stream systems are colored in dark blue.

TABLE A10: OCTOBER 31, 2019 STORM EVENT NORMALIZED RESULTS

	km^2	m^3 / s	m^3/s	hrs	m^2/s	m/s	hrs/km^2	m - s
Research Sites	**Basin Area**	**Q Baseflow cms**	**Q Peak cms**	**ttp hours**	**vel**	**Q/BA**	**Lag/BA**	**BA/V**
Accotink Creek	134.68	0.12	29.17	31.00	1.15	2.17E-07	0.23	1.17E+08
Piscataway Creek	102.30	0.32	5.41	25.75	0.45	5.29E-08	0.25	2.25E+08
NE Branch Anacostia	188.55	0.65	69.66	27.00	0.91	3.69E-07	0.14	2.08E+08
St. Marys River	62.16	0.24	0.79	13.25	0.23	1.27E-08	0.21	2.68E+08
Fourmile Run	32.63	0.37	84.67	1.33	1.04	2.59E-06	0.04	3.13E+07
Rock Creek	161.10	2.52	47.29	27.00	0.48	2.94E-07	0.17	3.33E+08
Seneca Creek	261.59	11.58	102.79	3.33	1.38	3.93E-07	0.01	1.89E+08
Sligo Creek	16.71	0.11	21.38	0.75	0.70	1.28E-06	0.04	2.38E+07
NW Branch Anacostia	138.56	0.75	37.94	3.00	1.23	2.74E-07	0.02	1.13E+08
Zekiah Swamp Run	206.94	1.24	2.42	9.25	0.15	1.17E-08	0.04	1.38E+09
Mattawoman Creek	141.93	0.79	4.25	28.00	0.40	2.99E-08	0.20	3.51E+08
St. Clements Creek	47.91	0.35	0.61	37.75	0.11	1.28E-08	0.79	4.49E+08
Hawlings River	69.93	0.61	26.62	28.50	0.68	3.81E-07	0.41	1.03E+08
Bennet Creek	162.65	1.14	76.46	7.25	0.99	4.70E-07	0.04	1.64E+08
Tenmile Creek Boyds	11.60	0.04	27.47	1.50	1.24	2.37E-06	0.13	9.37E+06
Tenmile Creek Clarksburg	8.73	0.03	25.32	1.50	1.24	2.90E-06	0.17	7.06E+06

TABLE A10: Urban stream systems are colored in red and non-urban stream systems are colored in dark blue.

TABLE A11: JULY 8, 2019 STORM EVENT NORMALIZED RESULTS

	km^2	m^3 / s	m^3/s	hrs	m^2/s	m/s	hrs/km^2	m - s
Research Sites	**Basin Area**	**Q Baseflow cms**	**Q Peak cms**	**ttp hours**	**vel**	**Q/BA**	**Lag/BA**	**BA/V**
Accotink Creek	134.68	0.20	161.97	5.00	2.10	1.20E-06	0.04	6.41E+07
Piscataway Creek	102.30	0.40	72.49	7.00	0.93	7.09E-07	0.07	1.10E+08
NE Branch Anacostia	188.55	1.80	80.99	1.92	0.99	4.30E-07	0.01	1.90E+08
St. Marys River	62.16	2.46	25.54	7.75	1.08	4.11E-07	0.12	5.76E+07
Fourmile Run	32.63	1.22	260.80	0.83	1.91	7.99E-06	0.03	1.71E+07
Rock Creek	161.10	4.11	46.72	4.50	0.48	2.90E-07	0.03	3.35E+08
Seneca Creek	261.59	5.47	272.69	3.33	2.11	1.04E-06	0.01	1.24E+08
Sligo Creek	16.71	0.12	23.11	1.25	0.74	1.38E-06	0.07	2.25E+07
NW Branch Anacostia	138.56	0.31	19.51	1.25	1.01	1.41E-07	0.01	1.37E+08
Zekiah Swamp Run	206.94	2.71	44.17	23.50	0.22	2.13E-07	0.11	9.51E+08
Mattawoman Creek	141.93	3.03	108.74	11.50	1.11	7.66E-07	0.08	1.28E+08
St. Clements Creek	47.91	1.03	8.35	4.75	0.38	1.74E-07	0.10	1.26E+08
Hawlings River	69.93	0.80	47.01	6.00	0.95	6.72E-07	0.09	7.40E+07
Bennet Creek	162.65	2.75	124.59	4.25	1.15	7.66E-07	0.03	1.42E+08
Tenmile Creek Boyds	11.60	0.13	106.75	2.00	2.42	9.20E-06	0.17	4.79E+06
Tenmile Creek Clarksburg	8.73	0.08	58.90	1.25	1.86	6.75E-06	0.14	4.70E+06

TABLE A11: Urban streams are colored in red and non-urban streams are colored in blue.

TABLE A12: MARCH 10, 2019 STORM EVENT NORMALIZED RESULTS

	km^2	**m^3/s**	**m^3/s**	**hrs**	**m^2/s**	**m/s**	**hrs/km^2**	**m- s**
Research Sites	**Basin Area**	**Q Baseflow cms**	**Q Peak cms**	**ttp hours**	**Velocity**	**Q/BA**	**Lag/BA**	**BA/V**
Accotink Creek	134.68	0.61	8.89	5.75	0.76	6.60E-08	0.04	1.78E+08
Piscataway Creek	102.30	2.27	7.19	9.00	0.49	7.03E-08	0.09	2.08E+08
NE Branch Anacostia	188.55	2.82	21.86	4.50	0.45	1.16E-07	0.02	4.18E+08
St. Marys River	62.16	1.59	2.53	4.00	0.39	4.07E-08	0.06	1.60E+08
Fourmile Run	32.63	0.87	13.20	3.00	0.38	4.04E-07	0.09	8.51E+07
Rock Creek	161.10	3.14	13.48	5.75	0.24	8.37E-08	0.04	6.83E+08
Seneca Creek	261.59	7.14	16.20	7.92	0.62	6.19E-08	0.03	4.22E+08
Sligo Creek	16.71	0.24	2.82	3.33	0.16	1.69E-07	0.20	1.07E+08
NW Branch Anacostia	138.56	1.25	8.38	4.75	0.79	6.05E-08	0.03	1.76E+08
Zekiah Swamp Run	206.94	6.99	8.35	16.75	0.18	4.04E-08	0.08	1.18E+09
Mattawoman Creek	141.93	3.99	6.43	13.00	0.46	4.53E-08	0.09	3.08E+08
St. Clements Creek	47.91	1.18	2.19	5.25	0.20	4.57E-08	0.11	2.42E+08
Hawlings River	69.93	1.78	6.00	6.50	0.29	8.58E-08	0.09	2.43E+08
Bennet Creek	162.65	4.19	13.79	5.25	0.59	8.48E-08	0.03	2.75E+08
Tenmile Creek Boyds	11.60	0.29	2.23	2.00	0.36	1.92E-07	0.17	3.24E+07
Tenmile Creek Clarksburg	8.73	0.35	1.80	2.25	0.35	2.07E-07	0.26	2.52E+07

TABLE A12: Urban streams are colored in red and non-urban streams are colored in blue.

TABLE A13 STORM INTENSITY BY STORM DURATION

Storm Event	**Date**	**Duration**	**Total Precipitation**
Storm Event 1	March 10, 2019	02 hours	0.50 inches
Storm Event 2	October 27, 2019	9.2 hours	1.44 inches
Storm Event 3	July 8, 2019	14 hours	4.98 inches
Storm Event 4	October 31, 2019	29 hours	3.07 inches
Storm Event 5	October 18, 2019	40 hours	1.97 inches

TABLE A13: Table of storm events selected for research organized shortest to longest storm duration in hours.