Sources of Stream Discharge in the North East and North West Branches of the Anacostia Watershed

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Geology 394

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Abstract

The sources of water conveyed to streams during storm events was determined for the two main streams in the Anacostia River watershed using a simple, well established two-component mixing model. The hydrograph separations were used to quantify the amount of storm discharge entering the stream form each source during a storm event. There are two dominant sources of water discharge to streams in urban watersheds during storms: a) event water, which is direct precipitation and water that takes overland flow paths to the stream: and b) pre-event water, which is groundwater discharge to the streams (baseflow). The use of electrical conductivity as a tracer for groundwater flow in this study allowed for continuous sampling at each site. End-member conductivity values were determined by field sampling, the use of baseflow data from USGS gauging stations, and the availability of precipitation conductivity data from NADP.

Results were obtained from hydrograph separations of twelve separate storm events for both streams. Although both sites have similar amounts of impervious surfaces, the amount of runoff was different for the two streams and the percentage generated from overland flow was also different. A linear relationship between total, event water and pre-event water runoffs and rainfall was established for both streams. Differences in runoff behavior between the two streams could be due to the placement of impervious surfaces throughout the two watersheds, the size of the watershed area, interactions between the stream and the riparian zone, differences in storage potential for the watershed or other causes.

Introduction

Statement of the Problem

The response to stream discharge to precipitation events generates storm flow; a storm hydrograph is created by plotting instantaneous discharge as a function of time (fig. 1). Hydrographs are important tools to determine the rate at which water is delivered to stream channels, lag times, or the total volume of runoff. However, they do not provide direct information about the source of water or the proportions of water from each source (Ladouche et al., 2001). The amount of storm runoff depends on many variables such as storm magnitude, storm intensity, antecedent moisture conditions, land use, watershed area and the underlying soil and rock characteristics (Betson, 1964).

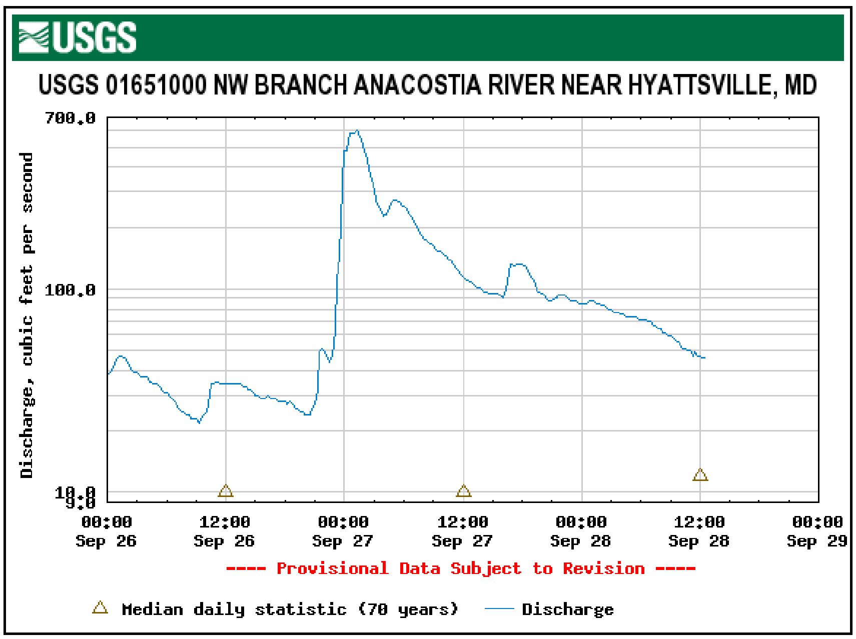


Figure 1: This is a storm hydrograph from the NW Branch of the Anacostia River from the USGS real-time water data website. The Y axis shows discharge in cfs and the X axis represents time. Discharge and other data can be downloaded from the USGS website for this station in 15 minute intervals.

Water can take a variety of pathways to reach a channel during and after storm events. There are four principal sources of storm flow: direct precipitation, overland flow runoff (both from impervious and saturated soil), groundwater flow, and shallow subsurface flow, through what is normally the unsaturated zone (Rice, 1998). Overland flow runoff can be generated due to low infiltration capacities of the soil or impervious surfaces and the runoff generated reaches the stream by a variety of processes (Betson, 1964). For urbanized watersheds, the network of curbs, gutters, and storm drains are the dominant conduits for overland flow runoff to reach the channel (Gremillion et al., 2000). For hydrograph separation purposes, direct precipitation and overland flow runoff are the two processes that convey "event water" to the stream. Event water is water contributed by the storm and identified by its chemical signature.

Water also seeps into stream channels from the unsaturated zone, below the water table and provides stream baseflow (Fetter, 1994). In regions such as Maryland that have high summer evapotranspiration rates, the groundwater table and stream baseflow show seasonal minima in the late summer and seasonal maxima in the late spring (fig. 2). The seasonal recharge of the shallow groundwater system may change the composition of the groundwater that flows to the stream (O'Connell, 1998).

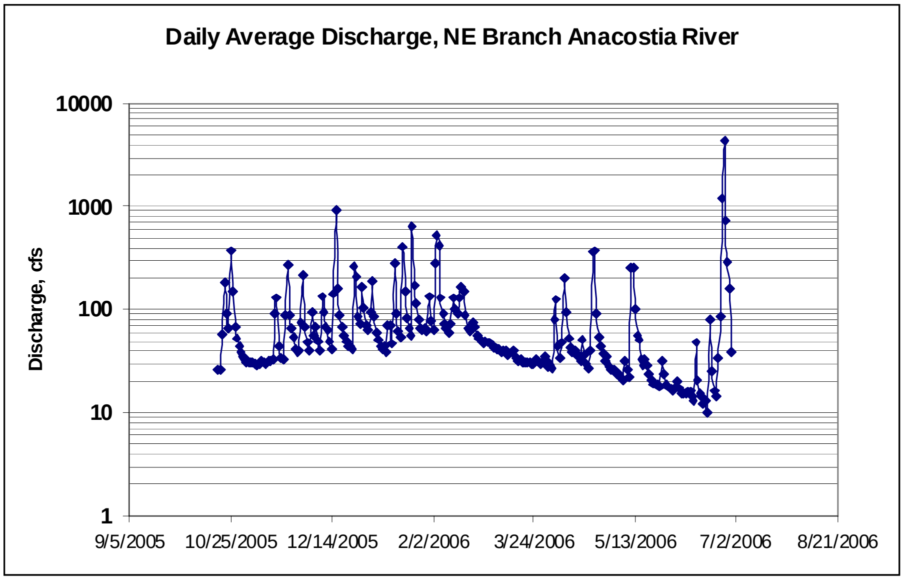


Figure 2: Daily Average discharge, showing the rise of baseflow during the winter months and the decline during the summer months (From Devereux, 2006).

During storm events, water that infiltrates into the ground can raise the water table position, which can increase the groundwater discharge to stream channels. This water includes both the long-term groundwater and the additional groundwater that is mobilized during the storm event by the change from tension-saturated conditions to saturated conditions in the capillary fringe (Fetter, 1994).   This water is termed pre-event water because it was already in the ground before the storm event occurred.

Shallow sub-surface flow is due to temporary saturation of the unsaturated zone, or transmission of water through interconnected macro-pores in the soil, which carry some infiltrated water to the stream (Dunne and Black, 1970). These macro-pores are formed by tree roots and biota that live in organic-rich soils. Shallow subsurface flow is an important storm flow process primarily in steep, first order, forested watersheds that have steep hydraulic gradients and macro-pores that result in subsurface flow paths with relatively short residence times (Pilgrim et al., 1979). The North East Branch of the Anacostia has a relatively high amount of impervious surfaces except for low-gradient regions near the stream which suggests that shallow sub-surface flow is not a dominant conduit for water to reach the stream channel during a storm event. With this information in mind, shallow sub surface flow is not considered to be a dominant pathway for storm runoff to the Anacostia River.

Researchers have been able to quantify the proportions of various inputs of stream discharge over the course of a storm hydrograph by using mass balance equations of conservative tracers to track sources of discharge (Ladouche et al., 2001). While previous studies have examined the tools necessary to quantify the amount of flow delivered by each pathway, there are few studies that use hydrograph separation procedures to examine sources of runoff in urbanized watersheds. In addition, many studies or runoff generation by hygrograph separation are designed to identify these processes in small, natural watersheds. There have been fewer studies of hydrograph separations in large or urban watersheds, or at multiple locations within a watershed. The use of tracers to perform hydrograph separations conducted at multiple locations within an urbanized watershed would provide information on the sources of water within urban watershed systems, and test the assumption that land use information can predict the amount of overland flow runoff.

In this study, hydrograph separations have been performed at multiple watershed locations within a moderately urbanized watershed. I have examined whether electrical conductivity can be used as a tracer to determine the proportions of overland flow runoff and sub-surface runoff to a channel. The relationship between event water and the amount of impervious surfaces can be explored because this study has examined multiple locations throughout the watershed that have different proportions of impervious surfaces and contain sites that may serve as re-infiltration sites for storm water runoff. The major hypotheses to be tested are as follows:

Hypotheses

1. Electrical conductivity can be used to separate hydrographs into event water (direct precipitation and overland flow) and pre-event water (groundwater) components in urban watersheds.

2. The amount of event water discharge in the stream is directly proportional to the amount of impervious surfaces found within the sub-watershed.

3. At each watershed location the proportion of event water discharge should be similar for different storm events because it reflects the amount of impervious surfaces, which remain constant. The runoff ratio, therefore, does not change due to differences in storm intensity or storm duration.

Previous Research

Researchers who have conducted previous studies (e.g. Pilgrim et. al. 1979, Weiler et al., 1998, Gremillion et al., 2000, and Heppel & Chapman, 2006) have reported on various ways to quantify the amount of water that each storm flow pathway described above contributes to the storm hydrograph. There are two main approaches to the determination of water sources: physical measurements of event water and pre-event water discharge (e.g. Dunne and Black, 1970) that are primarily conducted in small catchments and geochemical proxy studies that can be applied to watersheds of various sizes (Huth et al., 2004; Joerin et al., 2002). Some studies also combine physical and geochemical measurements (O'Connell, 1998).

Geochemical studies use various tracers such as stable isotopes of oxygen and hydrogen or ions in solution like chloride, sodium and silica, or physical parameters like temperature and electrical conductivity. Under the assumption that levels of these tracers are homogeneous throughout the water source reservoirs, (e.g. groundwater or rainwater) they use simple mass balance equations to separate the components of stream discharge into its original contributors, be it groundwater reservoirs, subsurface runoff, or surface runoff assuming they can be identified as part of the event water or pre-event water discharge (Gremillion et al., 2000). This process of dividing the storm hydrograph into its components is called hydrograph separation (Weiler et al, 1999).

Ladouche et al. presents a widely used mass balance equation for hydrograph separation commonly used throughout the literature:

$$Q_t = Q_a + Q_b \qquad (1)$$

$$Q_tC_t = Q_aC_a + Q_bC_b \qquad (2)$$

where Q_t is total stream discharge, Q_a is the discharge from point source a and Q_b is the discharge from point source b. C_t is the total tracer concentration of the stream, C_a is the tracer concentration from point source a, and C_b is the tracer concentration from point source b. Given the concentrations of C_a and C_b known along with Q_t and C_t, equation two can be solved for Q_a and Q_b. An example separation shows there is a clear distinction between storm discharge sources, overland flow runoff and sub-surface flow as seen below in figure 3.

These equations are for use under steady-state conditions; therefore, there are some assumptions that must be made in order to use the equation properly. The concentrations designated to represent the two end-member tracers (event water and pre-event water) must represent an average concentration of their respective reservoir. Also, the end-member concentrations must be significantly different from one another (Gremillion et al., 2000).

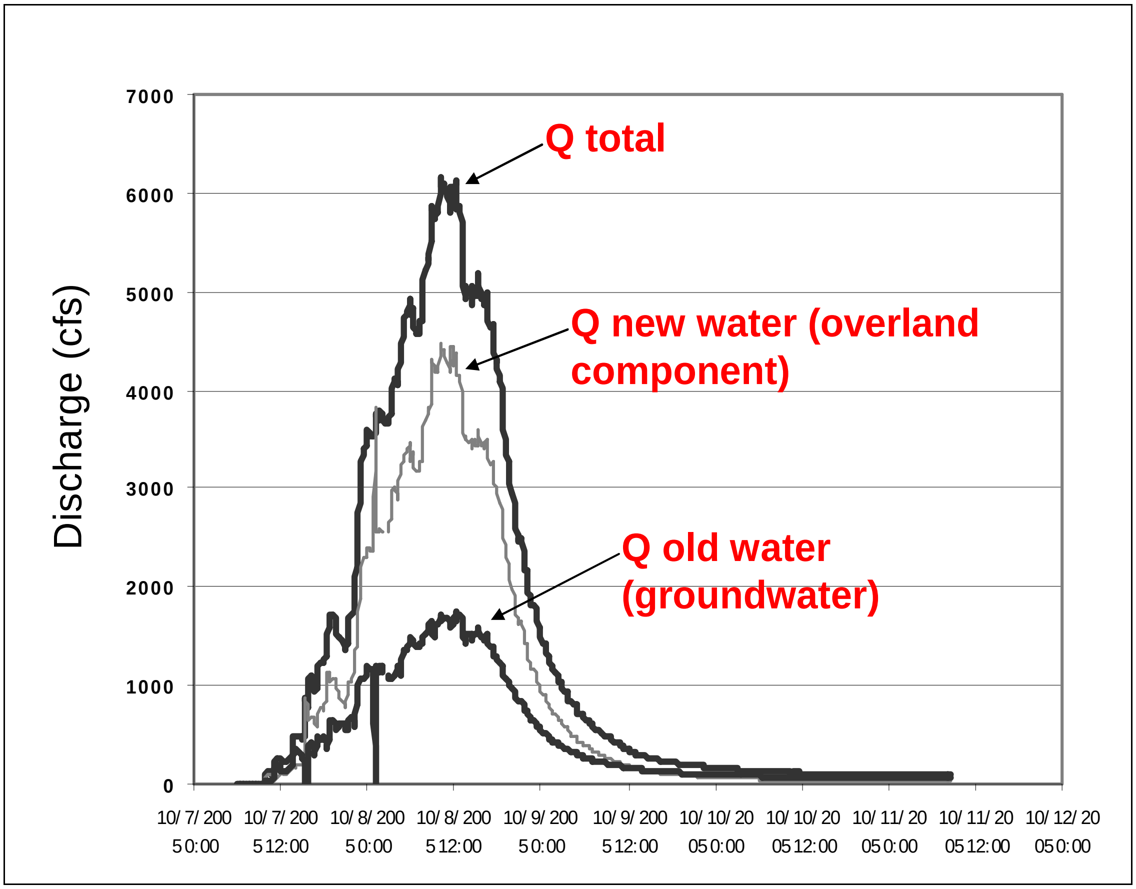


Figure 3: This is an example storm hydrograph separation for an October 2006 storm at the NE branch of the Anacostia River USGS gauging station. Note that the old water component increases during the storm hydrograph, but is smaller than the new water component.

Study Sites and Methods

In order to fully explore the relationship between event water and impervious surfaces, the study sites are located within a watershed with spatially variable amounts of urbanization. The NE Branch of the Anacostia Watershed has four sites chosen for this study, two are instrumented with USGS stream gauges, and two sites have University of Maryland-Geology gauges (fig. 4).

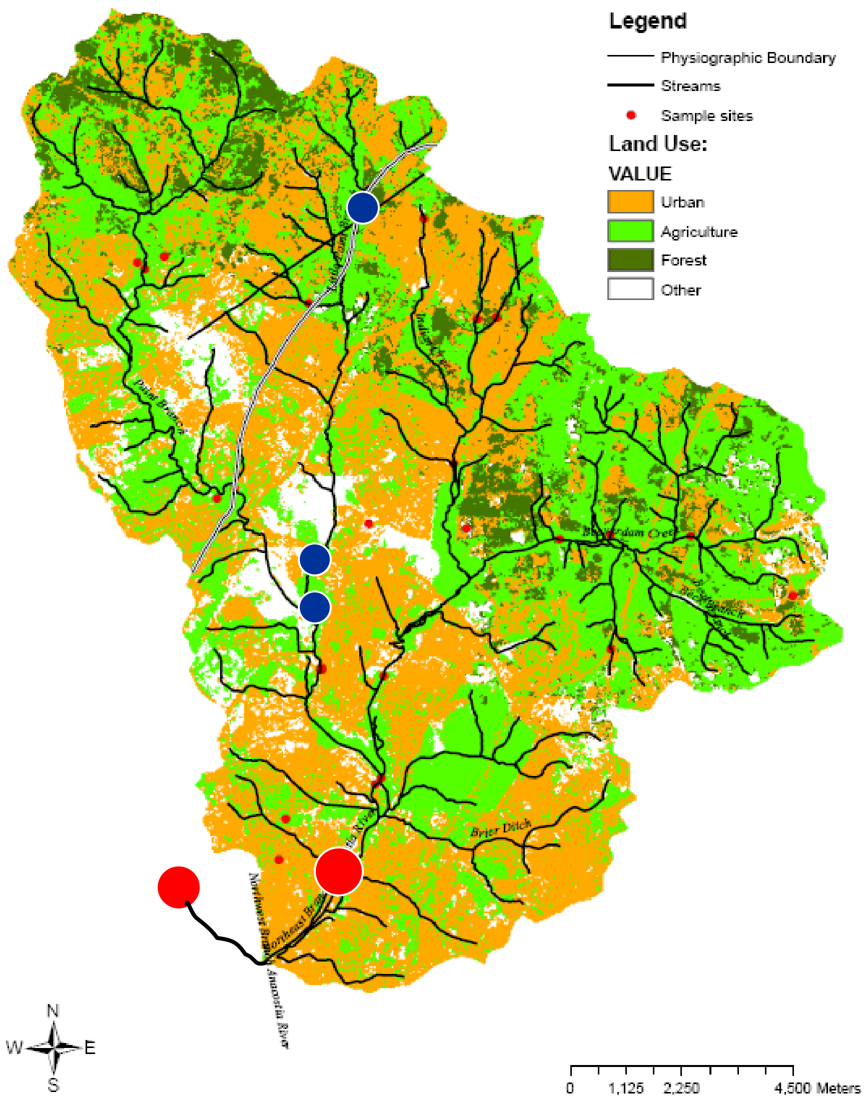


Figure 4: This is a map of the NE branch of the Anacostia watershed. The two red downstream locations are USGS gauges and the three upstream locations are UMD gauges. The map also shows land use (Image taken from Prestegaard and Devereux, 2008).

The five gauged sites drain watershed areas with a range of impervious surfaces from eleven percent to twenty-six percent within the NE branch watershed (Devereux and Prestegaard, 2008). With this range of percent impervious surfaces, I should be able to monitor different proportions of overland flow runoff within the watershed (Table I).

Table I: the gauge location and the amount of impervious surfaces with the site (Adapted from Devereux and Prestegaard 2008).

Gauge Name	Gauge Ownership	Watershed Area in square miles	Percent Impervious Surfaces
Green Castle	UMD	N/A	11
Cherry Hill	UMD	N/A	19
Downstream Cherry Hill	UMD	N/A	19
NW Branch of the Anacostia	USGS	49.4	23
NE Branch of the Anacostia	USGS	72.8	26

Location of Stream Gauges:

1. USGS Gauged sites:

The two downstream gauges, shown in red on figure 3, are the NE and NW branch USGS gauging stations, which automatically record gauge height, specific conductivity, temperature, pH, turbidity, and dissolved oxygen at 15 minute intervals. The NE branch of the Anacostia River gauge is located at lat 38°57'08.4", long 76°57'57.8" and is identified as USGS gauge 01651000. The NW branch of the Anacostia River gauge is located at Lat 38°57'36.9", long 76°`55'33.5" and is identified as USGS gauge 01649500. Data for these sites are available online for up to 60 days, after which it is archived and available from the USGS district office.

These gauges have been in place for approximately 60 – 70 years, and the relationship between gauge height and stream discharge is well-defined by empirical rating curves. These rating curves are quite stable for channelized sections of river, such as the NE and NW branch. Data extracted from the USGS website for its gauged sites includes both gauge height and discharge. The reason they are able to provide discharge calculations for their sites is because they have spent many years creating reliable discharge rating curves, which are graphs of the relationship between gauge height and discharge by taking physical measurements of velocity and cross sectional area at different values of gauge height.

2. UMD Gauged Sites:

The three blue sites on figure 3 are gauges maintained by Dr. Karen Prestegaard, graduate student Zachary Blanchet of the University of Maryland and myself. The relatively close proximity of these gauges to one another was chosen because both sites experience the same amount of impervious surfaces, but may experience different amounts of interaction between the river and riparian zone. The care of these gauges consists of a trip to the field to recover the instruments, a light cleaning of various sensors, downloading of data, then redeployment of the gauges in the field. This data extraction process happens about every two weeks. The UMD sites are instrumented with Hydrolab MS5 (Hach, Loveland CO) gauges that are set up to record data every 7.5 minutes. They record specific conductivity, temperature, turbidity and gauge height. These gauges have been monitored for only a few years, and therefore measurements of area and velocity must be conducted frequently to determine stream discharge and establish a reliable relationship between gauge height and discharge.

We are currently working on creating discharge rating curves for each of the three UMD sites by making discharge measurement in the field when the height of the stream is at different gauge heights. Once established, a well-defined rating curve can be used to determine the discharge of the stream from the gauge height information. The establishment of a rating curve takes time, and it requires a range of flow events that occur during conditions that are safe to make stream discharge calculations.

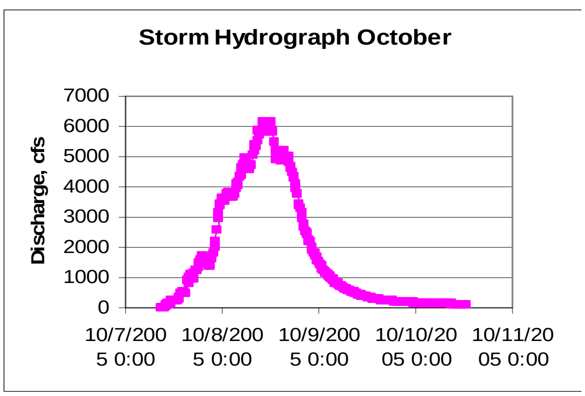
Field measurements required to measure discharge are as follows: In the field, a cross section of the stream is marked with a measuring tape stretched across the channel near the stream gauge. Starting at one side of the channel, a measurement of local depth and average velocity (at 0.4 depth) is made. These measurements are continued across the channel. Usually 10-15 measurements are required to estimate channel discharge within 5% to 10% of the actual value. At each measurement location, the local discharge for each stream segment is made by multiplying each velocity measurement, which is measured at a height that is 0.4 of the depth by a velocity probe, by the local depth and width interval. This measuring process takes about 30 – 45 minutes for each cross section.

We have a variety of velocity meters that can be used to measure velocity. For this project, an Ott meter, attached to a measuring rod is used to measure both channel depth and velocity. The Ott meter is a sensitive propeller meter, similar to a Price type A current meter. An electrical signal is sent to its processor every time the propeller has completed one fill circle. This number can be displayed as a count or as a velocity. There are three choices of time frames over which velocity measurements are taken: 30 seconds, 60 seconds, and 90 seconds. The processor tracks the velocity readings over the selected amount of time, and then displays an average velocity for the selected time frame. These measurements are then used to calculate discharge for a given cross section. Time intervals of at least 60 seconds are used for this project.

I have made a number of measurements to contribute to a rating curve at the UMD locations, and I recognize some of the difficulties involved in making these types of measurements. The hydrograph separations for the three UMD sites were not able to be completed for this project because a solid relationship between discharge and gauge height needs more data points. I have constructed theoretical rating curves for these sites, but have decided to archive the conductivity and gauge height data to be used when a more accurate rating curve is available.

Electrical Conductivity of Water Samples

Electrical conductivity is used as a tracer because, as discussed before, it allows for a continuous mode of sampling stream water at gauges located for each watershed location. An initial evaluation of the data indicates that there is a noticeable relationship between electrical conductivity and stream discharge. To explain this relationship, we can think about what we would expect the electrical conductivity of groundwater and rainfall to be. Because baseflow is composed entirely of groundwater discharge to the stream, it should have a higher electrical conductivity value than rainfall, which has not interacted with the ground. Water that has interacted with the sub-surface is likely to have a higher conductivity value because it has had a residence time in the sub-surface, allowing some ions to transfer into solution. We would expect the conductivity of the rainfall and overland flow to be much lower than that of baseflow, because it has not had time to interact with the sub-surface. Therefore, during a period of storm flow, we see that there is a sharp spike in stream discharge followed by a receding limb over time (fig. 5). When electrical conductivity is plotted for the same storm event, we see that values fall dramatically during the initial rise in the storm hydrograph and the values start to rise during the recession limb of the hydrograph.



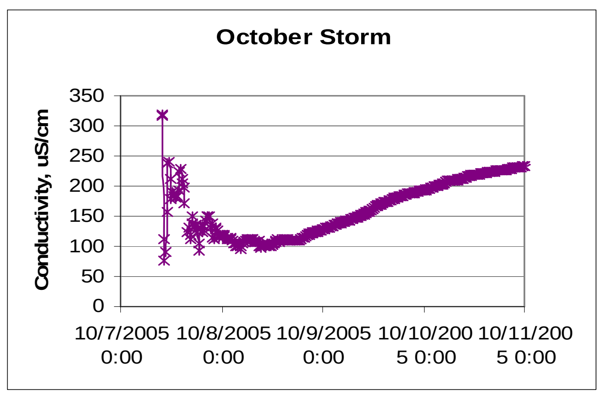


Figure 5: These plots show the inverse relationship between stream electrical conductivity and storm discharge. These data plots are from an October storm in 2006 at the NE branch of the Anacostia River.

The large difference in electrical conductivity values from each discharge source, event water and pre-event water, is a reason why this inverse relationship can be observed between discharge and electrical conductivity in an urban watershed that experiences both overland flow runoff and groundwater discharge. This likely makes electrical conductivity an effective tracer in urbanized watersheds that have a moderate amount of impervious surfaces.

For this study electrical conductivity values were obtained by direct field measurements and by continuous measurements with calibrated field probes. I also used data collected and compiled by NADP and USGS. Procedures for measurement and analysis of each type of data are reviewed below.

Field Measurements of Overland Flow and Precipitation Samples

Overland flow and precipitation samples were collected and analyzed in order to test the hypothesis that overland flow and precipitation values were similar and thus represented the same end member in a two component mixing model of the stream sources. I collected samples of overland flow runoff and precipitation (both constituents of event water) and sampled their conductivity during several storm events. These measurements were made of precipitation and overland flow runoff near the Cherry Hill and Downstream of Cherry Hill gauge sites on September 27th, 2008 and October 25th, 2008. These samples were tested in the field with a Hach SensION156 Meter®. Also, electrical conductivity measurements were taken of overland flow runoff samples collected from the major, minor and residential neighborhood streets surrounding the Cherry Hill site.

Conductivity measurements of overland flow samples and precipitation samples were made with a Hach sensION156 Meter®. The meter has a probe attached to the instrument that has an oval opening, about 5 cm long and 2 cm wide. Within this oval opening, two plates of platinum are faced parallel to one another, on opposite sides of the opening. When in operation, a current generated by the instrument is sent from one plate to the other, thus testing the conductivity (concentration of ions). The oval must be fully submerged in a fluid in order to test its conductivity.

Measurement of Stream Specific Conductivity and Electrical Conductivity

The UMD MS5 gauges from Hydrolab® track many water parameters, such as temperature, gauge height, pH, dissolved oxygen, turbidity and specific conductance. Like the Hach SensION156 Meter®, there is also an oval opening in which stream water is flowing through. There are two metal plates which create a current that runs between them, effectively measuring the specific conductance of the stream. The data are then stored on a data logger within the gauge until the probes are taken from the field, cleaned and the data are downloaded and stored on multiple computers. The gauges are anchored into the streambed of the site locations. Using and auger, Blanchet and fellow graduate student Erik Hankin created deep holes in which the anchor of the gauge was to be inserted. The anchor is made of PVC pipe filled with cement. Once the anchors were in place, the gauges were covered with PVC pipe as well to keep the gauges safe in times of high flow. The encased gauges were then secured to the anchor by thick metal wires. For all sites, the anchor was put directly in the channel near the stream bank.

The two other gauge sites used for this study are operated and maintained by the USGS and the data were downloaded from the USGS website. The stream data collected from these five gauged locations are all measured in situ. This automated collection of data allows for continuous sampling of conductivity (specific or electrical) and gauge height or discharge at each site. The use of the gauges also allows us to examine the conductivity of baseflow, or times when the stream is not experiencing storm runoff conditions because of the continuous sampling. Using electrical conductivity as a tracer concentration instead of a parameter like oxygen isotopes or specific dissolved ions allows me to consider examining four spatially distinct locations. An isotope parameter would involve taking multiple samples at each location, then performing laboratory analyses. Considering the number of sites and how often one must sample, the use of isotopes would be time extremely time consuming and only possible with many extra hands. Electrical conductivity is an effective tracer in this study because the event water has such different electrical conductivity than pre-event water. To compare runoff production at different locations in the watershed, I needed data at each location for the same storm events. Using the in situ gauging locations and the continuous time series of electrical conductivity allow me to gather data from multiple storm events.

Determination of Electrical Conductivity of End-Member Samples:

In this study, I am considering two end-member compositions (event water and pre-event water) from two initial sources: rain water and groundwater. The hydrograph separation procedures are effective if the two sources contributing discharge have significantly different values of conductivity (Gremillion, 2000). Therefore, a large facet of this research has been identifying what conductivity value best represents the event water and pre-event water end members.

- **Baseflow (groundwater) Characterization**:

Following previous research, the electrical conductivity of groundwater discharge, or pre-event water, is assumed to be the baseflow electrical conductivity prior to the elevated limb of the hydrograph caused by the storm event. Baseflow electrical conductivity and specific conductivity is measured in the channel prior to the storm events by the five gauges at their locations. The conductivity of the groundwater portion of discharge is an average of baseflow conductivities over a twenty-four hour period prior to the storm event.

- **Rainwater Conductivity Data:**

The electrical conductivity of event water that has been be used in this study is measured and recorded by the National Atmospheric Deposition Program at their site in Beltsville, MD. The data are available online, and Dr. Jeff Stehr in the University of

Maryland's department of atmospheric and oceanic science has been helpful in obtaining values that are not yet posted on the website. The Beltsville site is located within the NE Branch of the Anacostia River, thus we can assume that the rain water electrical conductivity is similar to the electrical conductivity of the rainfall on the N.E. branch watershed overall. In addition to the data obtained from the NADP, I have been collecting rainwater samples and testing their electrical conductivity with the Hach ion electrical conductivity meter.

Hydrograph Separation Procedures:

Once end-member compositions of event water and pre-event water were identified, hydrograph separation for each storm was conducted. To perform the hydrograph separations at each site, I have used the two mass balance equations from Ladouche et al., 2001.

$$Q_t = Q_a + Q_b$$

$$Q_tC_t = Q_aC_a + Q_bC_b$$

The subscript a is considered the event water component and the subscript b is considered the pre-event water component. Event water can be considered "new water" because it is precipitation and overland flow runoff that composed of storm event precipitation that has not penetrated the ground or had any type of interaction with the groundwater table. Pre-event water can be considered "old water" because it is water that has been stored in the system prior to the storm event and had some sort of residence time in the sub-surface before being deposited to the stream.

As noted above, it is important to note that the electrical conductivity values for each discharge source in the hydrograph separation equations are assumed to be homogeneous and to represent average concentrations of each discharge source. This means that the electrical conductivity of the event and pre-event waters is considered to be the constant over the time of the hydrograph. This assumption must be made in order to perform the hydrograph separations (Ladouche et al., 2001 and Gremillion et al., 2000).

Analysis of Error in the Hydrograph Separation Analyses

Error in two-component mixing models comes from three sources: the variability of the two end-members, taken in this study to be the standard deviations of the two end members and the analytical uncertainty in the measurement of stream values. These sources of error are described below (Genereaux, 1998).

This equation was used to calculate errors for the hydrograph separation analyses. In most cases, the error in the measurement of stream values is much smaller than the variability in the end member compositions. In this case, the standard upper and lower standard deviations of each end member can be used to calculate an error envelope. These two techniques will be compared in the hydrograph separation results.

$$W_{f_1} = \left\{ \left[\frac{C_2 - C_S}{(C_2 - C_1)^2} W_{C_1} \right]^2 + \left[\frac{C_S - C_1}{(C_2 - C_1)^2} W_{C_2} \right]^2 + \left[\frac{-1}{(C_2 - C_1)} W_{C_S} \right]^2 \right\}^{1/2}$$

Where W_{f1} is the error fraction for each measurement involved in the separation, C_s, C_1, C_2 are the conductivity of the stream, event water and pre-event water respectively, and W_{C1}, W_{C2}, and W_{Cs} are the uncertainties of the event water, pre-event water and stream conductivities respectively.

Determination of Rainfall-Runoff Relationships:

The overland flow proportion of runoff is determined from stream flow data and the composition of stream water and end member sources. Precipitation data is required to determine the total amount of runoff generated by the storm events. The United States Department of Agriculture, Beltsville site records rainfall quantity data every 15 minutes. While the daily totals are available online, George Meyers of the USDA- Beltsville was able to share the 15 minute interval data with me. The total amount of storm runoff is calculated from the hydrograph data (integrating under the curve) and divided by the watershed area to determine a point runoff value that can be compared with the point rainfall. This coupling of rainfall magnitude and event water runoff proportions for each storm discharge event allows us to examine rainfall/event water runoff ratios for all four site locations. The hydrograph separation information is then used to determine the relationships between precipitation and both groundwater and overland flow runoff at each site.

Results

Comparison of Overland Flow Conductivity to Precipitation Conductivity

It is often assumed that the electrical conductivity of precipitation is similar to that of overland flow runoff (Gremillion, 2000). This assumption can be made because the precipitation does not have a long residence time and does not make much contact with mineral soils (Weiler et al., 1999). Considering direct precipitation and overland flow runoff as our event water discharge, measurements were needed to be certain that their conductivities were similar. Therefore, I collected samples of overland flow runoff and precipitation at two sites. These measurements were conducted at the Cherry Hill and Downstream of Cherry Hill sites on September 26th, 2008 and October 25th, 2008 storm events. These samples were tested in the field with a Hach SensION156 Meter®. The results from the September 26th storm event are presented in table II.

Table II: This table is recorded conductivity values from the Cherry Hill site on September 26th, 2008. The time column represents the amount of time after overland flow runoff was being deposited out of storm drain into the stream channel. Each measurement was taken of each sample five times in order to obtain standard deviation.

Time	Average conductivity of overland flow runoff in µS/cm	Standard deviation
1	71.5	0.5
5	65.3	0.3
10	57.7	0.4
15	47.6	0.2
20	42.0	0.2

During the storm event, the electrical conductivity of the rainfall was also measured and yielded an average of 52.7 ± 0.3 µS/cm. The rainfall sample was tested a total of five times with the Hach SensION156 Meter®. The average overland flow runoff conductivity was 56.8 ± 12.2 µS/cm during the measurement period. This shows a similarity between the average conductivity value and the average rainfall conductivity value.

Similarly for the October 25th, 2008 storm event, overland flow runoff was collected from the Cherry Hill site, and shows the same similarity between overland flow runoff and precipitation conductivities. This data is shown in table III.

Table III: This table shows conductivity values from the Cherry Hill site on October 25th, 2008. Samples were collected as overland flow runoff was entering the stream via a storm drain. Each sample was tested a total of five times in order to obtain a standard deviation.

Time	Average conductivity of overland flow runoff in µS/cm	Standard deviation
3:00 PM	73.2	0.3
3:10 PM	59.3	0.9
3:15 PM	40.2	0.3
3:20 PM	23.9	0.8

Rainfall samples for the October 25th storm were also collected and tested 5 times to find its conductivity value, with a standard deviation. The rainfall conductivity value was 41.6 ± 0.3 µS/cm. The average overland flow runoff conductivity was measured as 49.23 ± 21.5 µS/cm. This also shows a similarity between the average overland flow runoff conductivity value and rainfall conductivity. Because of this similarity and the fact that only one conductivity value can represent event water concentration, we have used rainfall conductivity data to represent event water conductivity to define our event water end-member.

Baseflow-Groundwater End-member Composition:

In order to properly separate hydrographs into their main components of runoff, the assumptions that accompany these methods must be met. Therefore, as discussed earlier, identifying proper tracer concentrations for the end-member discharges (event and pre-event waters) is extremely important. Also, the end-member discharge concentrations must be significantly different from one another, and represent an average concentration value for the source of discharge.

As stated earlier, pre-event water concentrations are calculated as the average baseflow conductivity prior to a storm event. Figure 6 shows a plot of all pre-event water conductivities used for the twelve separations performed in this study. There is an average of 350.5 ± 52.8 µS/cm. While these values vary considerably with each storm, they are distinctly higher than rainfall and overland flow conductivity values.

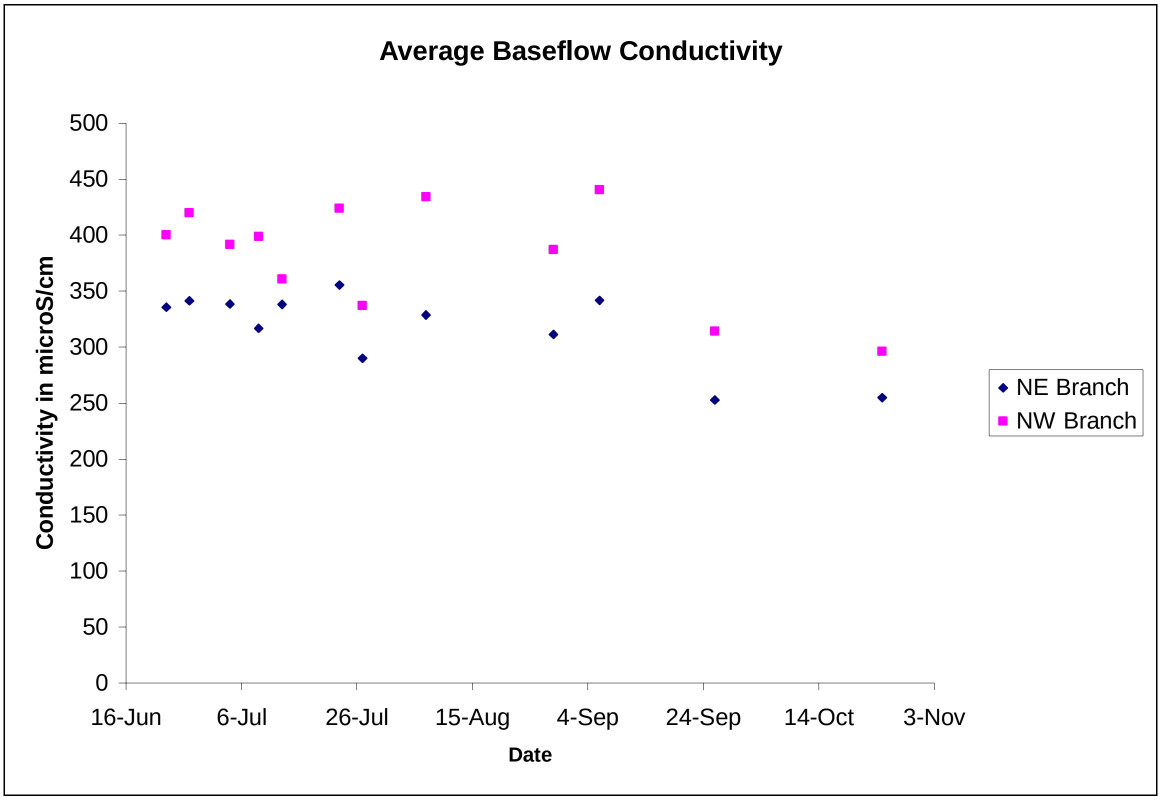


Figure 6: This plot shows the average baseflow conductivities based on data obtained prior to each of the twelve storm events evaluated in this study. Note that baseflow conductivities increase in the summer as evapotranspiration increases, and it decreases in the fall with lowered evapotranspiration rates. Winter data were not used due to the effects of road salts on the conductivity values.

Precipitation End-member Values:

Precipitation data, chosen to represent event water, gathered from the NADP, Beltsville site, is shown in figure 7. This plot was made with over 6 years of precipitation conductivity values. With an average of 26.2 ± 11.7 µS/cm, there is a clear difference between the conductivity of the event and pre-event waters.

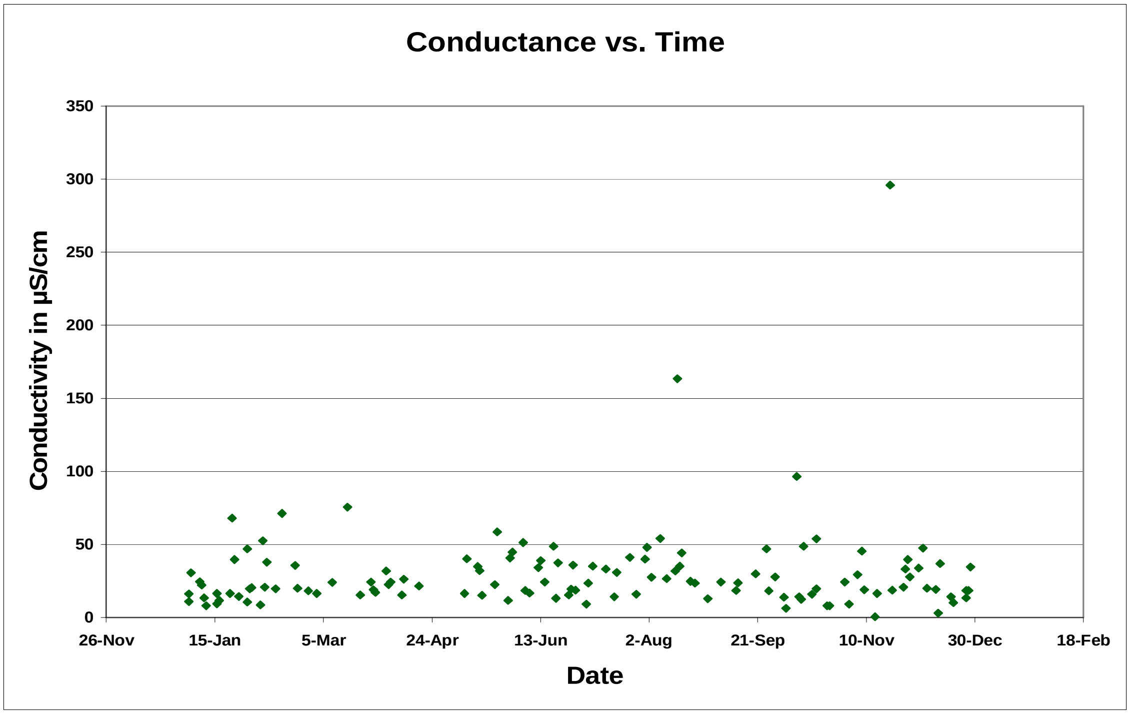


Figure 7: Seasonal variations in precipitation data from 2004 to 2008. The arithmetic mean is 25.0 µS per centimeter with a standard deviation of 12.7 µS per centimeter. This data was provided from NADP.

To assure the conductivity of event and pre-event waters are in fact end-member concentrations of the overall storm discharge conductivity, figure 8 has been included. In this plot the conductivity of average baseflow, overland flow runoff and precipitation and total storm discharge were plotted. From this plot it is clear that baseflow, or pre-event water, and precipitation and overland flow runoff, or event water, are in fact end-member scenarios of possible storm discharge conductivities. It is also evident from this plot that precipitation and overland flow runoff averages are similar within one standard deviation from their means.

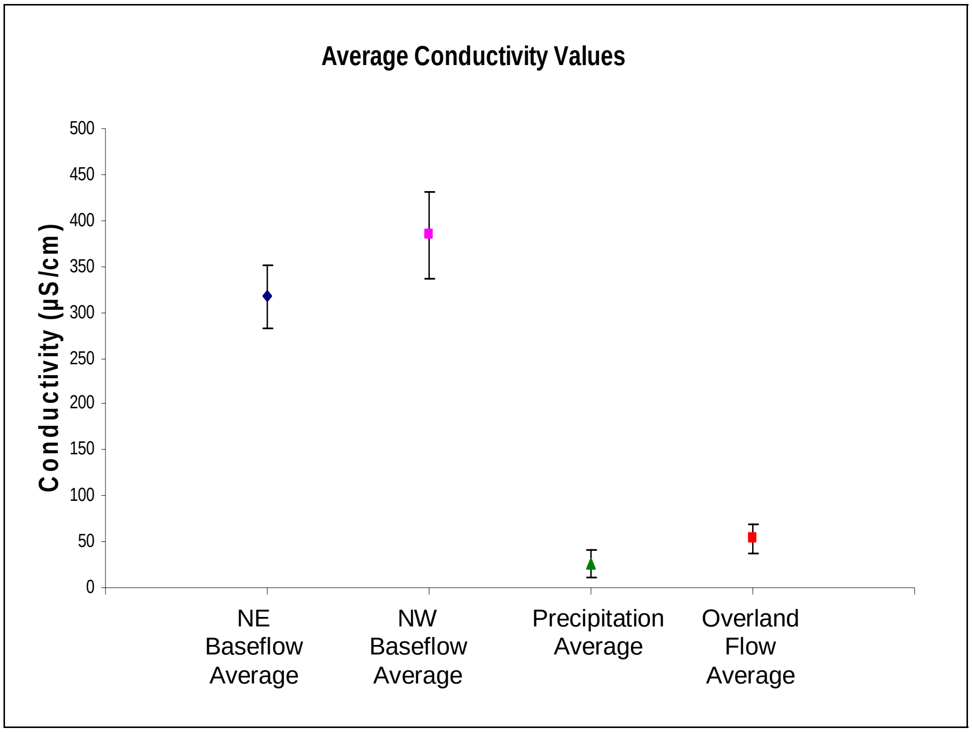


Figure 8: This plot shows the three end-member averages and standard deviations. Precipitation and overland flow runoff data overlap, while baseflow conductivity values are distinctly higher.

Average conductivity values of pre-event and event water were used in all hydrograph separations performed in this study, as well as the end-members having significantly different conductivities. Thus, the requirements for applying hydrograph separation analyses using electrical conductivity have been met. Therefore, this is consistent with the first hypothesis asserting that electrical conductivity can be used as a tracer to separate storm hydrographs in urban watersheds.

Hydrograph Separation Results and Error Analysis for Individual Storms:

The data set obtained for the NE and NW Branch gauges includes twelve storm events from June 23rd, 2008 to October 25th, 2008. The results for the NE Branch hydrograph separations are provided in Table IV. Table V contains the results from the NW Branch separations.

Table IV: This table shows the results of the hydrograph separation performed on twelve storm hydrographs in the NE Branch of the Anacostia River.

Date of storm	Percent of Pre-event	Percent of Event
June 23rd	59.5 ± 10.8	40.5 ± 10.8
June 27th	60.2 ± 4.0	39.8 ± 4.0
July 4th	72.8 ± 6.1	27.2 ± 6.1
July 9th	51.7 ± 3.4	48.3 ± 3.4
July 13th	51.8 ± 4.1	48.2 ± 4.1
July 23rd	38.2 ± 3.3	61.8 ± 3.3
July 27th	56.8 ± 3.6	43.2 ± 3.6
August 7th	50.0 ± 3.5	50.0 ± 3.5
August 29th	82.1 ± 6.5	17.9 ± 6.5
Sept. 6th	37.9 ± 5.8	62.1 ± 5.8
Sept. 26th	47.3 ± 7.8	52.7 ± 7.8
October 25th	59.8 ± 3.5	40.2 ± 3.5

Table V: This table shows the results from the hydrograph separations performed over twelve storm hydrographs in the NW Branch of the Anacostia River.

Date of storm	Percent of Pre-event	Percent of Event
June 23rd	61.7 ± 3.6	38.3 ± 3.6
June 27th	45.5 ± 3.7	54.5 ± 3.7
July 4th	74.3 ± 2.8	25.7 ± 2.8
July 9th	41.1 ± 3.1	58.9 ± 3.1
July 13th	36.9 ± 4.2	63.1 ± 4.2
July 23rd	24.8 ± 3.2	75.2 ± 3.2
July 27th	34.1 ± 3.7	65.9 ± 3.7
August 7th	49.0 ± 2.9	51.0 ± 2.9
August 29th	53.5 ± 12.8	46.5 ± 12.8
Sept. 6th	16.8 ± 3.3	83.2 ± 3.3
Sept. 26th	43.6 ± 9.0	56.4 ± 9.0
October 25th	40.0 ± 7.7	60.0 ± 7.7

For the twelve storms separated for this study, it is clear that there are varying degrees of pre-event and event water proportions for both site locations during different storm hydrographs. The intensity and duration that is specific for each rainfall event may account for this wide variation between storm hydrograph contributions.

The uncertainty seen in Tables IV and V was calculated using an error enveloping technique. This was accomplished by separating each storm hydrograph a total of three times using different conductivity values of pre-event and event water. The first separation was performed using the average conductivity vales, the second using the average plus one standard deviation from the mean, and the third using the average minus one standard deviation from the mean. This process effectively gives an upper and lower bound to the amount of uncertainty that comes with using averages.

It is important to note that this error enveloping technique does not take into account the error that is encountered by measuring the gauged stream conductivity. While this error is exceptionally small when compared to the uncertainty of the average conductivity values for the pre-event and event waters, it is important to explore how incorporating this small error will affect the results. The equation from Genereux, 1998 was used to compare the results of the error enveloping technique with an equation that calculates stream conductivity error.

The results of this equation yielded the same results as the error enveloping technique. This is most likely because the uncertainty in the stream conductivity as measured by the stream gauges is ± 0.001 µS/cm.

Event and pre-event water contributions to runoff

After determining the values of event and pre-event water for each storm hydrograph, they are compared to the amount of rainfall caused by each storm. The rainfall data used for each storm event was obtained from George Meyers of the United States Department of Agriculture, Beltsville Agriculture Center for Research. This data is appropriate to use because it was collected in the study watershed.

A plot of the total runoff, event water runoff and pre-event water runoff for the NE Branch is found in Figure 9. Most values for total, event water and pre-event water runoffs fit a decent trendline. A predictable relationship between the rainfall and various types of runoff is observed in this plot. The relationship shows that as rainfall increases, the amount of runoff increases as well, suggesting that they are proportional to one another.

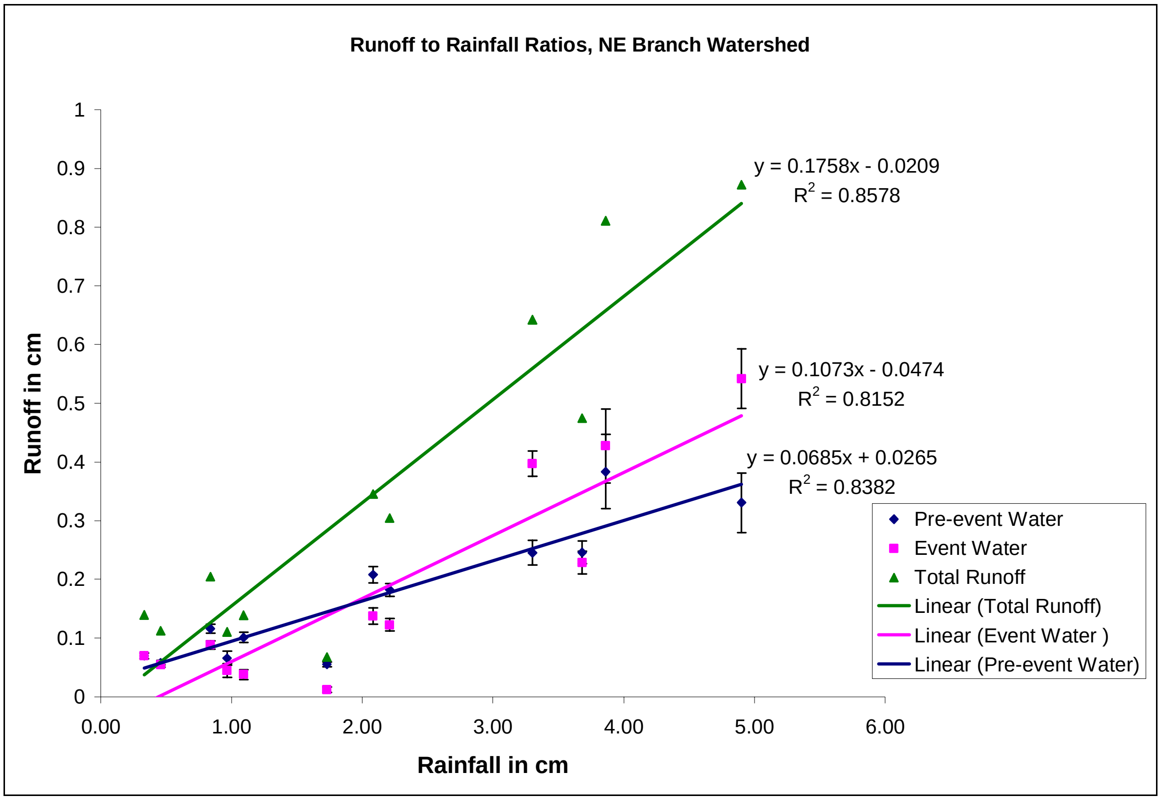


Figure 9: This plot shows the relationship between rainfall and runoff for 12 storm events in the NE branch of the Anacostia River. Upper diagram shows total runoff, which indicates runoff is ~18% of rainfall, significantly less than the amount of impervious surface in the watershed. Overland flow runoff accounts for 61% of the total runoff, while subsurface flow accounts for 39% of total runoff.

Figure 9 shows that total runoff in the NE Branch accounts for approximately 18% of the total rainfall, which is significantly less than the amount of impervious surfaces for this site, which was 26%. This is further broken down into event water contributing approximately 11% of total rainfall and pre-event water contributing approximately 7 %. Because of the large amount of impervious surfaces at this site, it is expected that event water runoff would be the dominant storm discharge source. Of the total runoff for the NE Branch (18% of total rainfall) approximately 61% is produced from event water and approximately 29% from pre-event water. This larger proportion of event water is expected from a watershed with 26% impervious surfaces.

The point at which the event water and pre-event water trendlines intersect shows us the magnitude of rainfall that needs to occur for one runoff process to dominate the total storm hydrograph. In this case, it takes approximately 1.9 cm of rainfall for event water runoff to be the dominant discharge source over pre-event water. If there is less than 1.9 cm of rainfall, pre-event water runoff will dominate the storm discharge.

Results for the NW Branch are found in Figure 10. This plot relates total, event-water and pre-event water runoff values for eleven out of the twelve storms. The storm event that occurred on September 6th, 2008 was excluded from the plot because of an extremely high level of runoff to rainfall that was not consistent with the rest of the data points. This extreme runoff value could have been caused by spatial variability in the precipitation values, or an added level of complexity with regard to contributing flow paths.

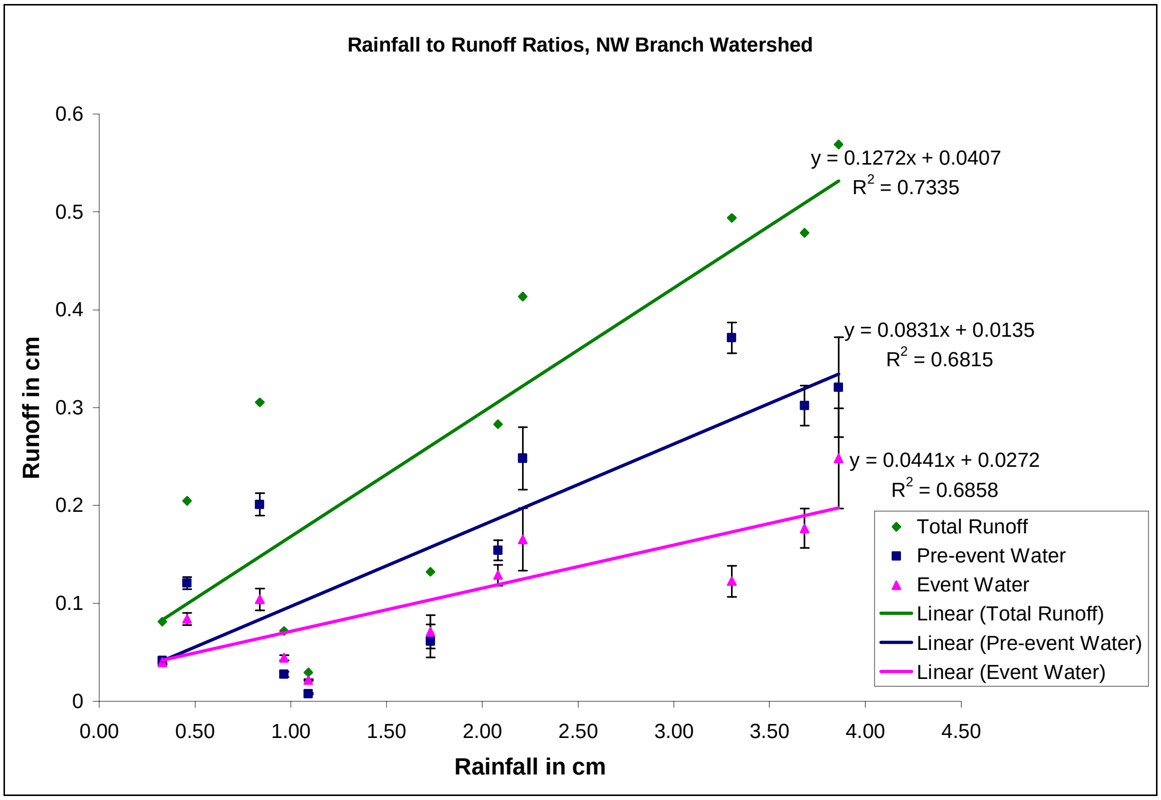


Figure 10: This plot shows the relationship between rainfall and runoff for 12 storm events in the NW branch of the Anacostia River. Upper diagram shows total runoff, which indicates runoff is ~13% of rainfall, significantly less than the amount of impervious surface in the watershed. Overland flow runoff accounts for 35% of the total runoff, while subsurface flow accounts for 65% of total runoff.

The data points in Figure 10 do not fit the trendline as well as in Figure 9. Figure 10 shows more scatter with the data points than in Figure 9. This scatter may be caused by a large amount of cement lined channels contributing to the gauged site. Even though the NE Branch site has a much larger contributing watershed area, this scatter of points for the NW Branch site tells us that there are most likely some added levels of complexity within the NW Branch's flow paths during storm events. This could be due to the fact that there are more complex concrete channels in the NW Branch stream system which could potentially complicate the groundwater mechanics of the watershed at those points.

The large amount of scatter could also be due to a spatial variability in the amount of precipitation at the NW Branch. The data from one rain gauge was used to represent the amount of precipitation that has contributed to runoff for both sites, and there may be some variability in the intensity and overall accumulation of precipitation, leading to more scattered data points.

Figure 10 tells us that approximately 13% of total rainfall is expressed as total runoff. Once again, the amount of total runoff at this site is significantly less than the amount of impervious surfaces (23%). Conversely to the NE Branch, the NW Branch is dominated by pre-event water discharge, which accounts for 8% of the total rainfall. Event water discharge accounts for 4 % of total rainfall. However, these percentages were calculated from the trendlines, which the data does not completely fit.

Even though the data points in Figure 10 do not fit the trend perfectly, there is still this increase of event water runoff with increasing rainfall. The amount of impervious surfaces stayed constant throughout the study. However, the trendlines from Figure 10 should all have an x-intercept, meaning there needs to be some amount of rainfall present for runoff to be generated. This is not the case in Figure 10. All trendlines have a positive y- intercept meaning that there is already runoff occurring without any rainfall necessary. This is not something that we see in this watershed, and does lead to some inconsistency with regard to the results from this site.

Evaluation of Hypotheses

As demonstrated earlier, the tracer conditions for hydrograph separation analysis were met. This included using significantly different, well defined average end-member conductivities in order to separate the storm hydrographs. This means that electrical conductivity can be used as a tracer to separate hydrographs in urban watersheds, which is consistent with my first hypothesis.

While a linear relationship was developed between the amount of runoff and the amount of rainfall, it was clear that the amount of total runoff is not proportional to the amount of impervious surfaces for each site. Also, the amount of event water runoff for each site was not proportional to the amount of impervious surfaces. The amount of impervious surfaces for the NE branch was 26% and event water runoff accounted for 11% of total rainfall. These values are not proportional to one another. Similarly for the NW branch, the amount of impervious surfaces is 23%. The event water runoff accounted for 4% of the total rainfall. This once again demonstrates that event water runoff is not proportional to the amount of impervious surfaces, thus refuting my second hypothesis.

As seen in Table VI, it is clear that the event water runoffs to rainfall ratios are not constant within the amount of uncertainty for all storm events. This inconsistency can be seen for both the NE and NW branch sites. This is inconsistent with my third hypothesis.

Table VI: This table shows the event water runoff to rainfall to runoff ratio for both NE and NW branch location. For each site, it is clear that the ratio is not constant within the allotted uncertainty.

Gauge Location	Date of storm	Event water runoff to rainfall ratio
NW	June 23rd	0.05 ± 0.00
NW	June 27th	0.06 ± 0.01
NW	July 4th	0.02 ± 0.00
NW	July 9th	0.18 ± 0.01
NW	July 13th	0.05 ± 0.01
NW	July 23rd	0.04 ± 0.00
NW	July 27th	0.12 ± 0.01
NW	August 7th	0.12 ± 0.01
NW	August 29th	0.04 ± 0.01
NW	Sept. 6th	0.06 ± 0.01
NW	Sept. 26th	0.06 ± 0.01
NW	October 25th	0.07 ± 0.01
NE	June 23rd	0.05 ± 0.01
NE	June 27th	0.07 ± 0.01
NE	July 4th	0.03 ± 0.01
NE	July 9th	0.12 ± 0.01
NE	July 13th	0.06 ± 0.01
NE	July 23rd	0.12 ± 0.01
NE	July 27th	0.11 ± 0.01
NE	August 7th	0.21 ± 0.01
NE	August 29th	0.01 ± 0.00
NE	Sept. 6th	0.11 ± 0.01
NE	Sept. 26th	0.11 ± 0.02
NE	October 25th	0.06 ± 0.00

Discussion

Figures 9 and 10 point out that rainfall is not equal to total runoff. In fact, from these plots we see that there is considerably more rainfall then runoff at both sites. This implies that there is some sort of rainfall storage happening within both watershed sites for this study. For the NE Branch, there is approximately 82% storage of rainfall and 87% storage of rainfall for the NW Branch. These are both very large numbers and can offer some insight into the storage mechanics of the watersheds.

Even though a proportionality between runoff and rainfall has been established, when viewing the raw data for each site's separated storm hydrograph it is evident that the runoff to rainfall ratios are not constant from one storm to another within their uncertainties. This suggests that storm intensity or other factors do have an effect on the amount of runoff generated for each site.

The fact that the amount of impervious surfaces has stayed constant throughout the study can offer some insight into how they might affect the runoff to rainfall ratios. It was initially thought that the amount of impervious surfaces would dictate the amount of runoff generated at each site. Using the hydrograph separation techniques discussed above, it is clear that the amount of runoff generated is dependant upon the size of the storm. Variables such as the infiltration capacity of the ground, water table height, capillary fringe height, storm magnitude, and storm intensity may dictate the amount of overland flow runoff generated by individual storm events. In effect, more than impervious surfaces only dictate the amount of overland flow runoff experienced at each site location.

The event water runoff to rainfall ratio for both sites did not remain constant for storms of different magnitudes. This may have something to do with the fact that event water was considered to be a mixture of direct precipitation and overland flow runoff. Because of this assumption, as total rainfall increases, the amount of direct precipitation will increase proportionally, but the amount of overland flow runoff may be affected even by the amount of time in between storms which can dictate the rate at which water can permeate the ground water table at infiltration zones. If a storm is occurring the day after a major storm event, the characteristics of infiltration could be drastically different in the infiltration zones. Conversely, if the storm event is occurring during dry conditions, or drought conditions, this could also affect the infiltration characteristics of the infiltration zone. The uneven spacing of storms used in this study could account for the runoff to rainfall ratios that are not constant.

Although the two watershed sites chosen for this study display similar amounts of impervious surfaces, the hydrograph separation results shown in Figures 9 and 10 show a difference pertaining to the dominant source of runoff. This may be attributed to differences in urban land use, amount of cement lined channels and the amount of channelization in each reach. This raises an interesting question about differences in land use, and what is truly meant by an impervious surface.

Suggestions for further study

Once proper rating curves have been created for the three UMD gauged sites, hydrograph separation analyses should be performed on the storm hydrographs that have been collected. This will offer some insight as to how event water runoff, and even runoff in general operates throughout the entire NE Branch watershed, from the headwaters at the Greencastle site to the mouth, the NE Branch USGS gauge.

The proximity of the two UMD sites, Cherry Hill and Downstream Cherry Hill, allows us to observe how runoff varies over a relatively short distance of stream channel with a significant flood plain that might provide sites for re-infiltration of storm water. These two gauges drain almost the same watershed area and amount of impervious surfaces; we would expect to see similar amounts of runoff generated at each site. These two sites also have a moderately sized floodplain along the reach. The determination of proportions of event water and pre-event water to each site can provide information about the intimate relationship between the channel and the floodplain, and the surface and sub-surface. Tying this information together with the USGS sites, we can have a better understanding of how overland flow runoff evolves in an urbanized watershed and how it is effected by the presence of impervious surfaces

Conclusion

Twelve storm hydrographs were separated for two different locations within the Anacostia Watershed. Using electrical conductivity and established two-component mixing models, we were able to estimate the amount of runoff from pre-event and event water sources. The testing of end-member conductivities indicates that electrical conductivity can be used within urban watersheds to separate storm hydrographs, because they are distinctly different from one another.

The hydrograph separation results for each site indicate a range of event and pre-event water contributions for each storm event. When compared with the magnitude of the rainfall, a relationship developed relating the amount of runoff, total, event water and pre-event water, and total rainfall. This relationship is created by the presence of impervious surfaces. While this relationship was demonstrated more strongly in the NE Branch data, the relationship was still apparent for the NW Branch. The NW Branch data exhibited more scatter with its runoff to rainfall data points, which most likely hints to the underlying complexity of flow paths within the watershed, or a spatial variability in the rainfall data.

These results in connection with future separation studies for the three UMD gauges could offer a more concentrated approach to understanding how runoff is routed throughout watersheds from its headwaters to its mouth. It could also tell us more about the complex storage system within the NE Branch watershed.

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Honor Pledge

I pledge on my honor that I have not given or received any unauthorized assistance or plagiarized on this assignment.