ABSTRACT

Title of Thesis: COMPARISON OF HYDROLOGIC AND HYDRAULIC CHARACTERISTICS OF THE ANACOSTIA RIVER TO NON-URBAN COASTAL STREAMS

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Streams in urban areas often utilize channelization and other bank erosion control measures to improve flood conveyance, reduce channel migration, and overbank flooding. This leads to reductions in evapotranspiration and sediment storage on floodplains. The purpose of this study is to quantify the evapotranspiration and sediment transport capacity in the Anacostia Watershed, a large Coastal Plain urban watershed, and to compare these processes to a similar sized non-urban watershed. Times series data of hydrologic and hydraulic changes in the Anacostia, as urbanization progressed between 1939-2014, were also analyzed. The data indicates lower values of warm season runoff in the non-urban stream, suggesting a shift from evapotranspiration to runoff in urban streams. Channelization in the Anacostia also increased flow velocities and decreased high flow width. The high velocities associated with channelization and the removal of floodplain storage sites allows for the continued downstream transport of sediment despite stream bank stabilization.

COMPARISON OF HYDROLOGIC AND HYDRAULIC CHARACTERISTICS OF THE ANACOSTIA RIVER TO NON-URBAN COASTAL STREAMS

by

Mallori McDowell

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List of Symbols and Abbreviations

km^2	Kilometers Squared
%	Percent
USGS	United States Geological Survey
km	Kilometers
PPT	Precipitation
ET	Evapotranspiration
RUN	Runoff
ΔS	Change in Storage
PRISM	Precipitation-elevation Regressions on Independent Slopes Model
cm	Centimeters
n	Total Number of Events
w	Width
d	Depth
v	Velocity
a	Width Coefficient
c	Depth Coefficient
k	Velocity Coefficient
Q	Discharge
b	Width Exponent
f	Depth Exponent
h	Velocity Exponent
R^2	R Squared Value, Describing the Fit of a Regression
cms	Cubic Meters per Second
m/s	Meters per Second
m	Meters
St.	Saint
m^3/s	Cubic Meters per Second
m^2	Meters Squared

Chapter 1: Introduction

1.1 Statement of the Problem and Previous Research

Urban and suburban lands represent a small but increasing fraction of Earth's total land surface area. Decreased permeability and increased hydrologic connectivity caused by impervious surfaces and storm sewer systems associated with urbanization have significant impacts on hydrologic processes, stream morphology, water quality, and ecosystem health (Leopold, 1968). Furthermore, many urban areas are located along major rivers, estuaries, and coasts where urban areas can have significant impacts on downstream water bodies (Paul and Meyer, 2001; Brown et al., 2009).

Quantification of the effects of urbanization on watershed hydrology and stream channel morphology received significant attention in the late 1960's to early 1970's (e.g. Wolman, 1967; Leopold, 1968; 1973; Rantz, 1971; Hammer 1972; Dunne and Leopold, 1978). These studies identified major changes in watershed hydrology that resulted from impervious surfaces (roads, roofs, parking lots, etc.) located in the watersheds. The combination of impervious surfaces and storm sewer systems increases storm runoff and decreases the time it takes for the hydrograph to respond (Leopold, 1968; Rantz, 1971; Paul and Meyer, 2001, Konrad and Booth, 2005). Consequences of urbanization are evident in stormwater hydrographs, which often exhibit shortened lag times, higher peak discharges, shorter duration floods, and lower baseflow discharge compared with pre-urban conditions (Leopold, 1968; Dunne and Leopold, 1978; Paul and Meyer, 2001;

Konrad and Booth, 2005). Many of these studies were conducted in small catchments that were significantly altered by urban development.

Watershed changes due to urbanization often generate larger and/ or more frequent peak discharges can cause a cascade of hydraulic changes in stream channels that can significantly alter channel morphology. An increase in discharge and flow depth in response to storm events can increase shear stresses, which can cause bed or bank erosion and channel enlargement (Hammer, 1972). Eroded sediment from overland flow runoff or bank erosion can significantly increase stream suspended sediment and/ or bedload sediment loads resulting in significant water quality impairment (Hammer, 1972). In some urban watersheds, coarse sediment supply might be limited, resulting in significant channel bed erosion that is not replaced by new sediment transport. Over time, these hydraulic changes can lead to channel incision (Simon et al., 1999; Simon and Darby, 1999), channel widening (Hammer, 1972), and in downstream reaches sediment aggradation. Local channel changes depend upon the supply and size of sediment, the changes in the flow regime, and the position within the watershed.

Early studies of the effects of urbanization on channel morphology suggested that channels would adjust (e.g. by channel widening) to these new urban flow regimes, leading to local quasi-equilibrium channel formation within a 10-30 year time interval (Hammer, 1972). Studies of channel incision, however, indicate that channel deepening may initiate a sequence of channel changes that may continue for decades or longer (Harvey and Watson, 1986; Simon, 1989; Thorne, 1999; Erskine, 1999). Consequences of channel widening can result in downstream sediment deposition and bed aggradation leading to local flooding. Channel incision may result in damage to bridges and other structures, and affect groundwater levels and riparian vegetation (Bravard et al., 1997). Blanchet, 2009, found that channel widening and bar formation could lead to non-linear changes in channel morphology adjustment that can cause shoaling of channel beds and re-attachment of channels to their floodplains.

Although research on channel adjustments to agricultural or grazing land uses have been conducted on large (> 100 km^2) watersheds (Schumm and Hadley, 1957; Leopold et al, 1964; Meyer, 1990; Patton and Schumm, 1975; Elliot et al., 1999), most of the research on channel changes in the urban setting has been conducted on small watersheds, often less than 10 km^2 (e.g. Hammer, 1972; Konrad and Booth, 2005). These small watershed studies often indicate that increases in runoff volume and peak discharge are proportional to the amount of impervious cover (e.g. Rantz, 1971; Konrad and Booth, 2005; Paul and Meyer, 2001, Beighley and Moglen, 2002) and that significant degradation of channel morphology and biological diversity can occur with impervious cover > 10% (Henshaw and Booth, 2000; Miltner et al., 2004). The Impervious Surface Model projects that stream hydrology, habitat, water quality and biotic indicators of stream health start to decline at approximately 10 percent impervious surface cover in small watersheds (Schueler et al., 2009). Application of these results to management practices has resulted in identification of non-urban regions where growth is to be limited (i.e. kept below 10%), and urban tiers where growth and infill development is to be encouraged (e.g. Maryland-National Capitol Park and Planning Commission, 2002). These urban development guidelines are geared to the protection of small watersheds from urban hydrologic impacts, hydrologic and geomorphic changes in large urban watersheds may be significantly different and require further research and different mitigation plans.

Studies of hydrologic processes and associated geomorphic responses are uncommon in relatively large (> 100 km^2) urban-suburban watersheds, and it is unclear whether the 10% impervious surface guideline for impairment, defined from research on smaller watersheds, applies to these systems. Research by Occhi (2010) of watersheds of varying size but with similar percentages of impervious surfaces, suggests that runoff ratios may be higher in small subwatersheds than the larger watershed to which they contribute. This suggests that large, complex watersheds may contain sites for runoff retention that are not commonly present in small watersheds. Possible sites for retention (surface or subsurface storage) are flood plains or riparian zones located along tributary and main trunk streams. Stored water can evaporate from surface storage, be transported by subsurface flow paths to support stream baseflow, or be used by plants and transpired to the atmosphere (Brutsaert, 2005). Recent research on small catchments suggests that storage functions regulate much of the hydrologic behavior of non-urban catchments (Kirchner, 2009). They may be even more important in larger watersheds that provide additional opportunities for water storage and evapotranspiration if they contain large, complex floodplains. Evapotranspiration and storage can be evaluated with water balance calculations, but it is difficult to separate evapotranspiration from storage, particularly in large watersheds.

Stream channel morphology is adjusted to bankfull stream discharge, which in many humid-temperate regions is a high frequency flood that occurs every few years (Dunne and Leopold, 1978). Therefore, stream morphology changes have been correlated to increases in the amount of impervious surface in a watershed (Dietz, 2007; Schueler et al., 2009). Stream enlargement is a common response of stream channels in urban watersheds to increased high frequency flood discharges (Hammer, 1972; Dunne and Leopold, 1978). Sediment and associated contaminants that are released by these channel adjustments are significant factors that contribute to the degradation of water quality in urban environments (Doyle, 2000). In many urban watersheds, channel incision resulting from bed erosion can reduce the frequency of overbank flooding (Doyle, 2000). Incised channels, stormwater and transportation infrastructure and entrenchment can all cause a disconnect between the stream channel and the floodplain (Craig et al, 2008). In recent years the floodplain has been demonstrated to play important roles in flood wave mitigation, sediment deposition, nutrient storage, and other stream and ecosystem processes (Tockner and Stanford, 2002). One of the most important roles of the floodplain is to facilitate the interaction between groundwater and surface water in a stream (Lundberg, 2011). Channels that adjust their beds through aggradation and gravel bar formation may also re-connect the storm hydrology to the floodplain. Overbank flows can transport sediment onto floodplains where sediment deposition can occur. Disconnection of the stream and floodplain leads to only one direction of groundwater and surface water flow, from the floodplains to the stream. The result of this one directional flow is less ability of the stream-floodplain system to retain sediment and nutrients (Noe and Hupp, 2005).

Watershed management and stream restoration goals should be focused on improving both *local* stream habitat and minimizing the *downstream* effects of urban and suburban land uses. While local effects of urban runoff may include channel erosion, loss of bank and bed habitat, decreased water quality, downstream effects can include turbidity (lack of water clarity), water quality impairment, and other changes that affect biological habitat, productivity, and diversity (Doyle, 2000). Early studies on the adjustment of stream channels to urbanization suggest that sediment loads would be high during construction and initial channel adjustment phases and then decline as new equilibrium conditions were established (Wolman, 1967; Hammer, 1972; Dunne and Leopold, 1978). This view of the interaction between urbanization and sediment mobilization is reflected in sediment management laws (sediment fences etc. during construction) and channelization and stream restoration practices in urban streams. Larger urban watersheds (>100 km^2) may experience heterogeneity in the timing and style of urban and suburban development. This may lead to sequential responses of stream channels to urbanization. Research on the adjustments of stream channels to ongoing urbanization or suburbanization indicates that channel responses may be highly non-linear and may include changes in sinuosity, transport rates, bar deposition, and other complex responses (Blanchet, 2009).

Flooding has long been a hazard to property and human lives. In urban areas, engineering design has been used to mitigate flood hazards. Stream channelization, or the engineering practice of straightening, deepening or widening of a natural stream channel, has been a common restoration practice to reduce flooding along major streams. Erosion control practices, such as placing riprap along the channel or lining the channel with concrete to protect the channel bed and bank from erosion also significantly modify channel form and process (Keller, 1978). Stream channelization has been used to control flooding, drain wetlands, improve river channels for navigation and prevent bank erosion

(Brooker, 1985). Although channelization of streams can be successful at protecting human occupied lands from flooding and erosion, they can also result in environmental degradation of adjacent floodplains or downstream ecosystems (Keller, 1978; Kroes and Hupp, 2010). In particular, channelized sections of river often have high velocities and shear stresses that transport sediment and contaminants efficiently downstream (Meierdiercks, et al., 2010; Meierdiercks, et al., 2010). Stream channelization is often conducted to open floodplains and adjacent areas to development, therefore stream channelization may be used prior to upstream development of the watershed or where storm water management practices are in place to mitigate runoff (Heatherly et al, 2007). Therefore, channelized streams are common features in large, urban watersheds, and in many cases, stream channelization occurred prior to evaluation of the effects of the procedures on hydrologic, ecologic, and hydraulic processes in the streams and adjacent floodplains.

While urbanization and suburbanization are continually increasing, research on the effects of urbanization on watershed hydrology and stream channel morphology is still mainly being conducted in small watersheds. In small watersheds the studies have found increased runoff volume and peak discharge are proportional to the amount of impervious cover, with significant degradation occurring with as little as 10% impervious cover. However, in relatively large urban-suburban watersheds studies of the hydrologic processes and associated geomorphic responses are uncommon. Previous research done suggests that larger watersheds with floodplains or riparian zones may have retention sites for water storage that is not commonly present in small watersheds. Stored water can then be evaporated from surface storage, be transported by subsurface flow paths to support stream baseflow, or be transpired to the atmosphere. Despite the importance of the retention sites in large watersheds, a common restoration practice is to channelize large urban streams. Channelization is the engineering practice of straightening, deepening, or widening the natural stream channel. This practice has been successful at protecting human occupied lands, however, it can also cause significant environmental degradation and the elimination of retention sites. This suggests that for large urban watersheds studying the water balance and the effects of channelization will be an effective approach to understanding the systems. Therefore, the purpose of this study is to: a) compare watershed hydrology and hydraulics (water balances, flow duration analysis, and hydraulic geometry) in a large urban watershed and a similar non-urban watershed, and b) to evaluate the progressive time series of hydrologic and hydraulic changes in an urbanizing watershed through the use of historical data.

1.2 Research Design

The approach of this study is to use United States Geological Survey (USGS) stream gauge data (Water Resources of the United States) to: a) compare watershed hydrology and stream hydraulics for the Anacostia River to similarly-sized non-urban coastal streams in the Maryland Coastal Plain; and b) conduct a time series analysis of watershed hydrologic and stream hydraulic changes in the Anacostia River as urbanization progressed between 1939 and 2014. The primary comparison watershed to the Northeast Branch of the Anacostia River is Zekiah Swamp Run. They are both coastal plain watersheds with similar watershed areas, climate, topographic relief, and morphology. Upstream sub-watersheds of Northeast Branch were compared with Coastal Plain Streams with similar basin area (St. Mary's River, Piscataway Creek, and St. Clements Creek). The comparison streams have less than 10% impervious surfaces.

Watershed hydrologic analyses, conducted for the comparison between urban and non-urban watersheds, include annual water balances and flow duration analyses. The annual water balance examines the amount of watershed precipitation (input) and the major outputs as (evapotranspiration and stream runoff). I also examined the relationship of evapotranspiration and runoff to increases in precipitation. Flow duration analysis is an evaluation of the probability distribution of daily discharge (runoff); these data can be compiled into 10-year average probability distributions, which averages out inter-annual climatic variations.

Geomorphic and hydraulic characteristics of stream channels are evaluated by comparing at-a-station hydraulic geometry for urban and non-urban streams, and progressive changes in hydraulic geometry changes over time in the Anacostia River. At-a-station hydraulic geometry relationships are the adjustment of width, depth and velocity to increases in discharge at a measurement station (Leopold and Maddock, 1953). The hydraulic geometry relationships and flow duration analyses were combined to provide probability distributions of flow velocities for each measurement station.

The results of this project quantify hydrologic, hydraulic, and stream energy distribution changes associated with both land use changes and stream channelization of the Anacostia River and its watershed. This research is important because it provides an assessment of both the hydrologic and hydraulic changes in a stream system, which can be used to target future restoration efforts.

1.3 Hypotheses

H1: Water balance analyses will indicate runoff has increased and evapotranspiration decreased in the Anacostia watershed compared to non-urban coastal plain watersheds (e.g. Zekiah Swamp Run).

H2: Hydraulic geometry analysis of the Anacostia should indicate much higher velocity coefficients and exponents in comparison to non-urban coastal plain streams, particularly in channelized reaches.

H3: Analysis of the Anacostia hydrology and hydraulics for earlier time intervals (1938-1960; 1970-1990) should indicate initially similar characteristics to non-urban Coastal Plain comparison streams.

Chapter 2: Methods

2.1 Selection of Study Sites

The Anacostia River watershed, which contains the North East portion of the Washington Metro area in Maryland and the District of Columbia, is one of the most densely populated Chesapeake Bay watersheds. Today it is considered to be a degraded urban ecosystem, but historically it was a prosperous natural and commercial resource. The land use in the watershed has changed from predominately forest in the early 17th century to agriculture after the time of European settlement until the Civil War and to progressive urbanization from the late 19th century until today (Anacostia Watershed Restoration Partnership, 2009).

The total Anacostia watershed area is 464 km^2 and urban or suburban land uses distributed throughout the watershed create impervious cover of 26% (Miller et al., 2007). Prince George's County makes up the largest percentage of the watershed at 49%, with Montgomery County making up 34% and the final 17% of the watershed flowing through the District of Columbia (MDNR, 2005). The Anacostia River has two main branches that join just upstream of the tidal estuary. The Northwest (NW) branch is primarily in the Piedmont Province and has little floodplain development. The Northeast (NE) branch, which is the primary focus of this study, is a 188 km^2 watershed primarily in the Coastal Plain province and it originally contained extensive floodplains that exist as fragments in the tributaries and have been channelized to contain floodwaters along the main stem (Miller et al., 2007; MDNR, 2005).

In order to compare the urbanized Northeast Branch of the Anacostia River to the pre-urban system and to recreate the pre-urban hydrology and hydraulics, I compare the Anacostia Watershed to several non-urban coastal plain watersheds. These non-urban coastal plain streams include Zekiah Swamp Run, St. Mary's River, Piscataway Creek, and St. Clements Creek. Zekiah Swamp Run is a 207 km^2 predominately non-urbanized coastal plain watershed, similar in size to the North East Branch Anacostia. Zekiah Swamp Run is a 34 km braded stream that runs through Charles County, Maryland. The watershed is situated with Cedarville State Forest at its headwaters along the Charles and Prince George's County border and the Zekiah Swamp Natural Environmental Area at its confluence with the Wicomico River. Between these two state properties are private landholdings that are mostly undeveloped. The watershed contains unfragmented forests, particularly in the floodplain. The natural floodplain of the Zekiah Swamp Run watershed makes it a good candidate site for reconstructing the pre-urbanization Northeast Branch of the Anacostia (Maryland Greenways Commission, 2000).

St. Marys River is located in Great Mills in St. Marys County Maryland and has a drainage area of 62 km^2. The drainage area for St. Clement Creek is 48 km^2 and it is located near Clements Maryland also in St. Marys County. Piscataway Creek has a drainage area of 102 km^2 and is located at Piscataway Maryland in Prince George's County. All of these watersheds are significantly smaller than either Zekiah Swamp Run or the Anacostia River and have suburban development, but no channelization (Water Resources of the United States, 2012).

2.2 USGS Data Collection

The data used for this study came from the USGS stream gauging network, which included about 7,400 gauges in 2007. The USGS runs an extensive network of stream gauges, which is defined as an active, continuously functioning measuring device in the field for which a mean daily streamflow or unit values are computed or estimated and quality assured for at least 355 days of a water year (Olson and Norris, 2007). The USGS list several criteria for an ideal stream gage in Rantz et al (1982) including: a stream channel that is straight for about 100m upstream or downstream, total flow passing the gauge is confined to a single channel at all discharges, and the stream bed is not affected by scour and fill, the channel banks are permanent, there is no tidal influence at the gauge location, there is a good cross section for measuring discharge near the gauge, and the site is readily accessible (Rantz et. Al., 1982; Juracek, K.E. and F.A. Fitzpatrick, 2009).

Cross sectional discharge measurements are collected at each gauging station to determine the discharge rating, or the relationship between stage and discharge, for the site. The USGS describes stage, or gauge height, as the height of the water above an established elevation. Discharge is the volume of water moving past a certain area in a stream in a certain unit of time. The discharge measurements involve observations of width, depth, area, and velocity taken at intervals across the stream channel. The majority of measurements are collected by wading in the stream but the high flow measurements are taken off of a bridge or cable way or even from a boat (Rantz et. Al., 1982; Olson and Norris, 2007).

Discharge measurements are made by dividing a stream cross section into several equal size subsections. The area of each subsection is calculated by measuring the width and depth of the subsection. The velocity of each subsection is measured by various techniques and then the discharge is calculated for that subsection by multiplying the velocity by the area. The width measurements are measured with a tape stretched across the stream, perpendicular to the flow, and the depth values are measured using a wading rod marked to the tenths. The velocity and area for each subsection are used to calculate a discharge for that subsection. The width, area, and discharge measurements for each subsection are added to get a total for the whole cross section. For the calculation in the study velocity is the average across the cross section and for depth it is the area divided by the width. The cross section measurements are taken at a similar location in the stream whenever collected to allow for comparisons and the creation of the stage-discharge relationship (Rantz et. Al., 1982; Olson and Norris, 2007).

2.3 Watershed Water Balances

In 1944, the meteorologist C. Warren Thornthwaite coined the term water balance to refer to the balance between the precipitation, entering into the watershed, and the evapotranspiration, stream discharge and change in soil storage leaving the watershed (Thornthwaite and Mather, 1955, 1957; Dunne and Leopold, 1978). Changes in land cover can lead to changes in infiltration, evapotranspiration, and runoff, thus are likely to modify the water balance. Constrained by data availability, the annual water balance is calculated for the period 1984-2013 for the Anacostia Watershed and Zekiah Swamp

Run. The annual water balance is also calculated for the entire period of record for the Anacostia River for time series comparisons.

The water balance accounts for the amount of water entering and leaving a watershed:

$$PPT = ET + RUN \pm \Delta S$$

where PPT is precipitation, ET is the evapotranspiration, RUN is the runoff and ΔS is the change in groundwater storage (Dunne and Leopold, 1978). The "long term water balance is determined only by the local interaction of fluctuating water supply (precipitation) and demand (potential evapotranspiration), mediated by water storage in the soil (Milly, 1994)." For gauged watersheds, annual evapotranspiration can be determined as [Evapotranspiration ± ΔStorage = Precipitation – Runoff]. It is relatively safe to assume that over a long time period, at least 5 – 10 years, changes in soil water storage are zero. Although on an annual basis there can be affects of soil water storage on evapotranspiration (Zhang et al., 2001). As mentioned in the introduction, evapotranspiration and storage can be evaluated with water balance calculations, but it is difficult to separate evapotranspiration from storage, particularly in large watersheds. Due to this, the evapotranspiration and change in storage are not differentiated for this study.

Annual precipitation and average monthly precipitation data, which is downloaded from PRISM website, was used to calculate the water balances. Average annual and monthly stream discharge data are obtained from the USGS. The stream discharge data is converted to runoff (cm) by converting discharge into water volumes (per year or per month) and dividing by watershed area.

2.4 Flow Duration Analysis

A flow duration analysis is a probability analysis of streamflow for a watershed based on hourly or daily data (Dunne and Leopold, 1978). The average flow duration curve is calculated using a data series of daily discharge data for ten years or longer which provides information on the average probability of daily discharges. Daily discharge is sorted from largest to smallest and rank probability is calculated as: (rank/n)*100, where n equals the total number of events in the data set. Flow duration curves are graphed as the discharge value versus the percent of time flow is equaled or exceeded. The flow duration analysis was done for the Northeast Branch of the Anacostia and Zekiah Swamp Run for the period from 1990 – 1999. Decadal analyses for Northeast Branch of the Anacostia were completed for 1940-2010.

2.5 Hydraulic Geometry Analysis

Discharge measurements and associated channel geometry data were used to evaluate at-a-station hydraulic geometry (Leopold and Maddock, 1953; Leopold et al., 1964; Dingman, 2007) for each Coastal Plain gauging station in the study. At-a-station hydraulic geometry relationships, which were introduced by Leopold and Maddock in

1953, express width, depth, and velocity as power functions of discharge at a single stream cross section (Leopold and Maddock, 1953; Millar, 2004, Dingman, 2007). The equations are usually expressed as:

$$\text{Width } (w) = aQ^{b}$$

$$\text{Depth } (d) = cQ^{f}$$

$$\text{Velocity } (v) = kQ^{h}$$

These hydraulic geometry relationships are only valid for in-bank flow at a particular cross section. Due to the power-law relationships of the hydraulic geometry equations they are constrained by the continuity equation. This equation states that discharge equals velocity times the cross-sectional area:

$$Q = v*A$$

Since the cross-sectional area can be divided into the width times the depth of the cross-section it means it is also true that discharge equals velocity times width times depth:

$$Q = v*w*d$$

Based on the continuity equation, changes in the discharge of a stream at a particular cross section must result in a change in the velocity, width and depth as well. The hydraulic geometry exponents and the coefficients are also constrained by the continuity equation, thus:

$$Q = ackQ^{b+f+h}$$

$$b + f + h = 1$$

$$a*c*k = 1$$

On log-log plots of w, d, and v against Q (discharge), a, c, and k are the coefficients and b, f, and h are the exponents of power functions of Q to geomorphic variables (Leopold and Maddock, 1953; Dingman, 2007).

Ferguson (1986) reviewed previous empirical and theoretical studies of at-a-station hydraulic geometry and found that a cross section with a constant shape and frictional characteristics and also a law that relates the velocity to the friction and depth, the at-a-station hydraulic geometry relationships are determined (Dingman, 2007). The width-discharge, depth-discharge, and velocity-discharge relationships will only be power-law functions if the width-depth and velocity-depth relationships are, according to Ferguson (1986). At-a-station hydraulic geometry is completely determined by cross-section geometry and hydraulic relationships (Ferguson, 1986; Dingman, 1984; Dingman, 2007).

Dingman (2007) calculated theoretical ranges for the exponents of the at-a-station hydraulic geometry and then compared the values calculated in various studies to these ranges. The theoretical range for the exponents was determined to be $0.0 \leq b \leq 0.4$, $0.33 \leq f \leq 0.67$, and $0.2 \leq m \leq 0.5$. The observed values for the exponents from previous studies were generally found to fall within the theoretical ranges. Although in a few of the studies the observed velocity exponent was higher than the theoretical range (Dingman, 2007).

Hydraulic measurements were analyzed for the Anacostia River and the non-urban Coastal Plain Streams chosen for this study, including Piscataway Creek, St. Marys

River, St. Clements Creek, and Zekiah Swamp. These low to non-urban reference stream comparisons will provide hydraulic geometry relationships for non-channelized stream channels. Hydraulic geometry relationships were defined over different time periods for all the streams in the study. This allows for comparison with different periods of the Northeast Branch Anacostia hydraulic history including the period of early urbanization (approximately 1938 - 1960), the period of rapid suburban development (approximately 1970-1990), and the period after this suburban expansion (about 1994-2014). Comparison of the hydraulic geometry relationships among river systems were for the same time periods in order to control climate or the factors that might affect stream discharge and stream channel adjustments. The hydraulic geometry for the Anacostia River was also calculated on a decadal basis to determine channel adjustments due to urbanization and channelization.

2.6 Probabilistic Evaluation of Stream Velocities

Results from the flow duration and the hydraulic geometry analyses were used to create velocity probability data for Zekiah Swamp Run and Northeast Branch of the Anacostia on decadal time scales. This analysis used the daily discharge values and their annual probabilities to calculate corresponding velocities and their annual probabilities using the velocity equation from the hydraulic geometry analyses for the same time period (graphs of which can be found in Figures A.15 through A.21, in the Appendix). The calculations from this novel technique will be used to compare velocity probability distributions for the Northeast Branch of the Anacostia and Zekiah Swamp Run and to create decadal box plots of velocity probability distributions.

2.7 Error Analysis of Cross Sectional Data

The majority of the error associated with all of the analyses used in this study come from the cross sectional data collected by the USGS. The width component of the cross section is considered to have very minimal, less than 1 percent, error associated with the measurements. This is especially true when the measurements are collected using a tape or tag line stretched across the stream perpendicular to the flow. Unlike width, the individual depth measurements are considered to have significant uncertainty associated with them. The amount of error associated with depth measurements depends on the type of measurements being made, the condition of the streambed, and the velocity of the streamflow (Sauer and Meyer, 1992). Sauer and Meyer (1992), indicate that for a stable streambed the depth error ranges between 2 and 5% while a mobile or unstable streambed can have error in the 10 – 15% range.

The error from the velocity measurements comes from several sources including instrument error, vertical and horizontal velocity distributions, velocity pulsation, and stream turbulence. The instrument error obviously depends on the type of instrument and also the velocity of the streamflow. Instrument error is generally considered to be below 5%, with the highest error in really slow velocities (Sauer and Meyer, 1992). The USGS uses two different methods for measuring velocity, the 0.6D method and the 0.2-0.8D method. This means that depending on the depth of the water (less than 2.5 feet for 0.6D and greater than 2.5 feet for the 0.2-0.8D method) the velocity is measured at either 6 tenths of the depth or both 2 and 8 tenths of the depth (Buchanan and Somers, 1969). There is less error due to pulsation and vertical velocity distribution associated with the two-point method. There has been no proof that stream turbulence is a source of significant error in a velocity measurement (Sauer and Meyer, 1992).

The overall error associated with a measurement encompasses all of the error from the various components of the measurement. The overall error can range anywhere from about two percent under the best conditions to almost 20 percent in the worst conditions and using shortcut methods (Sauer and Meyer, 1992). In their 1992 paper, Sauer and Meyer suggest, “most measurements probably will fall in the range 3 to 6 percent, which is typically considered a good measurement.”

Chapter 3: Results

3.1 Annual Water Balance Comparison

3.1.1 Coastal Plain Watershed Comparisons

The water balance, PPT = RUN + (ET ± DS), is driven by precipitation, therefore a comparison watershed to NE Branch should have similar monthly and annual precipitation. The annual precipitation data for Zekiah Swamp Run Watershed and the Northeast Branch Watershed are shown in Figure 3.1. This figure indicates that that the annual precipitation is very similar for the two sites, with a regression analysis of the two sites indicating a 1:1 relationship with an R^2 value of 0.86. This indicates variability between the two basins, but not a systematic variation. A double mass curve of the precipitation, which would detect temporal changes in precipitation over the common time interval, also indicates this 1:1 relationship of cumulative precipitation, with an R^2 value of 0.99 (Figure 3.2).

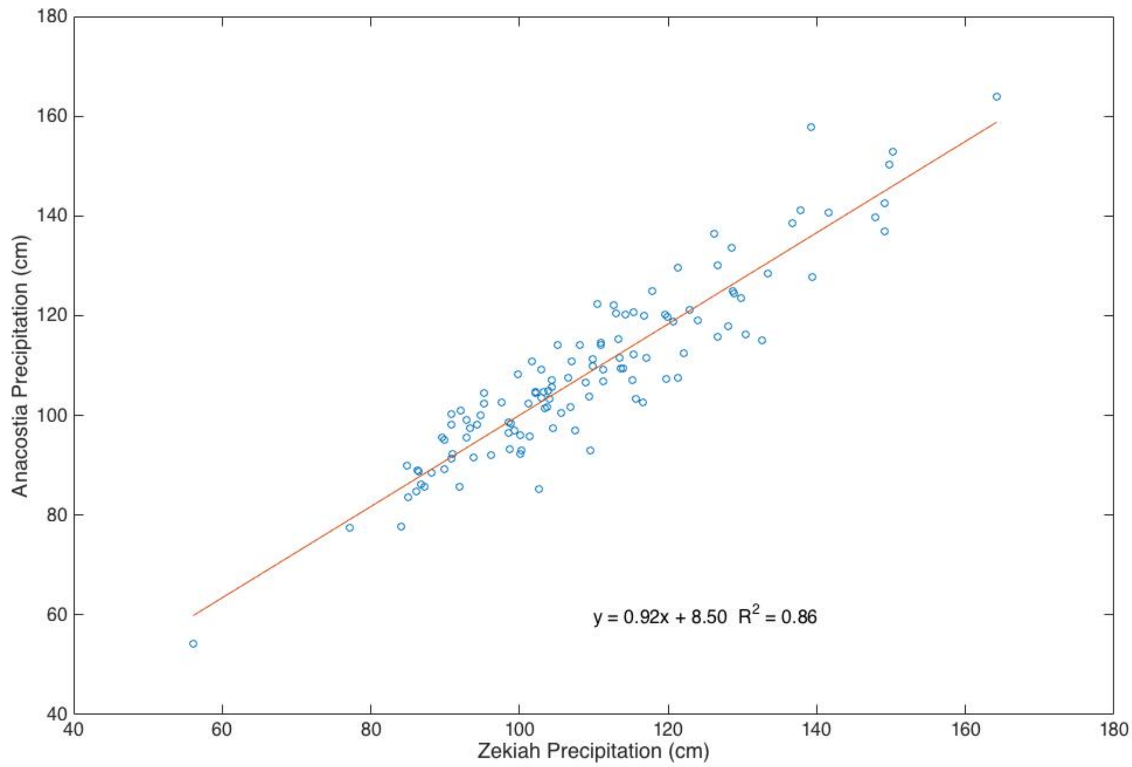


Figure 3.1. Comparison of the Annual Precipitation for Northeast Branch of the Anacostia River and Zekiah Swamp Run

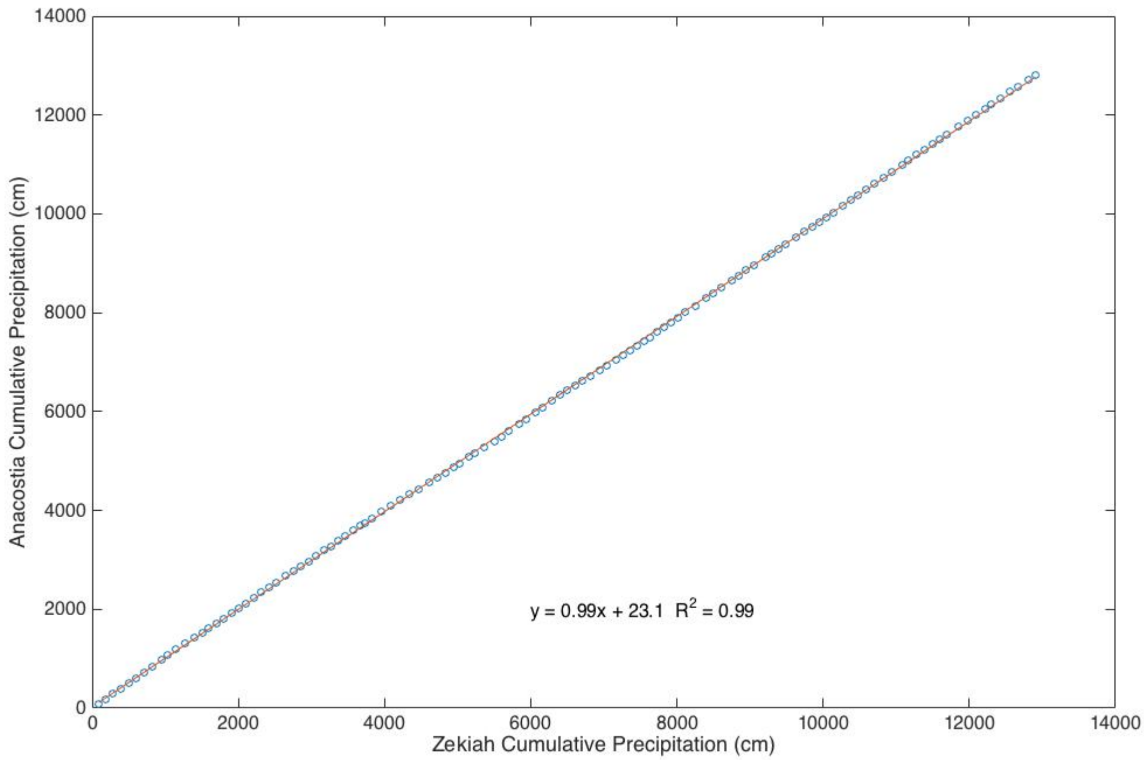


Figure 3.2. Double mass curve: Cumulative Precipitation for the Zekiah Swamp Run plotted against Northeast Branch of the Anacostia River

Differences in annual precipitation between the two watersheds do not show any trends with time. The percent difference between precipitation at Zekiah Swamp Run and the Northeast Branch of the Anacostia over time is presented in Figure 3.3. These data show that the percent difference averages to zero. The early percent difference values show more variance, which is likely due to less accurate measurements of precipitation in this time period improvements also occur in 1930 and 1970 and are likely associated with improvements in precipitation measurement technology. These data, however, indicate that the precipitation in the two basins remain similar to one another over the period of record.

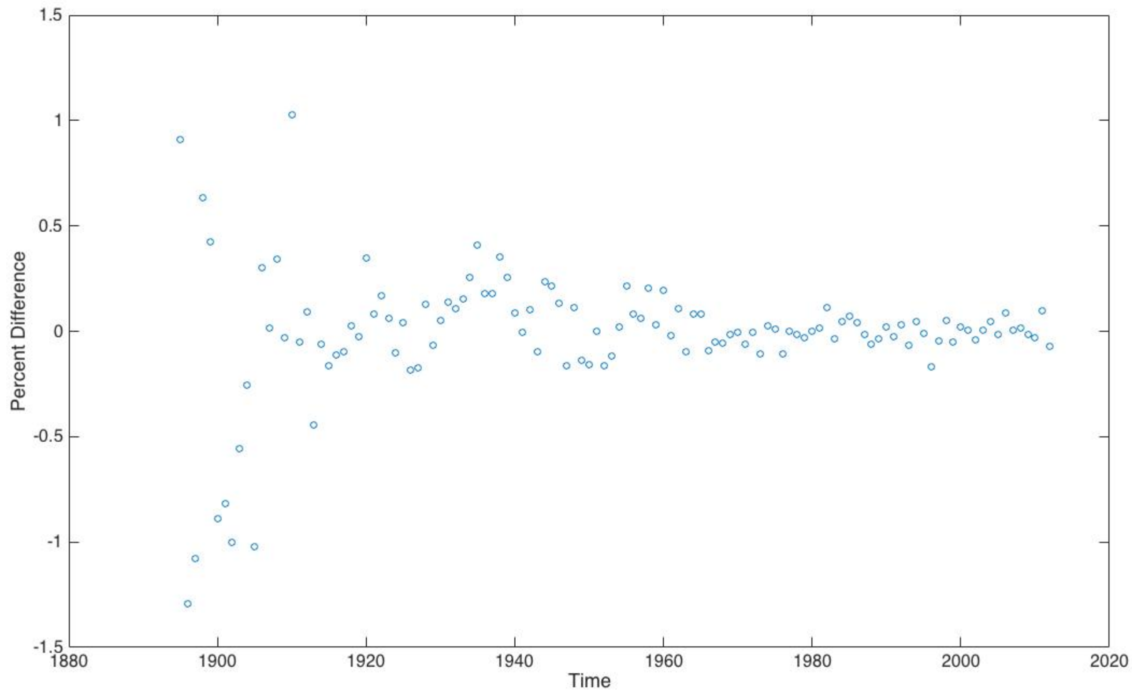


Figure 3.3. The Percent Difference between the Annual Precipitation for Northeast Branch and Zekiah Swamp Run

Annual precipitation variability was examined by comparing deviations of annual precipitation for each watershed to the long-term mean of each watershed. These data indicate an increase in variability of annual precipitation after the 1930s to 1940s. In particular, variations above the mean become greater, which reflects more years with above average precipitation. This change in precipitation, expressed as the standard deviations from the mean, can be observed in both the Northeast Branch of the Anacostia and Zekiah Swamp Run (Figure 3.4).

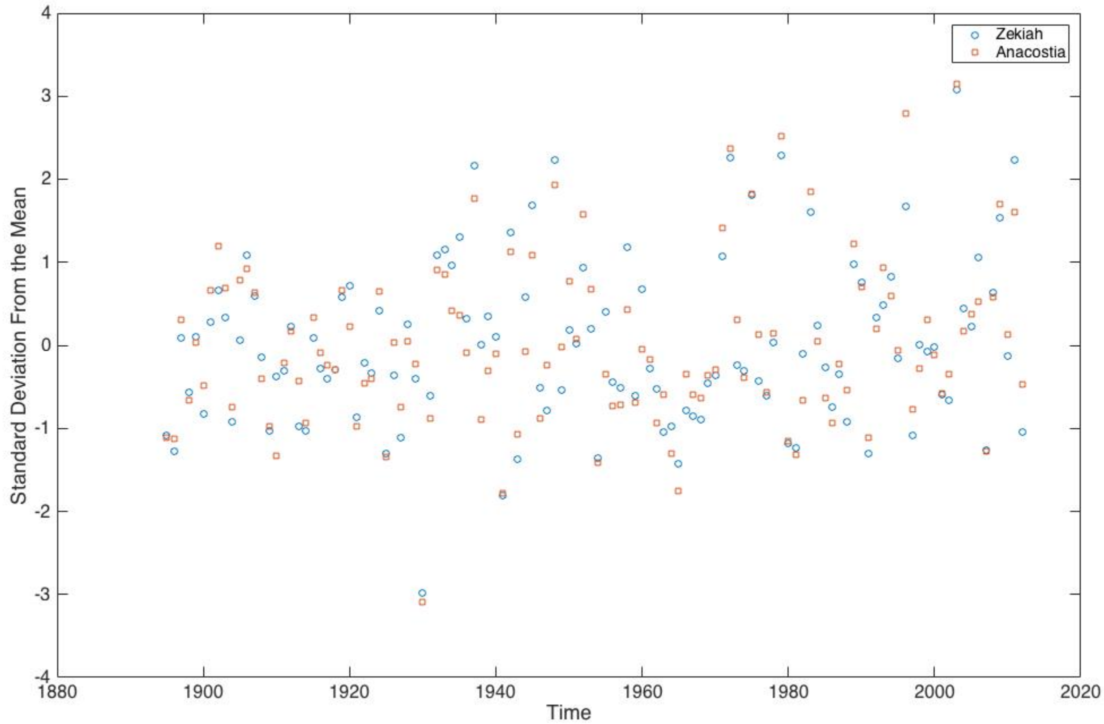


Figure 3.4. The Standard Deviation from the Mean for the Precipitation Values at both Northeast Branch and Zekiah Swamp Run for the Study Period

The annual precipitation data and USGS streamflow data are used to evaluate the annual water balance. Annual runoff, in cm (normalized by basin area) and the annual evapotranspiration is determined by subtracting runoff from precipitation. The runoff and evapotranspiration values for each year are plotted as functions of annual precipitation (Figures 3.5 and 3.6). These relationships are shown for both Zekiah Swamp Run and the Northeast Branch of the Anacostia. The mean precipitation, runoff, and evapotranspiration (in centimeters) were calculated for both the Northeast Branch of the Anacostia and Zekiah Swamp Run (Table 3.1). The mean precipitation was similar for both sites with values of 113.2 cm for Northeast Branch and 111.1 cm for Zekiah Swamp

Run. Mean runoff was higher for the Northeast Branch of the Anacostia with a value of 43.6 cm compared to a value of 38.7 cm at Zekiah Swamp Run. Mean evapotranspiration, on the other hand, is higher at Zekiah Swamp Run than the Northeast Branch of the Anacostia, with values of 72.4 and 69.6 cm respectively. Despite the differences seen in precipitation, runoff, and evapotranspiration between Northeast Branch of the Anacostia and Zekiah Swamp Run the mean values are not significantly different, which can be seen from the Standard Deviations of the values (see Table 1 for the Standard Deviations for these calculations).

Table 3.1. Mean Water Balance Values for the Northeast Branch and Zekiah Swamp Run for the Precipitation, Runoff, and Evapotranspiration (Standard Deviations)

	Anacostia (1984 – 2014)	**Zekiah (1984 – 2014)**
Mean Precipitation, cm	113.2 (± 18.5)	111.1 (± 17.8)
Mean Runoff, cm	43.6 (± 13.9)	38.7 (± 15.4)
Mean Evapotranspiration, cm	69.6 (± 8.2)	72.4 (± 9.0)

3.1.2 Relationship of Evapotranspiration and Runoff to Precipitation

To determine whether an increase in annual precipitation would likely result in an increase in runoff or an increase in evapotranspiration, regression analysis of annual runoff and evapotranspiration to annual precipitation were analyzed for both Zekiah Swamp Run and the Anacostia River (Figures 3.5 and 3.6). For Zekiah Swamp Run, evapotranspiration remains relatively constant with variations in precipitation and shows a poor correlation with annual precipitation ($R^2 = 0.25$). Evapotranspiration is the largest component of the water balance, but an increase in precipitation does not produce an increase in evapotranspiration. This suggests that vegetation receives close to its requirements every year, and that years with high precipitation generate more runoff. Runoff in Zekiah Swamp Run increases significantly with higher values of annual precipitation ($R^2 = 0.74$) and the values of runoff range from 15 to 80 cm. In the Anacostia River, however, both evapotranspiration and runoff are strongly correlated to annual precipitation. Regression coefficients are 0.51 for evapotranspiration and 0.83 for runoff. Annual runoff in the Anacostia River ranges from 25 to 90 cm, significantly higher than in Zekiah Swamp Run.

The percentage of annual precipitation lost to evapotranspiration was also examined and plotted against runoff for each watershed (Figures 3.7 and 3.8). Maximum evapotranspiration is 84% of precipitation at Zekiah Swamp Run and only 73% at the Northeast Branch of the Anacostia. Whereas maximum annual unit runoff is 79 cm for Zekiah Swamp Run and 91 cm for Northeast Branch of the Anacostia.

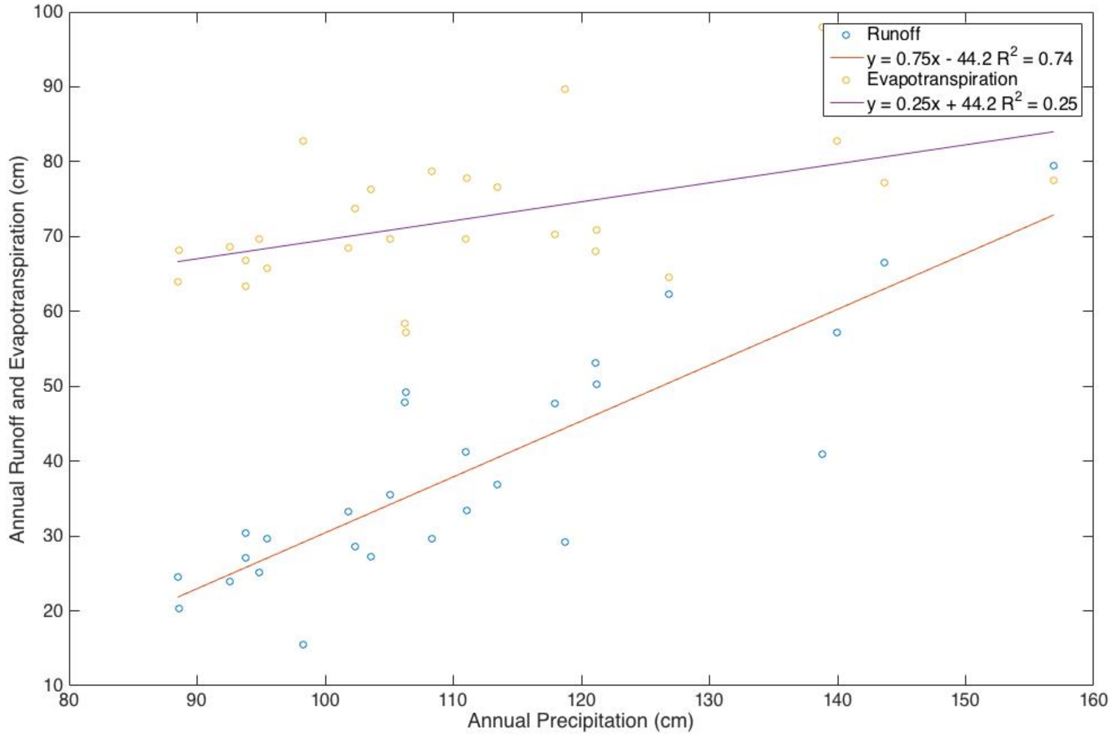


Figure 3.5. The Annual Runoff and Evapotranspiration versus Annual Precipitation (all in cm) for Zekiah Swamp Run for the Period from 1984 – 2012

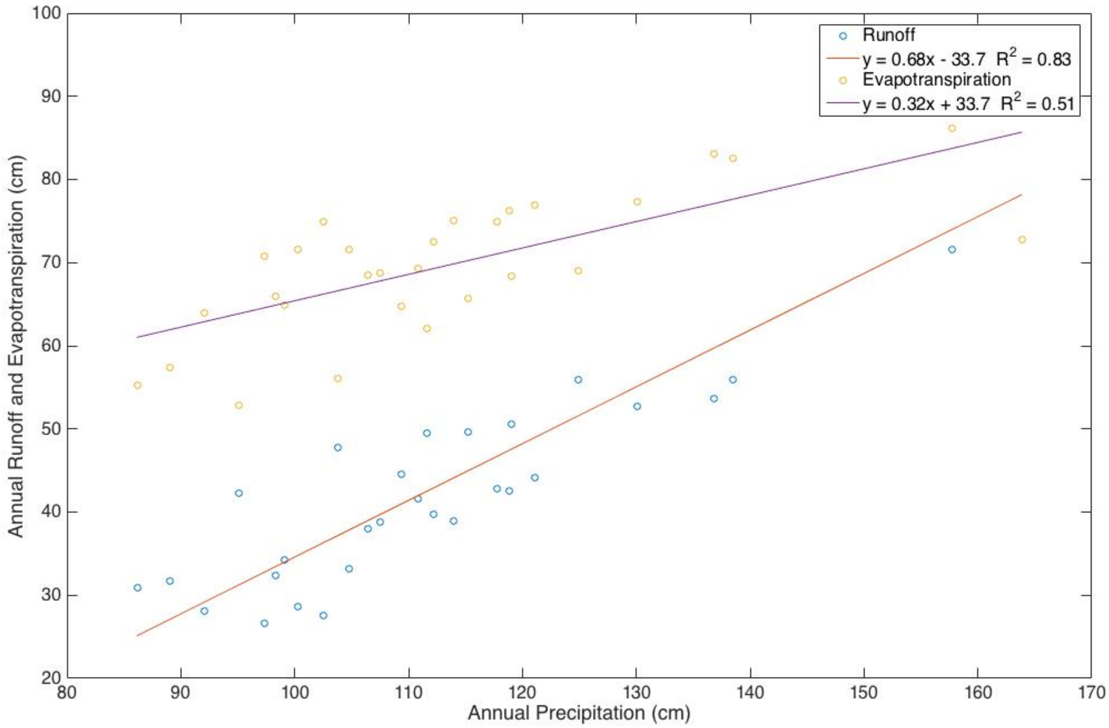


Figure 3.6. Comparison of the Annual Runoff and Evapotranspiration as a function of Annual Precipitation (all in cm) for Northeast Branch of the Anacostia River for 1984-2012

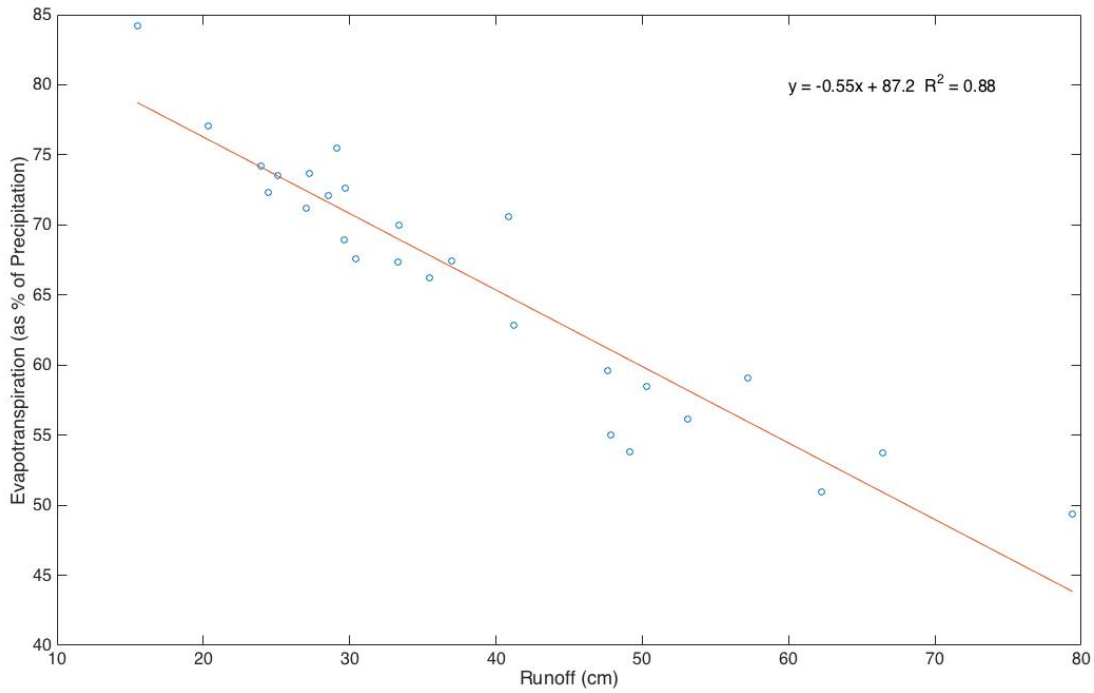


Figure 3.7. Evapotranspiration (as a % of Precipitation) versus Runoff for Zekiah Swamp Run during the Period from 1984 - 2012

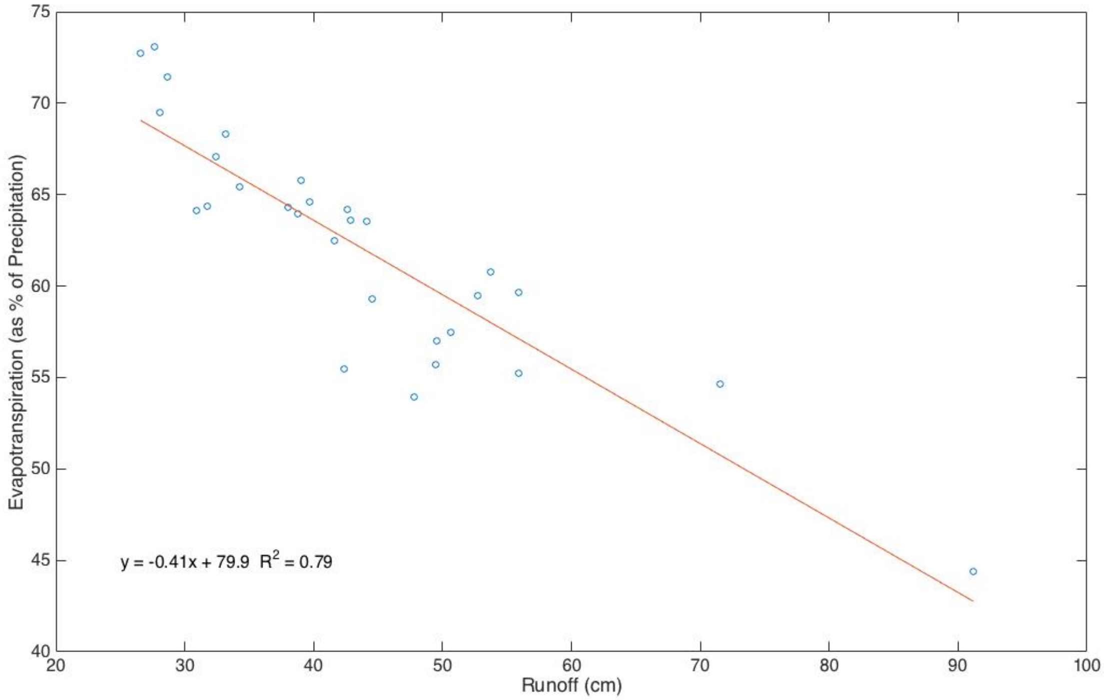


Figure 3.8. Evapotranspiration (as a % of Precipitation) versus Runoff for the Northeast Branch of the Anacostia River from 1984 - 2012

3.1.3 Water Balance Time Series Analysis of the Anacostia Watershed

Although discharge data are only available for the period 1984 to the present for Zekiah Swamp Run, discharge and annual runoff data are available for the period 1939 to the present for the Anacostia River. Therefore, the relationship of runoff and evapotranspiration to precipitation could be analyzed for different time intervals as watershed development and channelization progressed in the watershed. Annual runoff and evapotranspiration values are plotted as functions of annual precipitation for the Anacostia River for the time periods 1939 – 1960, 1970 – 1990, and 1994 – 2014 (Figures 3.9, 3.10, and 3.11). For the time period from 1939 – 1960 evapotranspiration varies from approximately 58 to 82 cm, and shows a good correlation with annual precipitation (R^2 = 0.76). Runoff during this time period shows a similar pattern of increase to evapotranspiration ranging from 20 to 50 cm. Runoff is also well correlated with annual precipitation with an R^2 value of 0.87. The annual evapotranspiration values for the period from 1970 – 1990 are similar to the earlier period; they range from approximately 60 to 78 cm however the correlation with annual precipitation is not as strong (R^2 = 0.51). The runoff values for 1970-1990 are higher than the previous interval and have a strong correlation with annual precipitation (R^2 = 0.89). Runoff values for the period range from 25 to 75 cm. These changes in evapotranspiration and runoff are also reflected in the analysis of data for the period from 1994 – 2014. Evapotranspiration values range from 60 – 85 and the R^2 value is 0.50. The runoff values for this period are also similar to the period from 1970 – 1990, with a range of 25 – 80 cm. The runoff correlation with annual precipitation is strong with a R^2 value of 0.82.

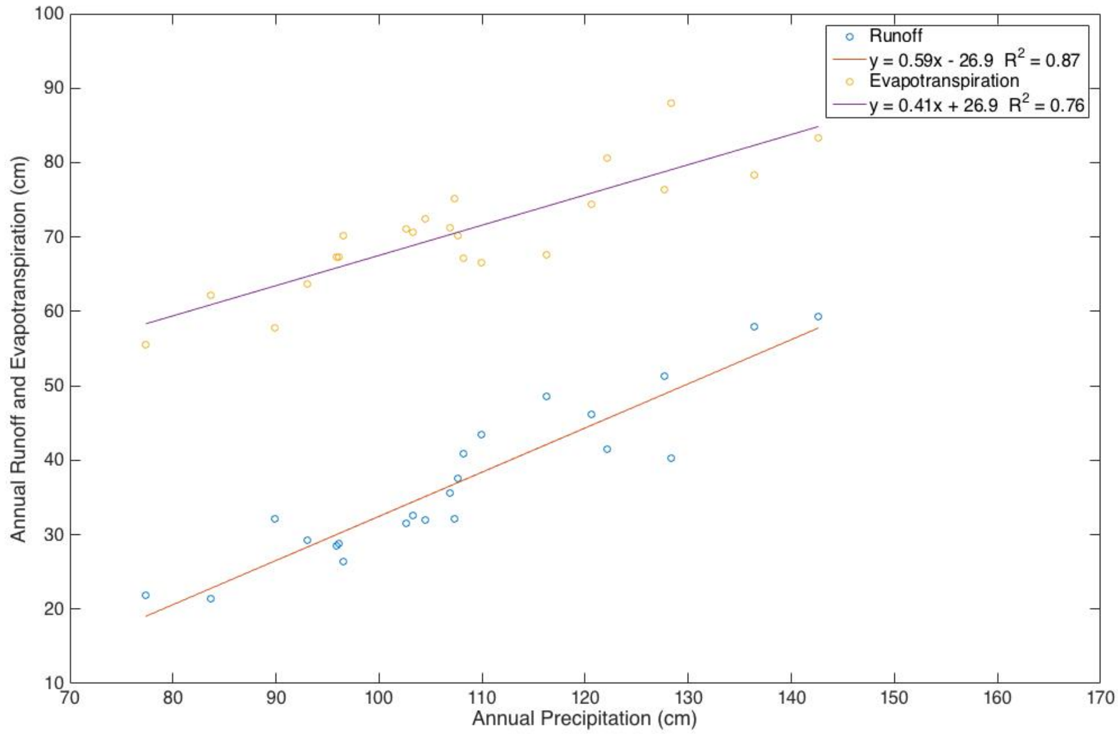


Figure 3.9. The Annual Runoff and Evapotranspiration as a Function of Annual Precipitation for the Period from 1939 - 1960

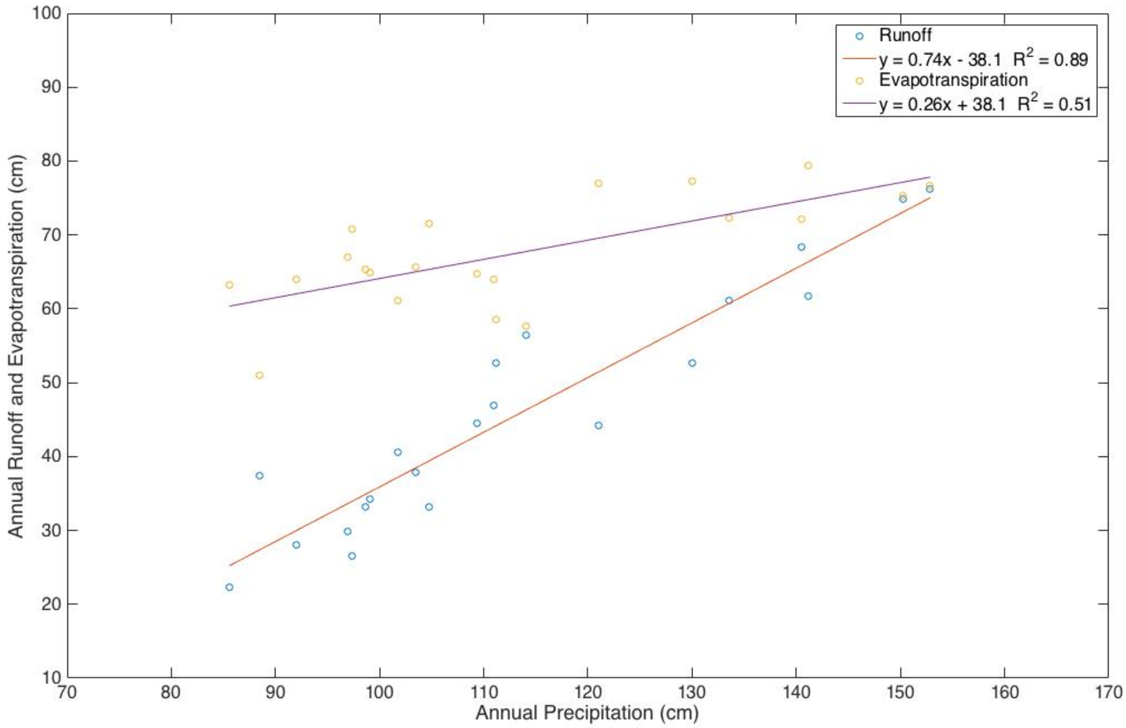


Figure 3.10. The Annual Runoff and Evapotranspiration as a Function of Precipitation for the Period from 1970 – 1990

Table 3.2. Summary Table of the Runoff and Evapotranspiration Statistics

	Zekiah 1984-2012	**Anacostia 1984-2012**	**Anacostia 1939-1960**	**Anacostia 1970-1990**	**Anacostia 1994-2012**
Runoff R^2	0.74	0.83	0.87	0.89	0.82
Runoff Slope	0.75	0.68	0.59	0.74	0.68
Runoff Intercept	-44.2	-33.7	-26.9	-38.1	-32.6
ET R^2	0.25	0.51	0.76	0.51	0.50
ET Slope	0.25	0.32	0.41	0.26	0.32
ET Intercept	44.2	33.7	26.9	38.1	32.6

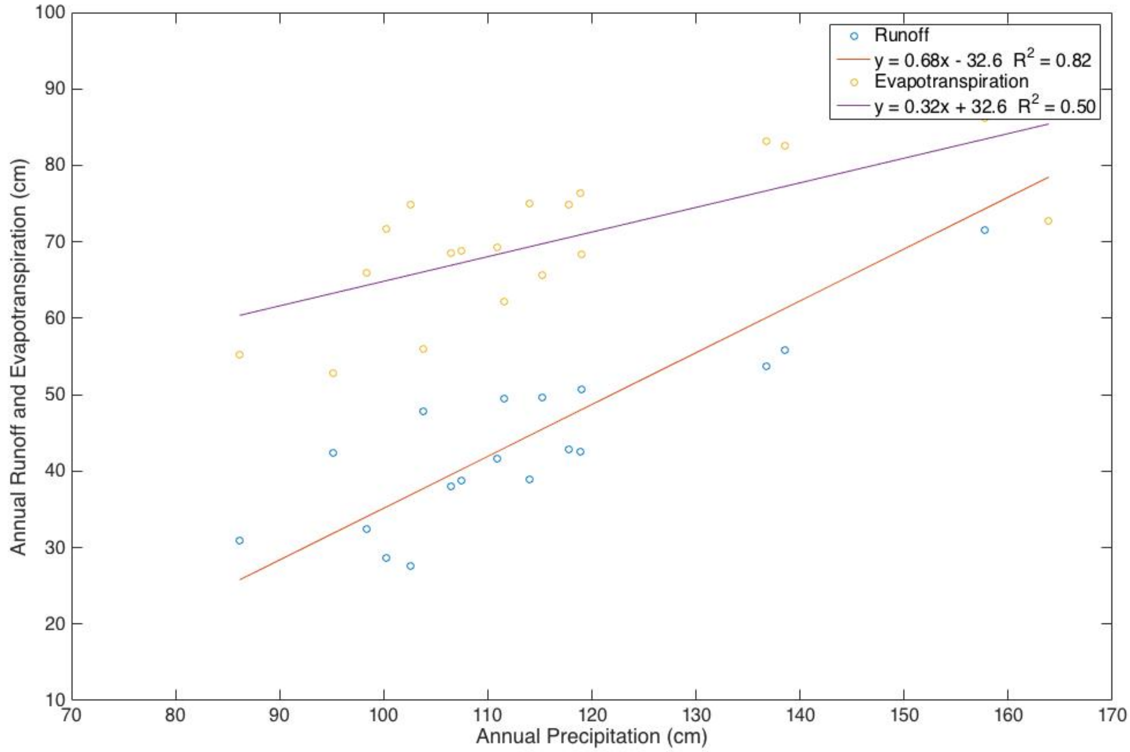


Figure 3.11. The Annual Runoff and Evapotranspiration versus Annual Precipitation for the Period from 1994 – 2012

The three graphs (Figures 3.12, 3.13, and 3.14) of Evapotranspiration (as a percent of Precipitation) versus Runoff (in centimeters) also indicate this decrease in evapotranspiration and an increase in runoff for the three chosen time intervals. The increase in runoff is more apparent than the decrease in evapotranspiration. Maximum evapotranspiration (expressed as a percentage of precipitation) for the periods 1939-1960, 1970-1990, and 1994-2014 are 74.4, 73.9, and 73.1 respectively. Maximum runoff decreases in the reverse order: 91.2 cm in 1994-2012, 76.3 cm for 1970-1990, and 59.3 for 1939-1960.

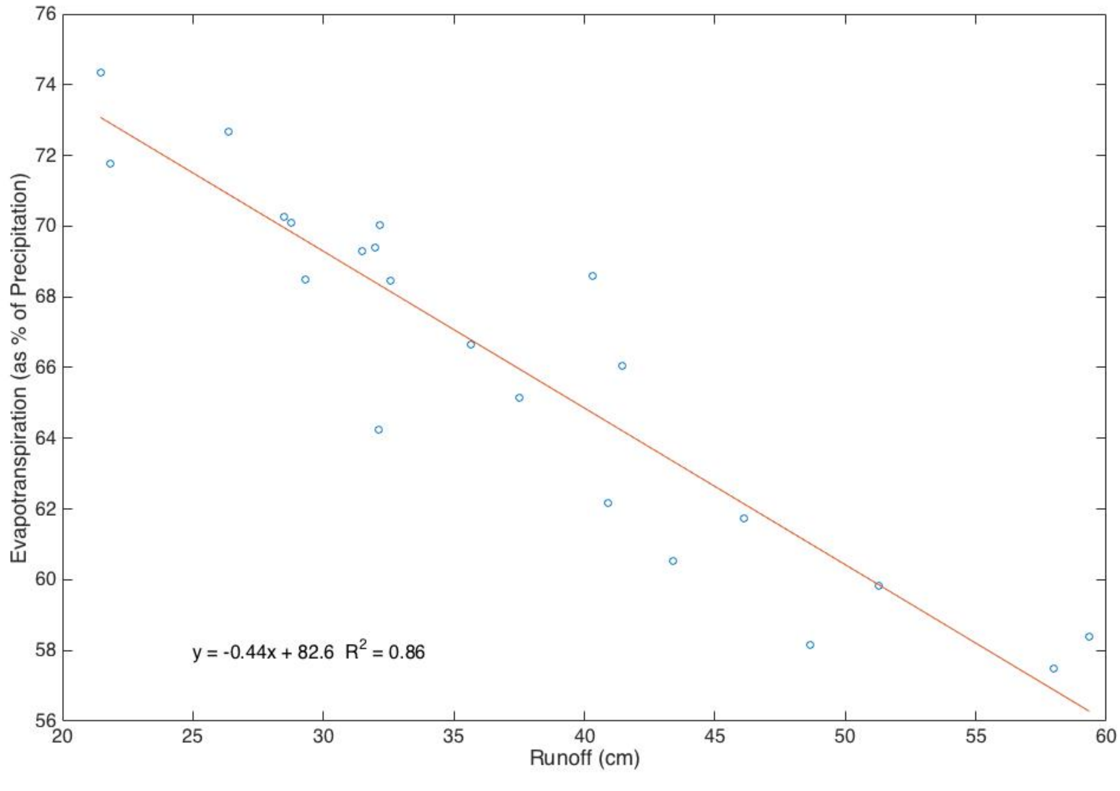


Figure 3.12. Evapotranspiration (as % Precipitation) versus Runoff for the Period from 1939 - 1960

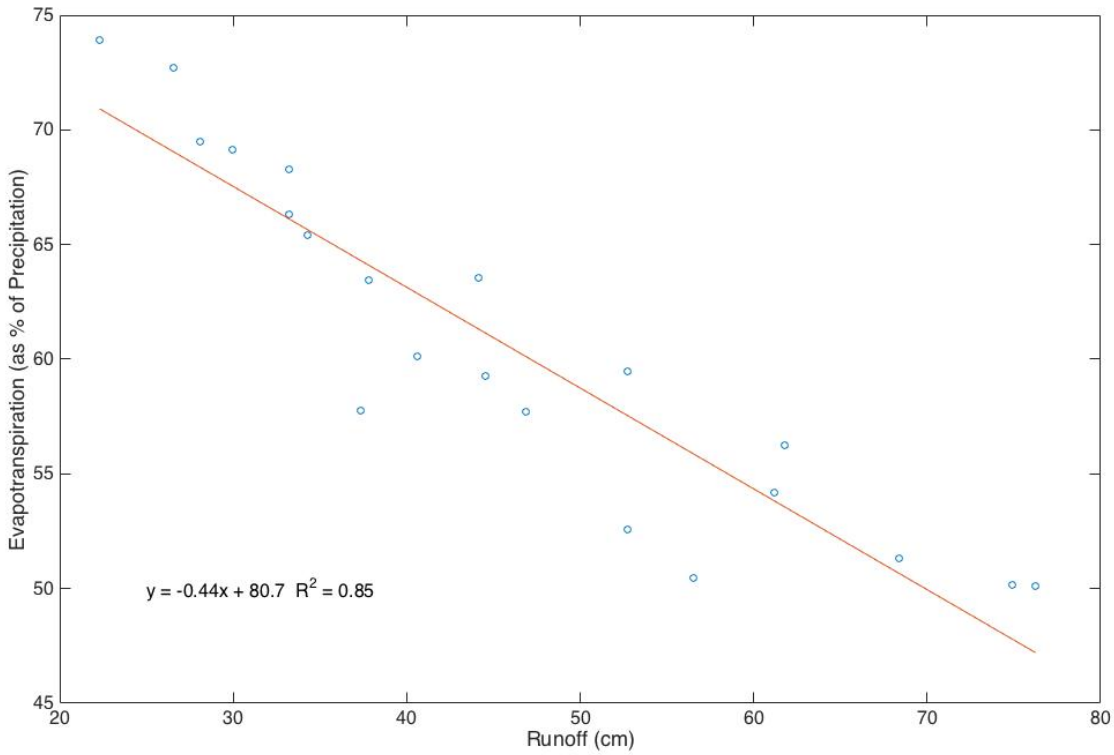


Figure 3.13. Evapotranspiration (as % of Precipitation) versus Runoff for the Period from 1970 - 1990

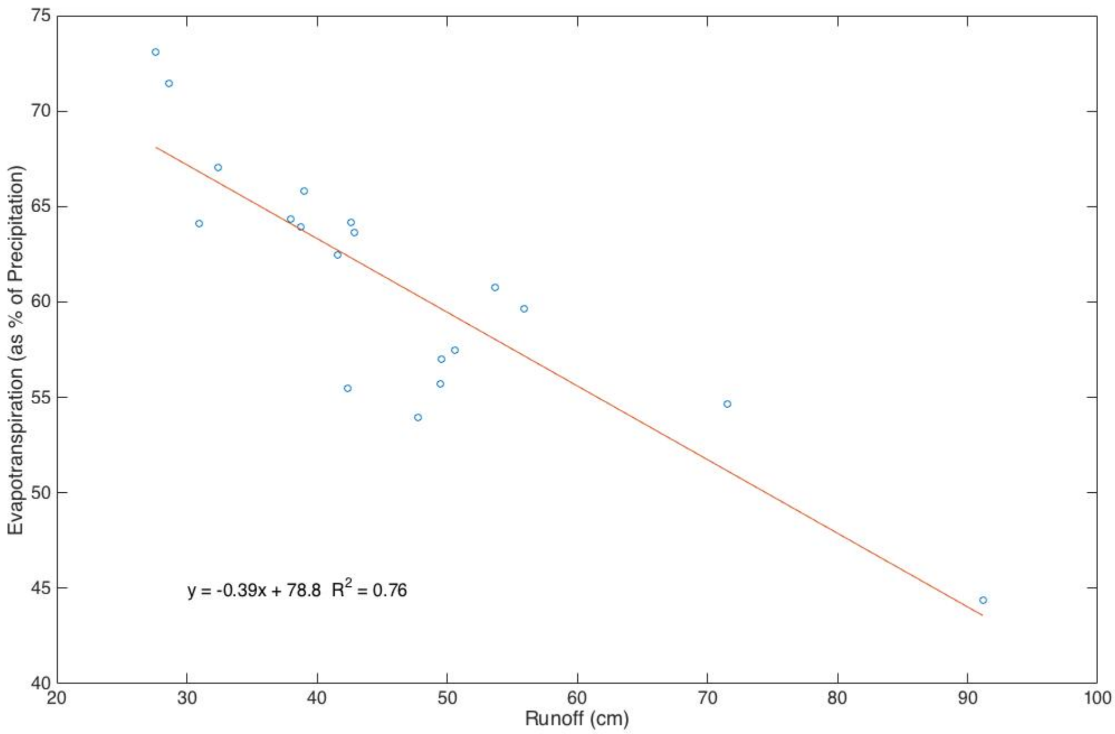
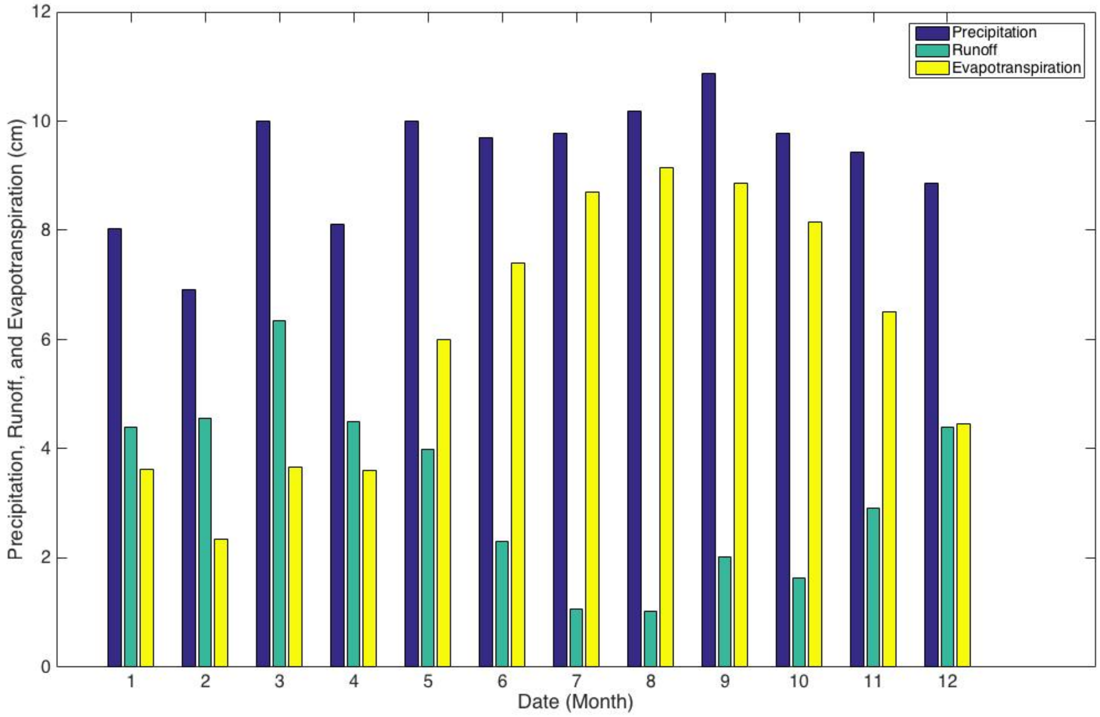


Figure 3.14. Evapotranspiration (as % of Precipitation) versus Runoff for the Period from 1994 - 2012

3.2 Average Monthly Water Balance Comparisons

The analysis of annual precipitation indicates general water use by vegetation and losses to evapotranspiration. There is significant seasonality in temperature in Maryland that drives plant growth and evapotranspiration, but precipitation does not show significant seasonality. Therefore, this seasonality in evapotranspiration drives seasonality in runoff within the region. To examine this seasonality, I examined average monthly precipitation, runoff, and evapotranspiration (calculated as a residual, which therefore also includes water storage as snow or soil water). These data are shown in

Figure 3.15. Despite similar monthly values of precipitation there is much more runoff in cool season months (November through April), than warm season months (May through October).



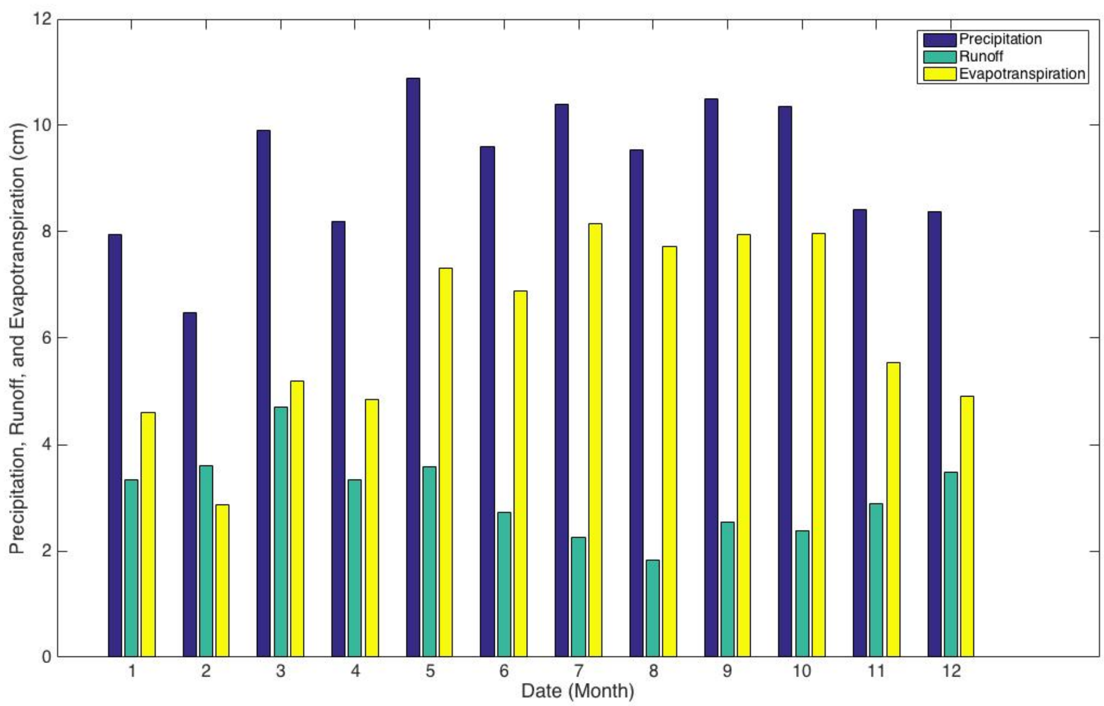
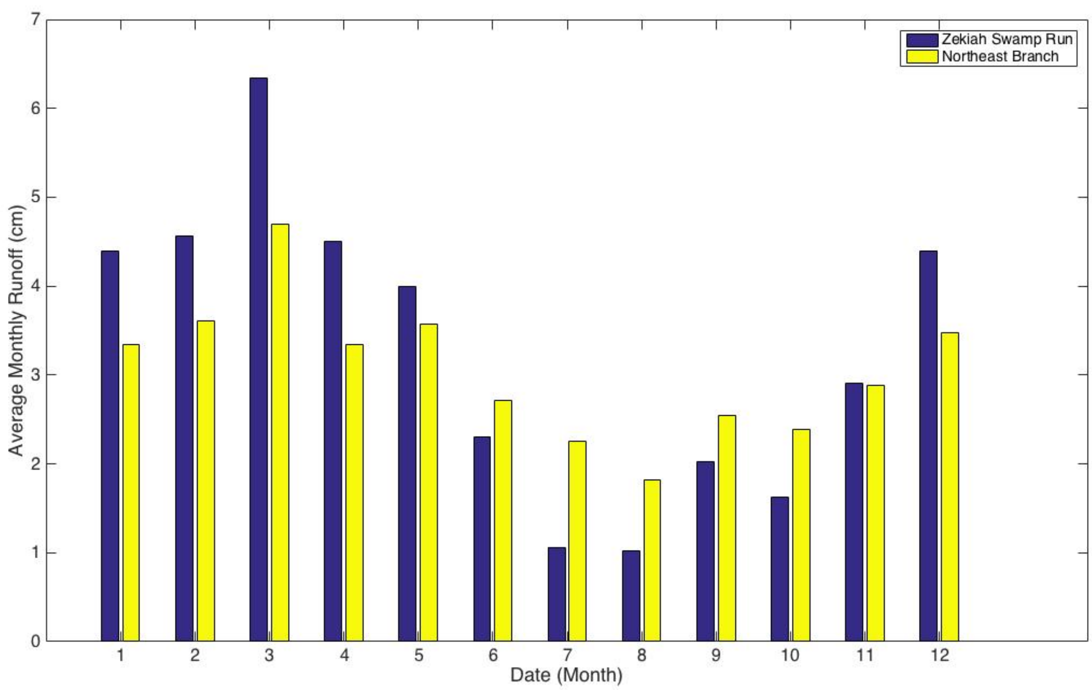


Figure 3.15. Zekiah Swamp Run (Upper) and Northeast Branch of the Anacostia (Lower) Monthly Water Balance (Calculated from data from the Period 1984 - 2012)

An average monthly water balance, based on average precipitation and runoff values for the period 1984-2012 are compared graphically in Figure 3.15. Monthly outflow components (Evapotranspiration and Runoff) of the water balance are compared in Figure 3.16. These data indicate significantly higher average runoff (Figure 3.16a) in summer months in the Anacostia River than in Zekiah Swamp Run. Figure 3.16b indicates significantly higher values of evapotranspiration in Zekiah Swamp Run for the summer months, although evapotranspiration and storage are higher in the Anacostia from January through April.



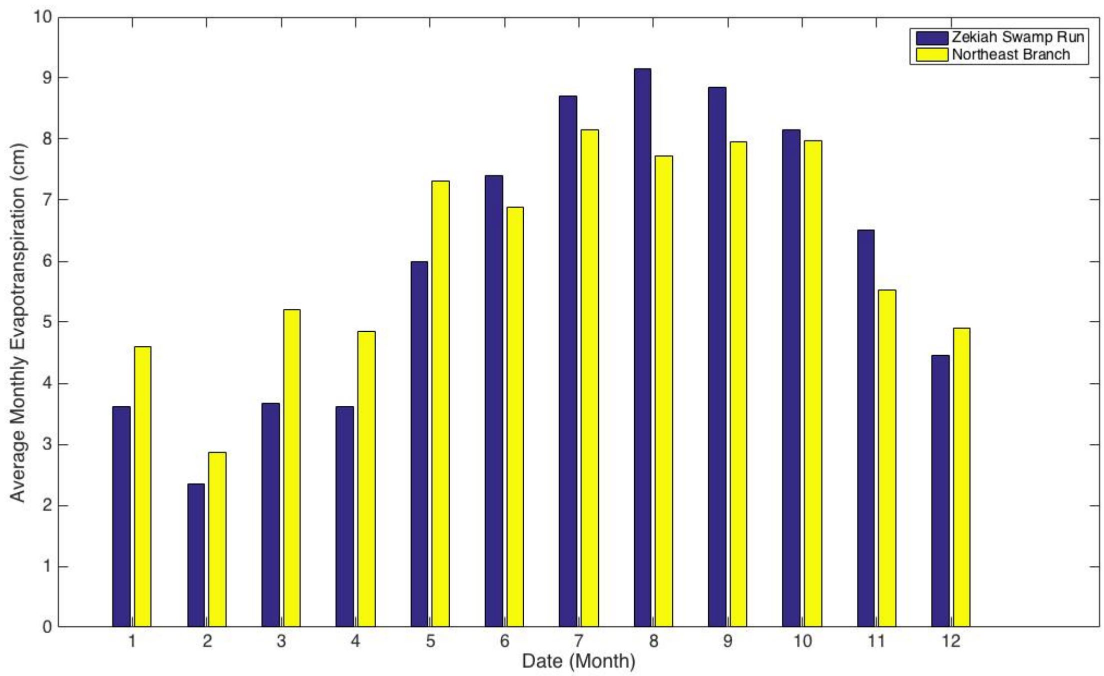


Figure 3.16. Comparison of the Monthly Components (Runoff Upper Graph and Evapotranspiration Lower Graph) of the Water Balance for the Northeast Branch of the Anacostia and Zekiah Swamp Run

These differences in average monthly runoff values should be reflected in the seasonality of daily discharges, which will be evaluated through flow duration analysis and other probability analyses for the time intervals of interest.

3.3 Daily Flow Probability Analysis

3.3.1 Daily Flow Probability Analysis Zekiah and Northeast Branch Anacostia

The seasonal variations in evapotranspiration observed in the average monthly water balance drive daily variations in discharge. Flow duration curves were calculated for the Northeast Branch of the Anacostia River and Zekiah Swamp Run for the period from 1990 – 1999. Flow duration graphs were created using ten years of the daily discharge data set. The daily discharge is sorted from largest to smallest and rank probability is calculated as: (rank/n)*100, where n equals the total number of events in the data set. Flow duration curves are graphed as the discharge value versus the percent of time flow is equaled or exceeded. The flow duration curves for the Northeast Branch of the Anacostia and Zekiah Swamp Run can be seen individually in Figure 3.17 and Figure 3.18, and also graphed together on Figure 3.19. The graphs show that the Northeast Branch has higher discharges for extreme events and for low flow events (baseflow), but Zekiah Swamp Run has slightly higher discharges for the events in the middle of the frequency curve.

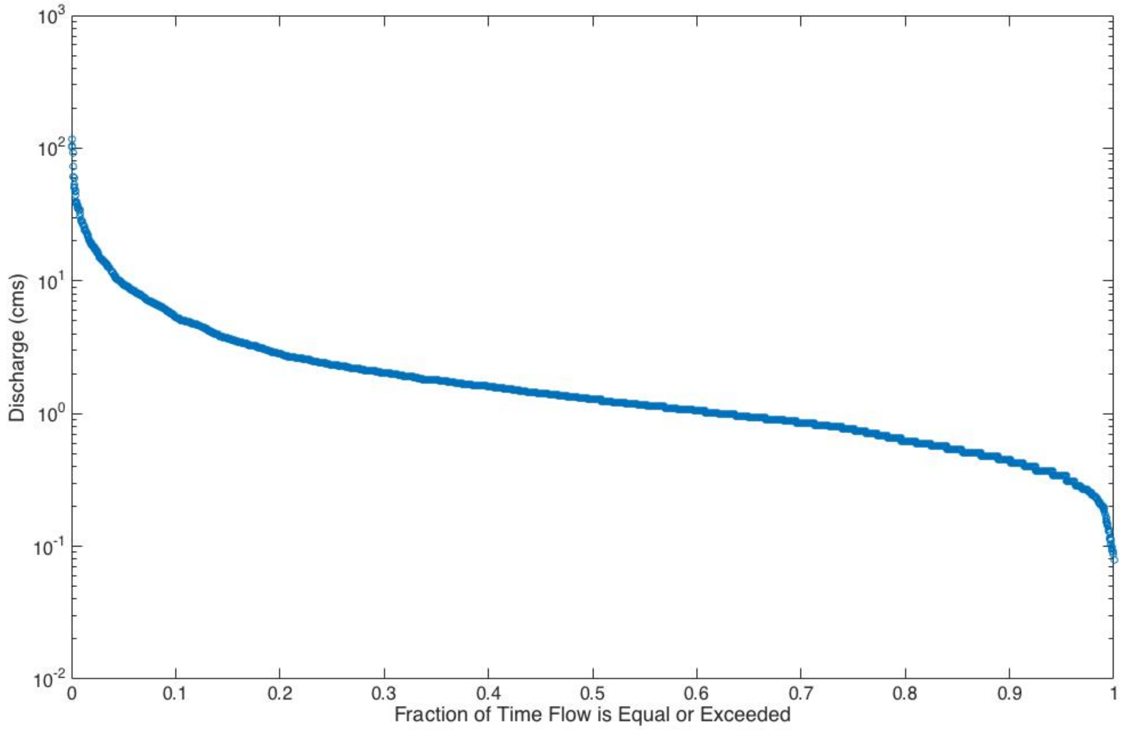


Figure 3.17. Northeast Branch of the Anacostia Flow Duration Curve for the Period from 1990 - 1999

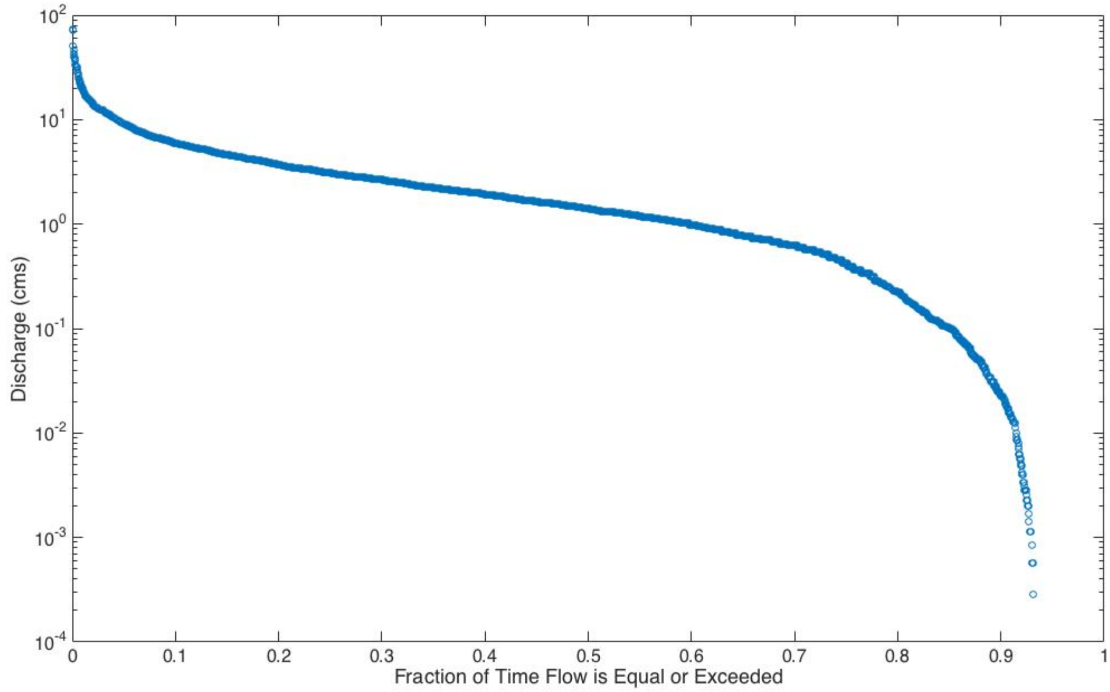


Figure 3.18. Zekiah Swamp Run Flow Duration Curve for the Period from 1990 - 1999

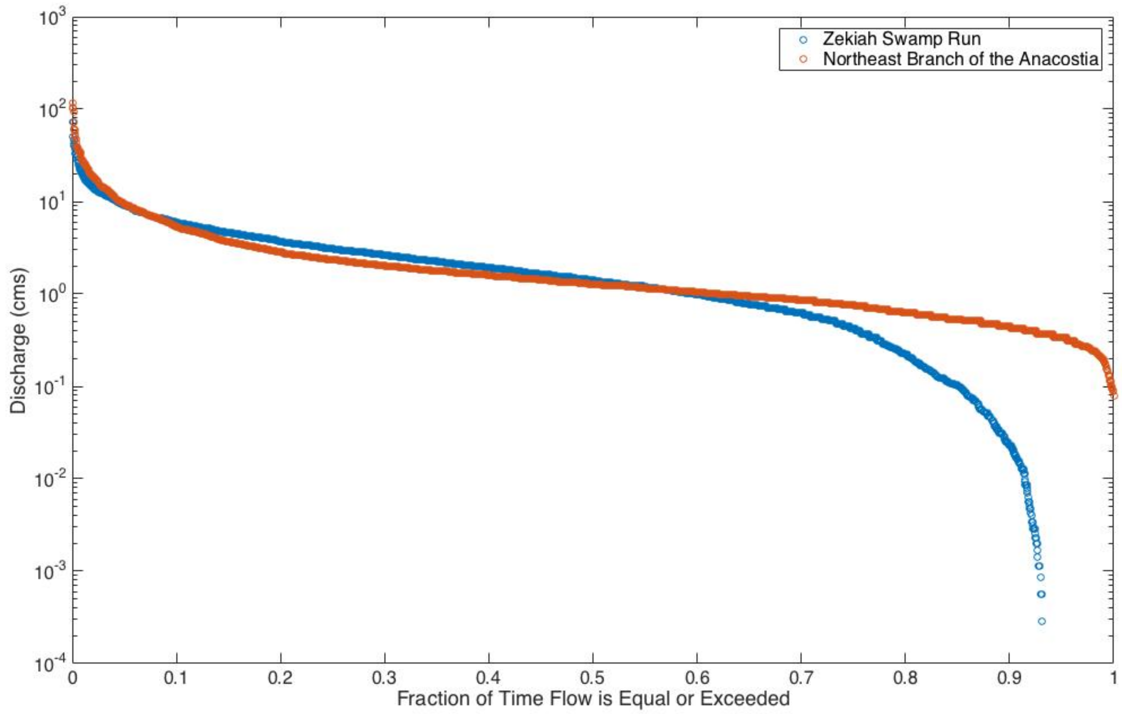


Figure 3.19. Flow Distribution Curve Comparison for Zekiah Swamp Run and the Northeast Branch of the Anacostia

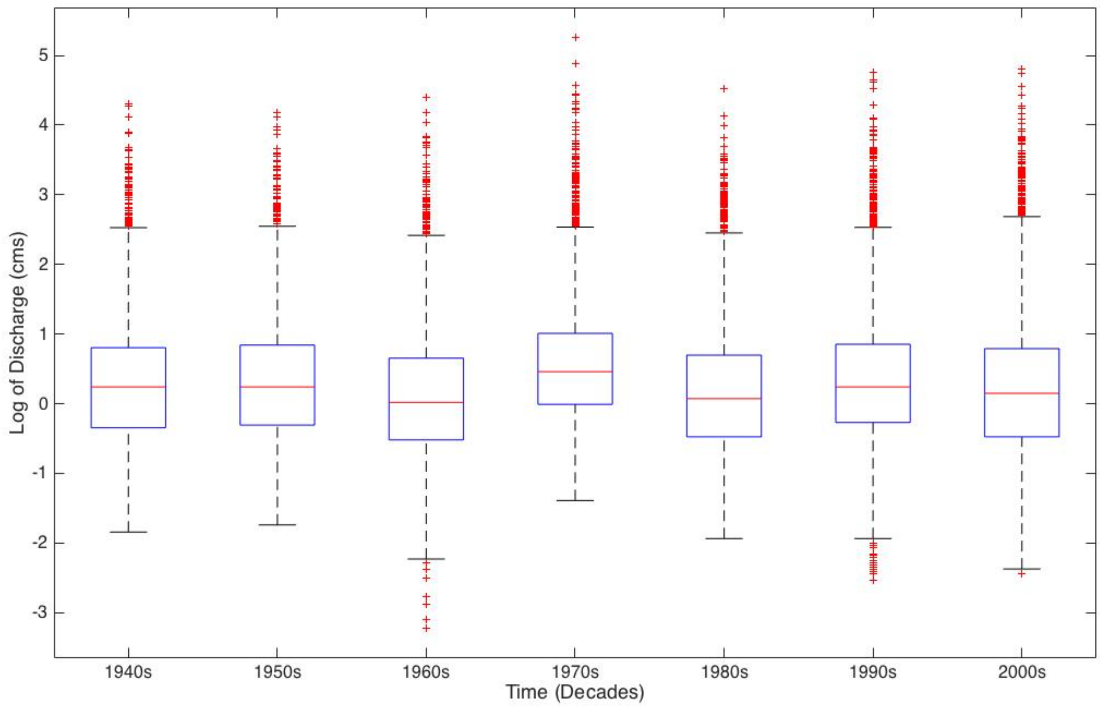


Figure 3.20. A Box Plot of the Distribution of Flows by Decade for the Northeast Branch of the Anacostia. A box plot is a statistical tool for depicting the distribution of data. The whisker portion of the plot shows the outlier points, the bottom box depicts the first quartile while the top box is the third quartile, and the line inside the box is the second quartile or the median.

3.3.2 Time Series Analysis of the Anacostia

The individual flow duration curves for the time series of the Northeast Branch of the Anacostia can be seen in the Appendix (Figures A.1 – A.7). A summary of all of the distribution of flows can be seen in Figure 3.20. The observed discharges, by decade, for the Northeast Branch of the Anacostia, were used to create the box plot shown in Figure 3.20. The box plot indicates variations in the extremes of daily discharges, but no trend in the median, 25%, and 75% values.

3.4 At-A-Station Hydraulic Geometry Analysis

At-a-station hydraulic geometry equations are empirical equations derived from cross section and velocity measurements at an individual gauging station. The relationship between discharge and width, depth, velocity, provides information on the accommodation of the stream to an increase in discharge at a given station. The exponents must sum to one, therefore, the largest exponents indicate the hydraulic variable that changes the most with stream discharge. For this analysis, I will compare at-a-station hydraulic geometry for the Northeast Branch of the Anacostia River for the recent time period, then I evaluated changes in hydraulic geometry for the Anacostia River for time intervals from 1938 to 2014.

3.4.1 Comparison of Coastal Plain Streams

For the time period 1983-2014, the data for the Northeast Branch gauge indicate the following hydraulic geometry relationships (as seen in Figure 3.21):

$$\text{Width} = 17.9Q^{0.12}$$

$$\text{Depth} = 0.24Q^{0.34}$$

$$\text{Velocity} = 0.23Q^{0.53}$$

The coefficients in the equations indicate the values of width, depth, and velocity for a discharge of 1 cms. These data indicate that channel width has much larger values than depth or velocity, but also that width changes little with an increase in discharge. Maximum values of width measured were 30 m. Thus, most of the accommodation to an increase in discharge is through increases in depth (exponent of 0.34) and velocity (exponent of 0.53). Velocity ranges from 0.05 to 2 m/s and depth has a similar range. The hydraulic geometry exponents and coefficients are constrained by the continuity equation; exponents should add up to equal one and the product of the coefficients should equal one. For the period from 1983-2014 for the Northeast Branch of the Anacostia the sum of the exponents is 1.00 and the product of the coefficients equals 1.00. There are no evident discontinuities in the power functions, although there is significant scatter at low discharges when inset channels are formed within channel bed sediments.

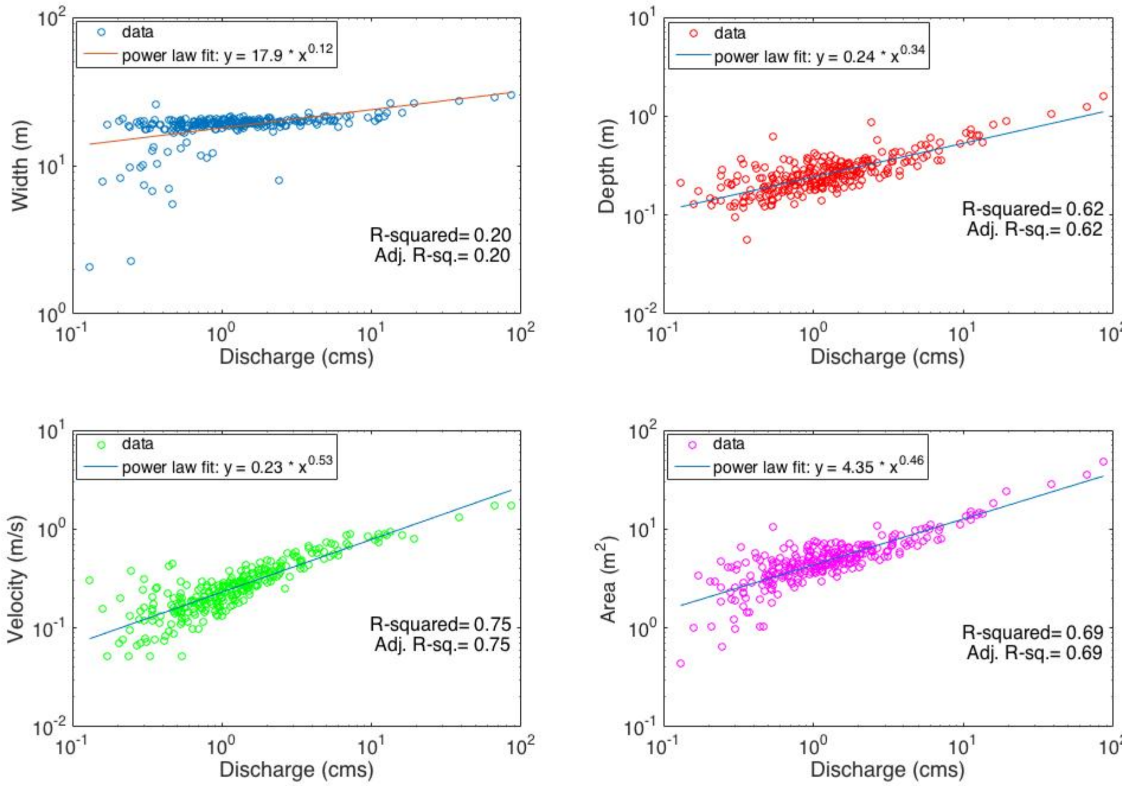


Figure 3.21. Northeast Branch of the Anacostia Hydraulic Geometry for the Period 1983 – 2014

The hydraulic geometry equations for Zekiah Swamp Run (Figure 3.22) for the period 1983-2014 are very different than those for the same period from the NE Branch of the Anacostia. Zekiah Swamp Run is an anastomosing river with multiple shallow channels that flows through a forested wetland. This results in shallow, rough flow, and little increase in velocity with discharge. The resulting hydraulic geometry relationships are shown below. Channel width has the highest values (coefficient of 26.0 m and a maximum value of 80 m). Width also shows the largest increase with discharge (exponent of 0.51). Velocity values are significantly lower (coefficient of 0.28) than in NE Anacostia and show a small increase with discharge (exponent of 0.13). Of the hydraulic variables, only depth has similar coefficients and exponents in both Zekiah Swamp Run and the Northeast Branch of the Anacostia River. For the time period 1984-2012, the data for the Zekiah Swamp Run gauge indicate the following hydraulic geometry relationships:

$$\text{Width} = 26.0Q^{0.51}$$

$$\text{Depth} = 0.28Q^{0.37}$$

$$\text{Velocity} = 0.13Q^{0.13}$$

For the period from 1983-2014 for Zekiah Swamp Run the exponents add up to equal 1.00. The coefficients multiply to equal 0.99. The data, however, also indicate significant non-linearities. Channel width remains nearly constant for discharge values above 7 cms; this is also reflected in the power function relationships for area.

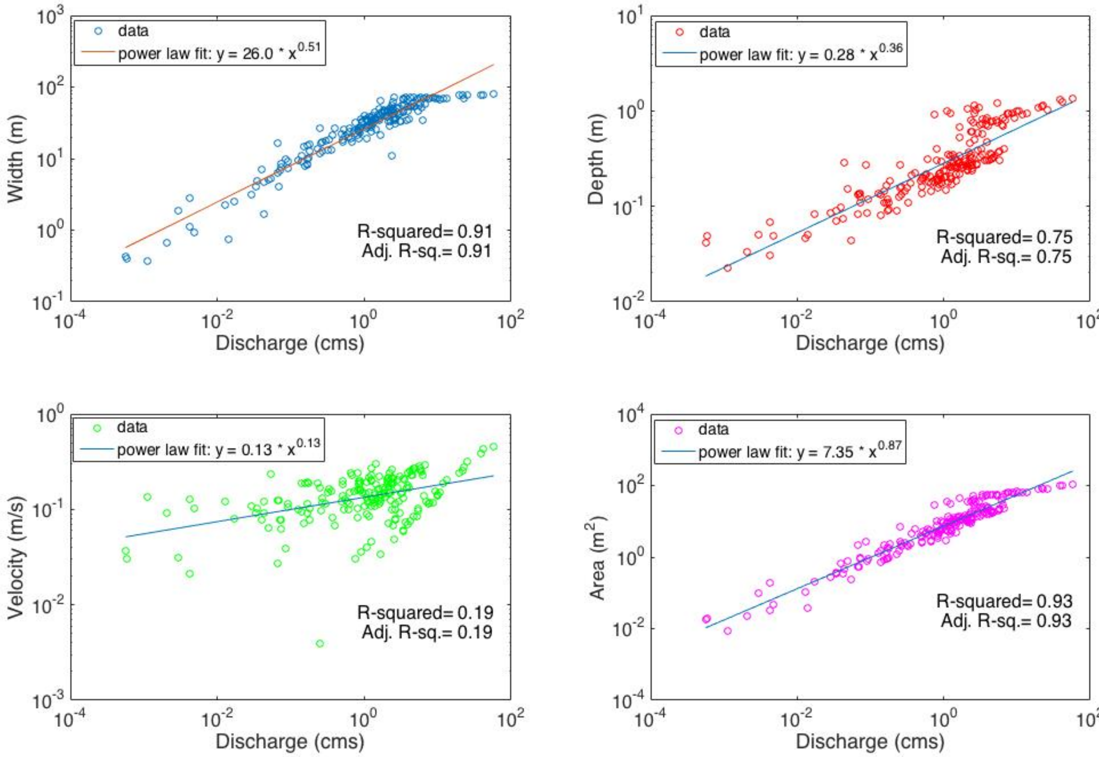


Figure 3.22. Zekiah Swamp Run Hydraulic Geometry for the Period from 1983 - 2014

At-a-Station hydraulic geometry analyses were also conducted for other less urbanized and unchannelized Coastal Plain streams. These streams include Piscataway Creek (Figure 3.23), St. Mary's River (Figure 3.24), and St. Clement Creek (Figure 3.25) and all have smaller drainage basin areas than the Northeast Branch of the Anacostia and Zekiah Swamp Run. The data for all five watersheds is summarized in Table 3.2.

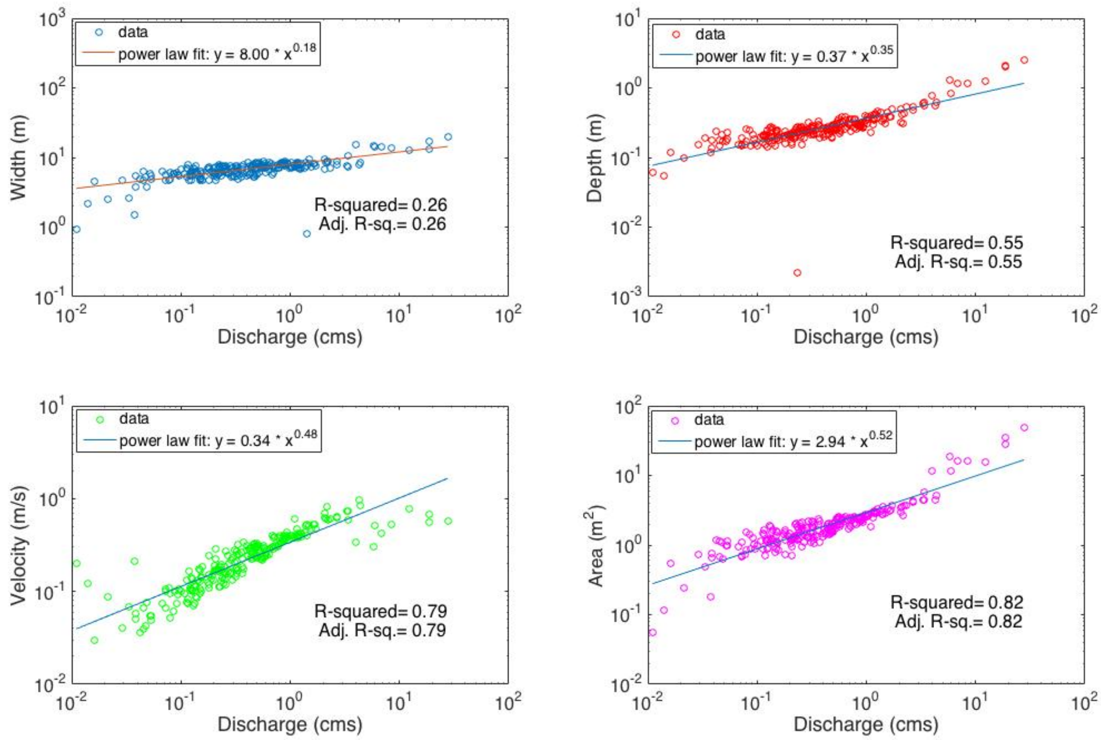


Figure 3.23. St. Mary's Hydraulic Geometry for the Period from 1983 – 2012

For the time period 1983-2014, the data for the St. Mary's River gauge indicate the following hydraulic geometry relationships:

$$\text{Width} = 8.00Q^{0.18}$$

$$\text{Depth} = 0.37Q^{0.35}$$

$$\text{Velocity} = 0.34Q^{0.48}$$

These data indicate that channel width for St. Mary's (62 km^2) has much larger values than depth or velocity, but also that it changes very little with an increase in discharge. This is similar to the width exponent for width for NE Branch. Thus, most of the accommodation to an increase in discharge is through increases in depth (exponent of 0.35) and velocity (exponent of 0.48), although width remains as the largest hydraulic dimension at high flows. The data for velocity indicate a discontinuity for discharges above 5 cms; at the higher discharges velocity remains relatively constant. Although exponents for width are similar to NE Branch, the relatively low velocities and discontinuities in the power functions are more similar to Zekiah Swamp Run.

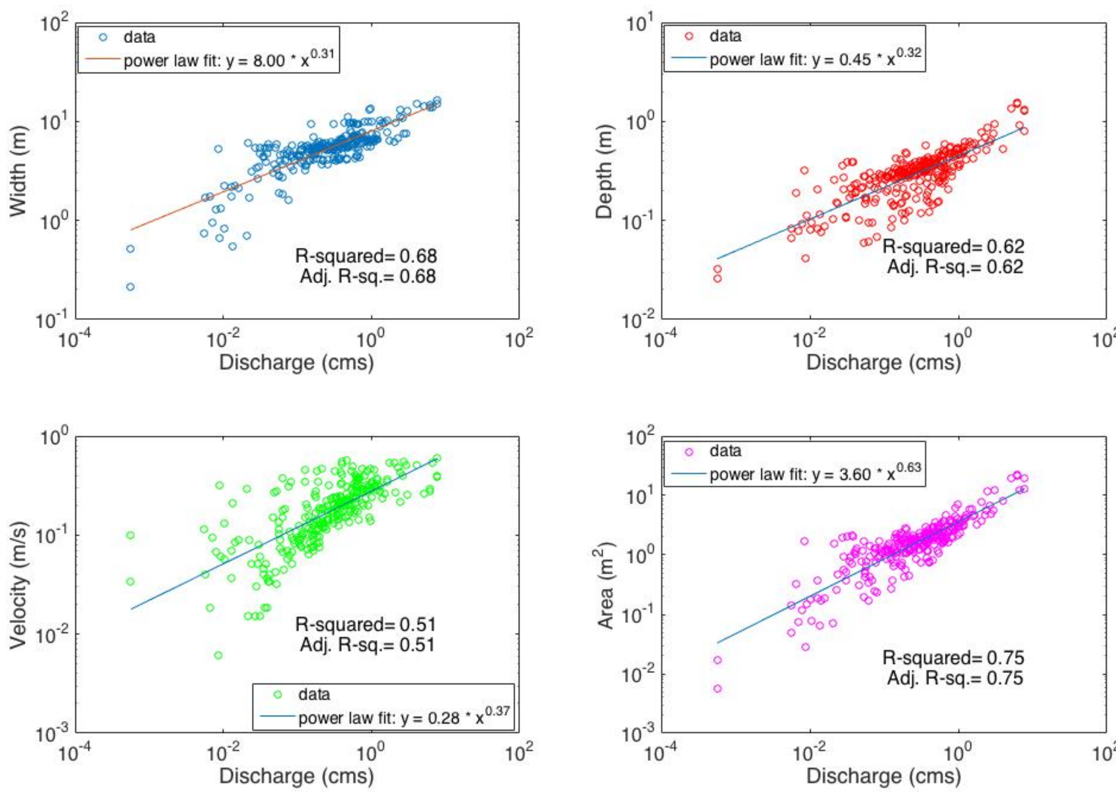


Figure 3.24. St. Clement Creek Hydraulic Geometry for the Period from 1983 – 2014

For the time period 1983-2014, the data for the St. Clement Creek gauge indicate the following hydraulic geometry relationships:

$$Width = 8.00Q^{0.31}$$

$$Depth = 0.45Q^{0.32}$$

$$Velocity = 0.28Q^{0.37}$$

These data indicate that channel width has much larger values than depth or velocity, but at this location, all hydraulic variables show similar increases with discharge. The exponent for width is 0.31, depth exhibits an exponent of 0.32, and velocity an exponent of 0.37.

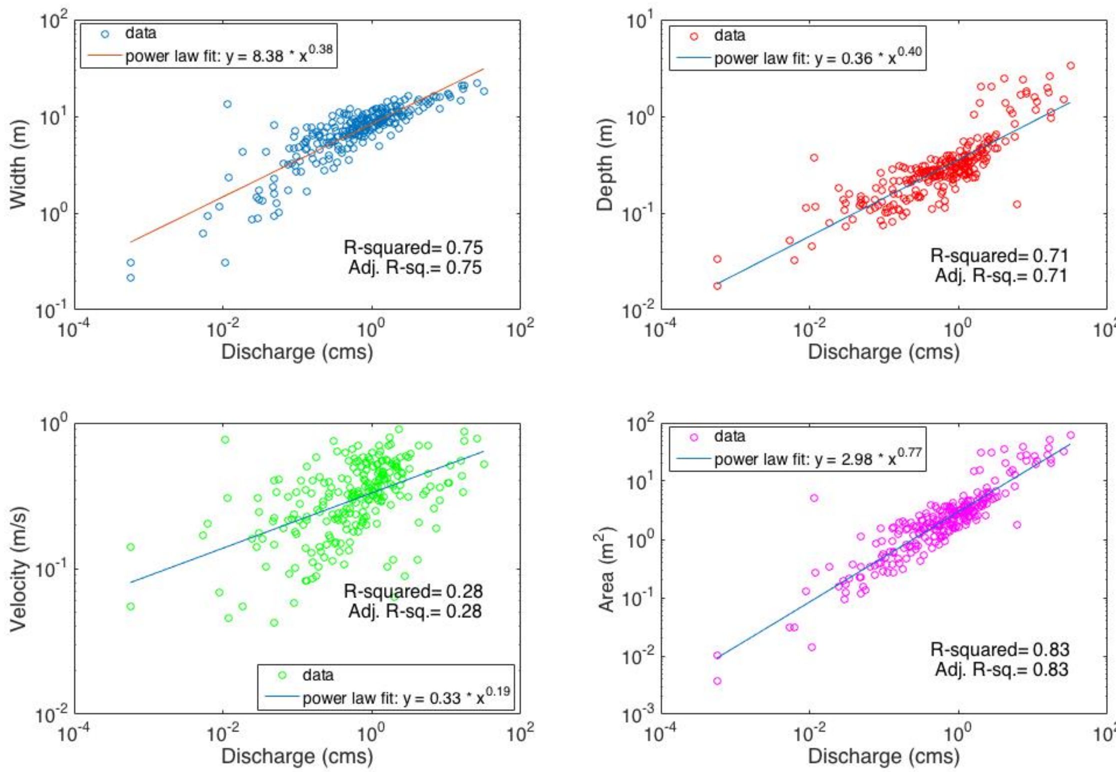


Figure 3.25. Piscataway Creek Hydraulic Geometry for the Period from 1983 – 2014

Piscataway Creek is about half of the size of Zekiah Swamp Run, but it also flows through a well-defined forested wetland valley. For the time period 1983-2014, the data for the Piscataway gauge (102 km^2) indicate the following hydraulic geometry relationships:

$$\text{Width} = 8.38Q^{0.38}$$

$$\text{Depth} = 0.36Q^{0.40}$$

$$\text{Velocity} = 0.33Q^{0.19}$$

These data indicate that channel width has much larger values than depth or velocity and that width and depth increase the most with discharge. Both values of velocity and the exponent for velocity are small, which is similar to Zekiah Swamp Run. Thus, most of the accommodation to an increase in discharge is through increases in width (exponent of 0.38) and depth (exponent of 0.40).

Table 3.3. Hydraulic Geometry Equations for the Comparison of Coastal Plain Streams

Site	**Basin Area, km^2**	**Width Equation**	**Depth Equation**	**Velocity Equation**
Anacostia (urban)	188.6	$W = 17.9Q^{0.12}$	$D = 0.24Q^{0.34}$	$V = 0.23Q^{0.53}$
Zekiah (non-urban)	206.9	$W = 26.0Q^{0.51}$	$D = 0.28Q^{0.37}$	$V = 0.13Q^{0.13}$
St Marys	62.2	$W = 8.00Q^{0.18}$	$D = 0.37Q^{0.35}$	$V = 0.34Q^{0.48}$
St Clements	47.9	$W = 8.00Q^{0.31}$	$D = 0.45Q^{0.32}$	$V = 0.28Q^{0.37}$
Piscataway	102.3	$W = 8.38Q^{0.38}$	$D = 0.36Q^{0.40}$	$V = 0.33Q^{0.19}$

3.4.2 Time Series Analysis of Channel Morphology and Hydraulics

The Northeast Branch of the Anacostia has adjusted to changes in stream flow and it has been channelized (straightened, widened, and deepened) to contain flood flows in the channel (See Figure 3.26). These adjustments have resulted in changes in the channel bed elevation, depth, width, flow resistance, and velocity of the channel. To examine changes in bed elevation during the time period of the study, I conducted a specific gauge analysis, which is a time series of the gauge height of the mean annual discharge for the period of record. The mean annual discharge for the Northeast Branch of the Anacostia gauge is 2.48 m^3/s. This analysis provides an examination of changes in bed elevation throughout the time period of the study. The specific gauge analysis data are shown in Figure 3.27; this graph shows both increases and decreases in the bed elevation for a discharge value of 2.48 m^3/s over the early period of the time series analysis and then a significant drop around the mid 1960s, which coincides with the main period of channelization of the lower portions of Northeast and Northwest branch streams. After channelization the streambed is much more stable although there appears to be incision occurring in the more recent time period.

Figure 3.26. Photographs of the Gage Location at the Northeast Branch of the Anacostia (photos courtesy of M. Peterson). Top Photo: Gage and looking downstream, Bottom: Looking upstream from the gage.

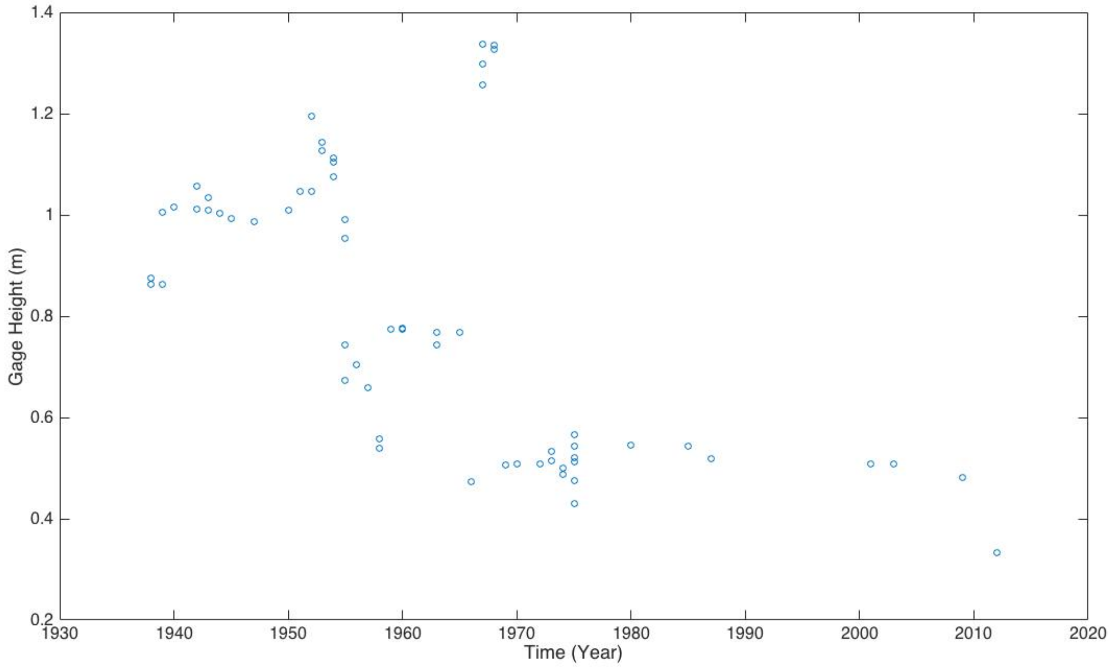


Figure 3.27. Specific Gage Analysis for the Northeast Branch of the Anacostia for the Gage Period of Record (1938 - 2014)

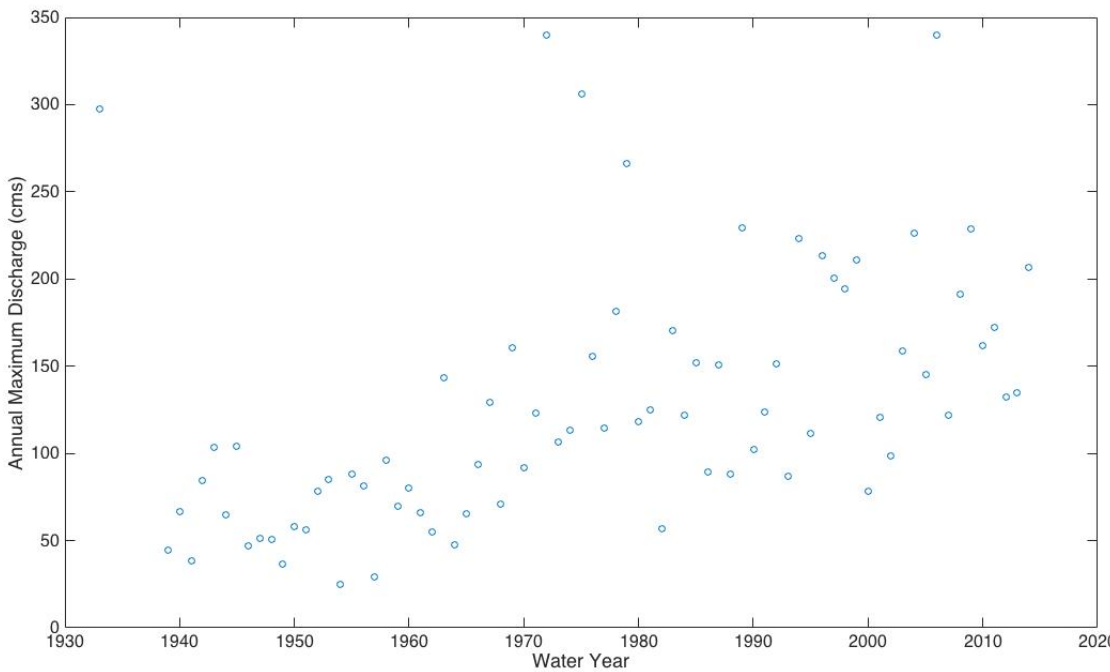


Figure 3.28. Annual Maximum Discharge Time Series for the Northeast Branch of the Anacostia

Figure 3.28 shows the Annual Maximum Discharge Time Series for the Northeast Branch of the Anacostia. This data series shows how the highest flow of the year has changed over time for the Northeast Branch. Although there is a lot of scatter to the data, there is a significant upward trend to the annual maximum discharge that is not observed in significantly less urbanized watersheds (Zekiah Swamp Run and Piscataway Creek).

For the at-a-station hydraulic geometry analysis, the data were divided into three major periods: The earliest period of the time series analysis was done from gauge establishment in 1938 up until 1960, which was after ditching of the tidal Anacostia River, but before the flood control channel was built in the Northeast Branch of the Anacostia and before the major increase in discharge associated with suburban development of the upper watershed (Figure 3.29). The at-a-station hydraulic geometry equations for the period 1938-1960 are significantly different from those derived for the most recent period of data for the Anacostia River. The at-a-station hydraulic geometry equations for the early period of data for Northeast branch are:

$$\text{Width} = 11.4Q^{0.25}$$

$$\text{Depth} = 0.28Q^{0.38}$$

$$\text{Velocity} = 0.31Q^{0.37}$$

These hydraulic geometry exponents and coefficients are constrained by the continuity equation. For the period from 1938-1960 the exponents add up to equal 0.99. The coefficients multiply to equal 0.99. The exponent for velocity is significantly lower for this earlier time period for Northeast Branch, but with a value of 0.37, it is still significantly higher than the values for Zekiah Swamp Run or Piscataway Creek. The width and depth exponents for this time period were 0.25 and 0.38 respectively. The coefficient for width indicates that the channel width was significantly narrower than for later periods, reflecting the interval of adjustment to the downstream channelization but prior to the building of the flood control channel.

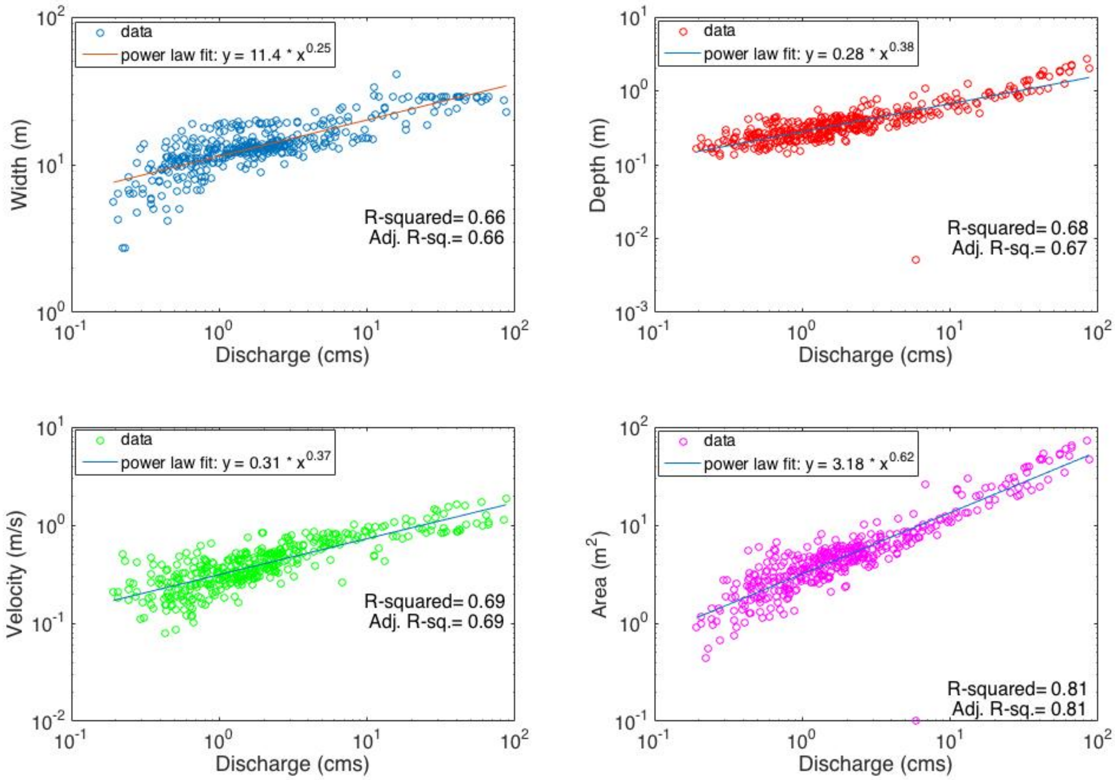


Figure 3.29. Northeast Branch of the Anacostia Hydraulic Geometry for the Period from 1938 – 1960

The next time period analyzed for the time series analysis was the period from 1970 – 1990 (Figure 3.30). I did not analyze the period between 1960 and 1970 because it included the construction of and adjustment to the flood control channel. This time period encompasses the period of channelization and urbanization in the watershed. The at-a-station hydraulic geometry equations for this period of data for Northeast branch are:

$$\text{Width} = 16.5Q^{0.14}$$

$$\text{Depth} = 0.24Q^{0.33}$$

$$\text{Velocity} = 0.26Q^{0.46}$$

The coefficient for width has increased, reflecting the much wider channel built for flood control. The exponent for width has dropped, but the exponent for velocity is significantly higher than for the previous interval. For the period from 1970 - 1990 the exponents add up to equal 0.93. The coefficients multiply to equal 1.01.

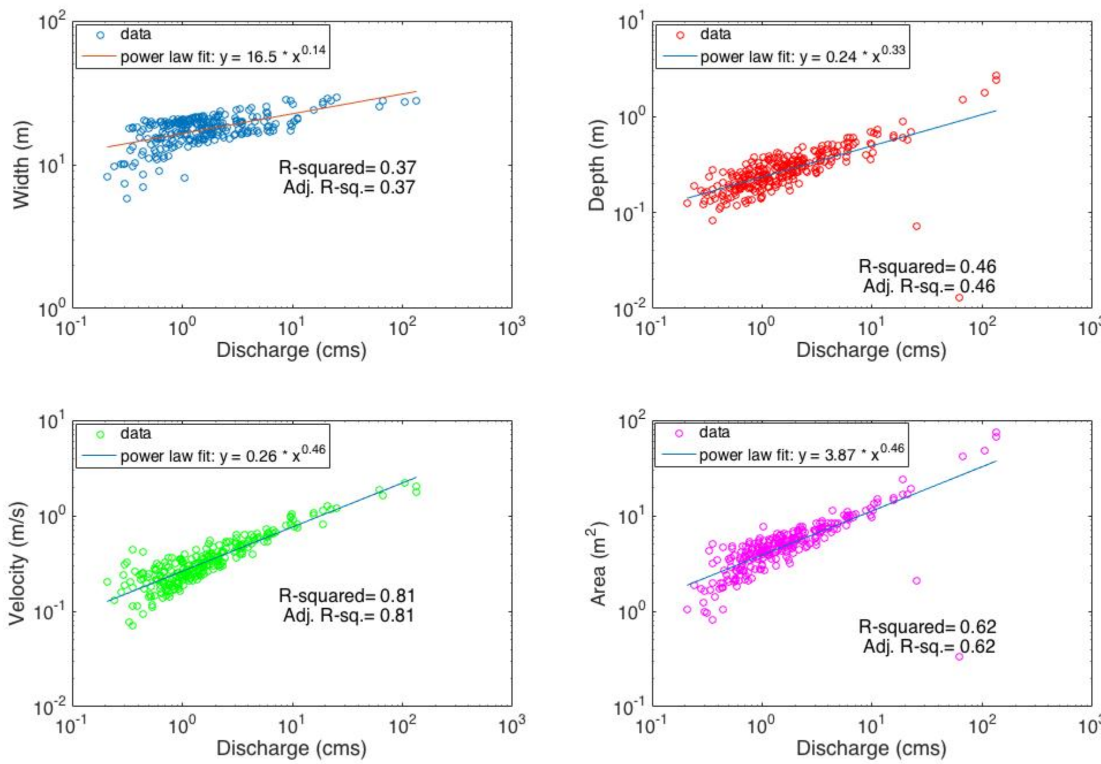


Figure 3.30. Northeast Branch of the Anacostia Hydraulic Geometry for the Period from 1970 – 1990

The final time period analyzed in this time series analysis was from 1994 until 2014 (Figure 3.31). This period accounts for the most recent time period with extensive urbanization and channelization. The at-a-station hydraulic geometry equations for this period of data for Northeast branch are:

$$\text{Width} = 18.1Q^{0.12}$$

$$\text{Depth} = 0.25Q^{0.32}$$

$$\text{Velocity} = 0.22Q^{0.56}$$

For the period from 1994 - 2014 the exponents add up to equal 0.99. The coefficients multiply to equal 1.00.

For this time period the width and depth exponents are 0.12 and 0.32 respectively. The velocity exponent has increased significantly to 0.56 in this period. Although width has the largest value of the three hydraulic variables, the increase in discharge is accommodated primarily through the increase in discharge. The exponent for channel area (width and depth combined) is only 0.43. These hydraulic changes have occurred after the formation of the flood control channel, but during a phase of channelization of upstream reaches and tributaries. These data suggest that upstream changes in velocity are carried downstream through this reach. For the period from 1994 - 2014 the exponents add up to equal 0.99. The coefficients multiply to equal 1.00.

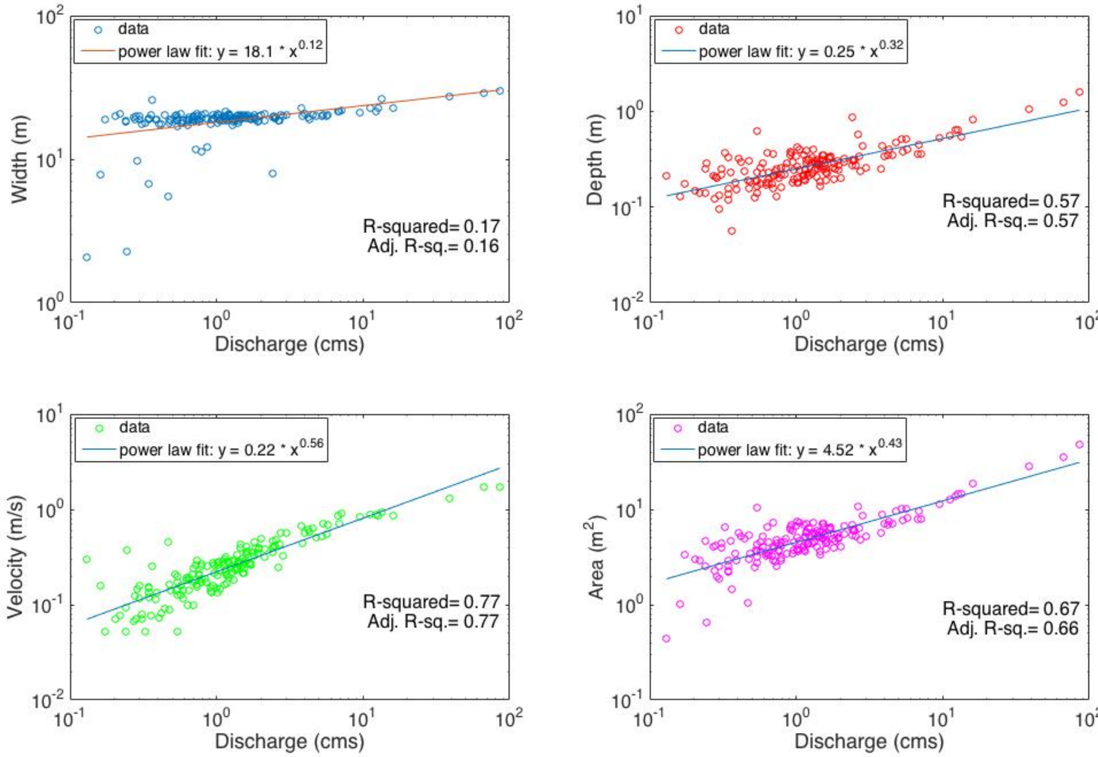


Figure 3.31. Northeast Branch of the Anacostia Hydraulic Geometry for the Period from 1994 – 2014

The hydraulic geometry equations for the various time periods in the Anacostia are summarized in Table 3.3. The associated exponents and coefficients for these equations are graphed as a function of time in Figure 3.32 and 3.33 to illustrate the geomorphic and hydraulic changes. The exponents plotted in Figure 3.32 indicate that width and depth exponents have decreased over time in the Northeast Branch channel, whereas the velocity exponents have significantly increased. The coefficient for width has changed significantly over time, reflecting widening of the channel. Coefficients for velocity and depth, however, have remained almost constant over time. The hydraulic geometry relationships were also calculated by decade like the flow duration curves, these graphs can be found in the Appendix (Figures A.8 – A.14).

Table 3.4. Hydraulic Geometry Equations for identified time intervals, Northeast Branch of the Anacostia

Time Interval	**Width Equation**	**Depth Equation**	**Velocity Equation**
1938 – 1960	$W = 11.4Q^{0.25}$	$D = 0.28Q^{0.38}$	$V = 0.31Q^{0.37}$
1970 – 1990	$W = 16.5Q^{0.14}$	$D = 0.24Q^{0.33}$	$V = 0.26Q^{0.46}$
1994 – 2014	$W = 18.1Q^{0.12}$	$D = 0.25Q^{0.32}$	$V = 0.22Q^{0.56}$

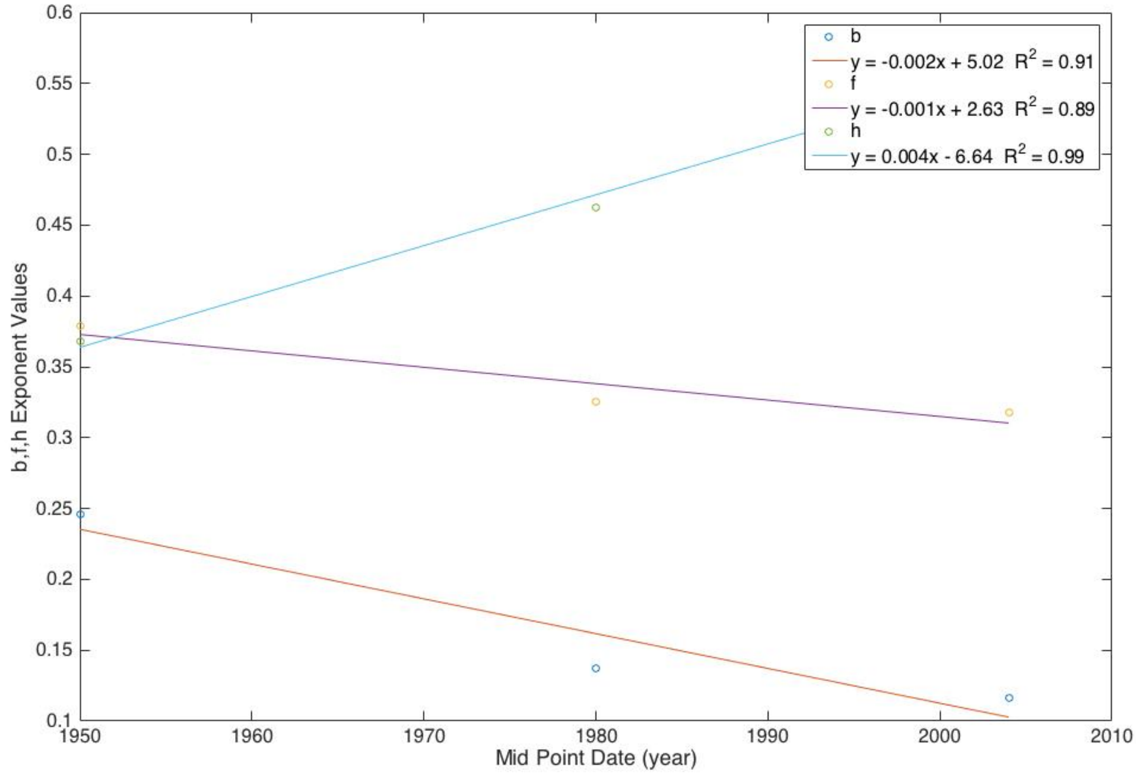


Figure 3.32. Exponents from the Time Series Analysis for the Northeast Branch of the Anacostia

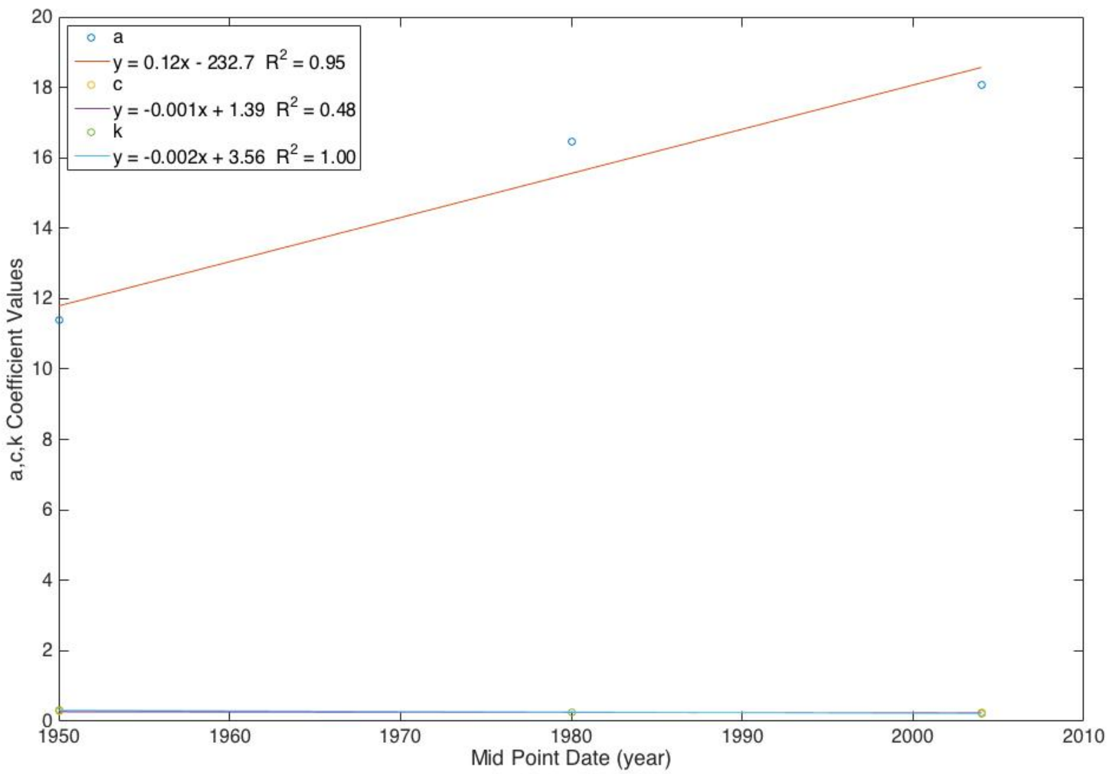


Figure 3.33. Coefficients from the Time Series Analysis for the Northeast Branch of the Anacostia

3.5 Probability Distributions of Daily Values of Channel Width, Depth, and Velocity

3.5.1 Velocity Daily Average Probability Distributions

In this analysis, the results of the hydraulic geometry analysis are combined with the 10-year flow duration analysis to determine velocity values for each daily discharge value in the flow duration analysis. This generates a probability distribution of velocities. The analysis was conducted for 10-year time intervals for the period of record for the Anacostia and for the period 1990-2000 for the comparison stream Zekiah Swamp Run.

The velocity probability curves for the Northeast Branch of the Anacostia and Zekiah Swamp Run are shown in Figures 3.34 and 3.35. Velocity values greater than 0.5 m/s are not observed in Zekiah Swamp Run, but they represent more than 15% of the velocity values for NE Anacostia. This 15% of the daily discharge represents flood hydrographs and it indicates that flood velocities in NE Branch of the Anacostia are beyond the range observed in the non-urban comparison stream. These high velocities would have a significant impact on the transport of suspended sediment and associated contaminants.

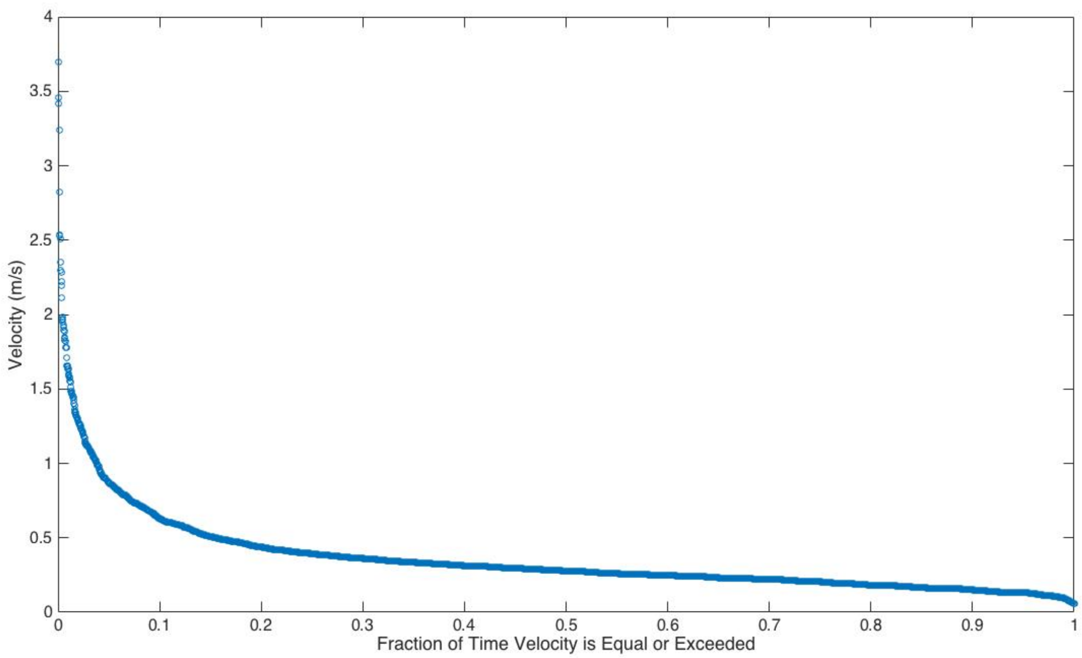


Figure 3.34. Northeast Branch of the Anacostia Velocity Duration Curve for the Period from 1990 - 1999

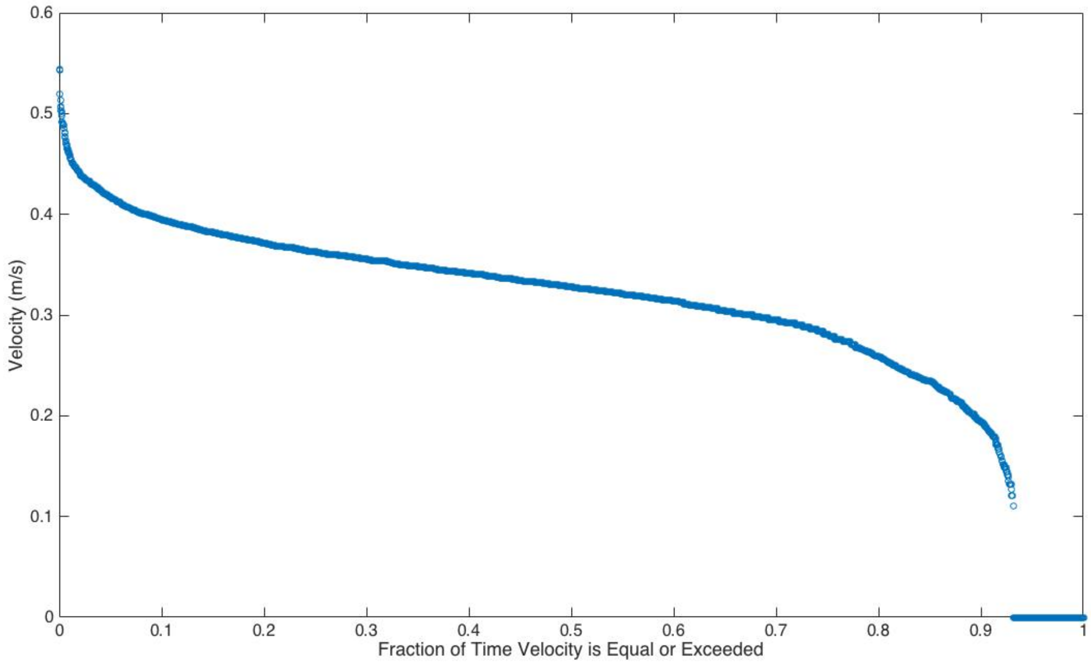


Figure 3.35. Zekiah Swamp Run Velocity Probability Distribution for the Period from 1990 – 1999

3.5.2 Decadal Analysis of Velocity Probability for Northeast Branch Anacostia

The same procedure used to generate the velocity probability curves was also used to generate velocity distributions for daily discharges for each decade. The hydraulic geometry relationships were calculated using decadal data from the Northeast Branch of the Anacostia, these data can be found in the appendix. These hydraulic geometry equations were used along with the probability analysis of daily discharge data for each discharge. This analysis was used to develop velocity probability curves for the Northeast Branch of the Anacostia (appendix, Figures A.15 – A.21). In addition to the velocity probability curves created, the velocity data were also used to create box plot of the distribution of velocities for each decade for the Northeast Branch of the Anacostia. The box plot graph (Figure 3.36) indicates a significant increase in the range of velocities after the 1960s and an increase in the number of high velocity outliers.

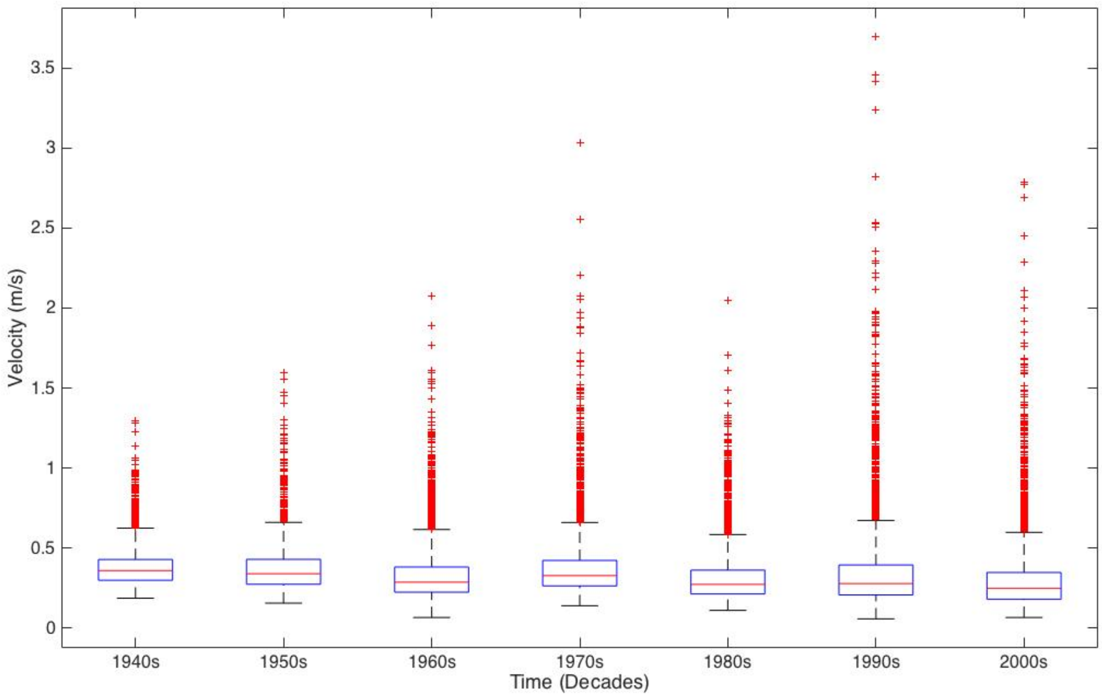


Figure 3.36. Box Plot of the Distribution of Velocities for the Northeast Branch of the Anacostia by Decade

3.5.3 Decadal Analyses of Daily Width and Depth Probabilities for the Anacostia

The procedures used to generate the velocity probability distributions by decade were also used to calculate daily average width, depth, and area values from the decadal analyses of daily discharge and the decadal hydraulic geometry equations. These results are shown in box plots of daily values of Width, Depth, and Area by decade. Figure 3.37 shows the width distributions for the Northeast Branch of the Anacostia by decade. The box plot shows that the width increased from the 1940s until about the 1980s. The data for the 1990s show a very small range of widths with a median that is higher than the 1980s. The 2000s look similar to the 1980s, in both the range of data and the median.

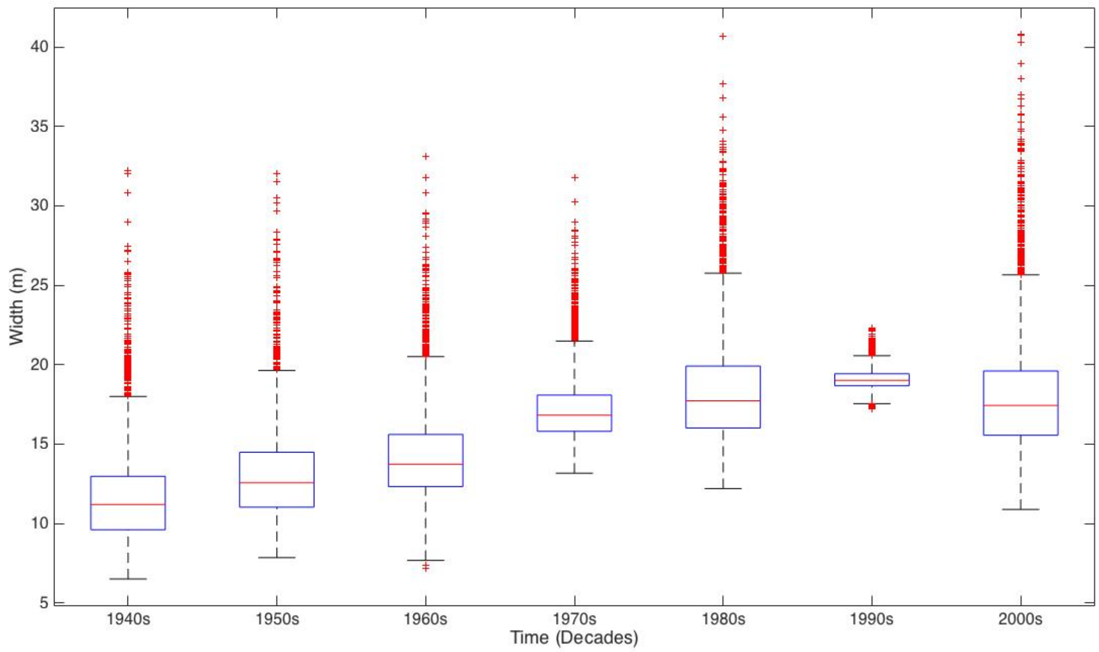


Figure 3.37. Box Plot of the Distributions of Widths for the Northeast Branch of the Anacostia by Decade

The probability distribution of depths for the Northeast Branch of the Anacostia by decades can be seen in Figure 3.38. Channel depths appeared to be mostly decreasing up until the 1980s and then began to increase slightly for the last two decades. The pattern for area (Figure 3.39) appears to be similar to the pattern for the depth distribution. The area distribution is decreasing for the most part until the 1900s and then begins to increase slightly.

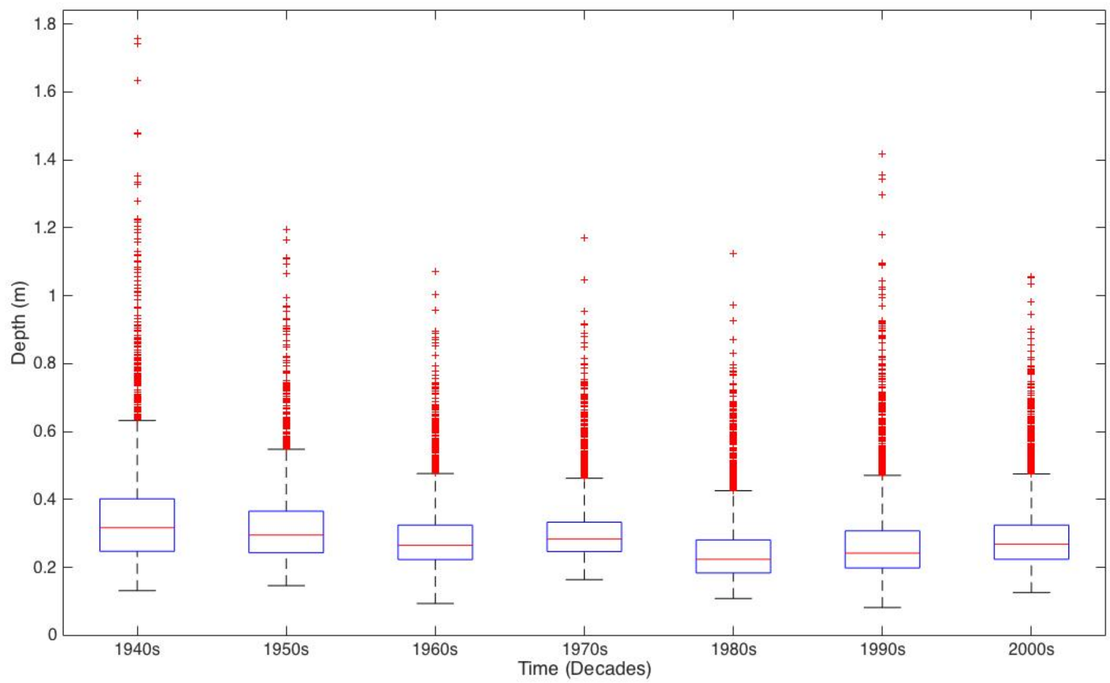


Figure 3.38. Box Plot of the Distributions of Depths for the Northeast Branch of the Anacostia by Decade

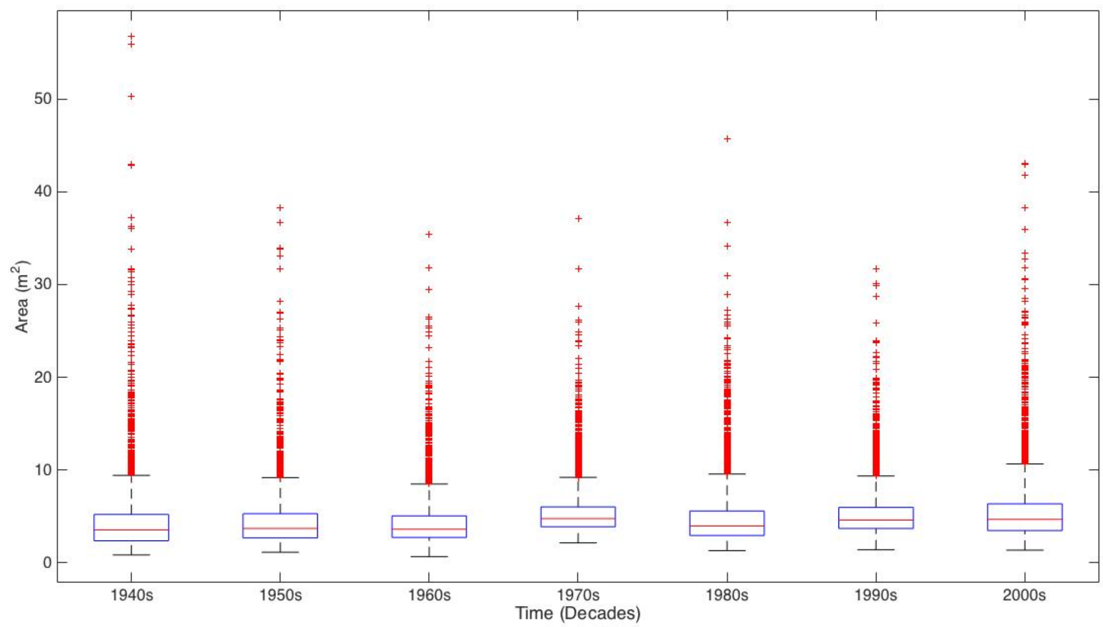


Figure 3.39. Box Plot of the Distributions of Area for the Northeast Branch of the Anacostia by Decade

Chapter 4: Discussion

The portion of the Earth's total land surface that is made up of urban or suburban lands is increasing (Paul and Meyer, 2001). Most studies of urbanization and the effects on the watershed hydrology and stream channel morphology have been done on small watersheds (less than 10 km^2) and have found that stream hydrology becomes significantly altered above 10% impervious cover (Hammer, 1972; Konrad and Booth, 2005; Henshaw and Booth, 2000; Miltner et al., 2004). Very little research has been done on large urban coastal plain watersheds, which can behave very differently than a small urban watershed. This study attempts to quantify those differences.

The purpose of this study was to examine how urbanization and associated channelization affected both runoff processes and stream hydraulics in the Anacostia River. The study involved calculating water balances, examining flow duration curves, doing hydraulic geometry analyses, and finally looking at velocity probability distributions. The examination was done by first comparing the hydrology and hydraulics of the Anacostia to the similarly sized Zekiah Swamp Run and then by doing a time series analysis of the Anacostia.

The hydrologic comparisons between the Anacostia River (an urbanized and channelized coastal plain stream) and Zekiah Swamp Run (a non-urbanized coastal plain stream) indicate some hydrologic differences, particularly in low and high flows, but also significant similarities in average hydrologic values between the two watersheds. The water balance comparisons indicate that evapotranspiration is higher in the Zekiah Swamp Run watershed and runoff is higher in the Anacostia watershed, although the difference in mean values is not statistically significant between the two watersheds. Although the mean and the standard deviations of the runoff and evapotranspiration are not significantly different the relationship to precipitation does show significant differences between the Anacostia and Zekiah Swamp Run and also in the time series analysis of the Anacostia. The monthly water balance shows the Anacostia has higher runoff in the summer and higher evapotranspiration in the winter than Zekiah Swamp Run.

The increase in runoff and decrease in evapotranspiration associated with urbanization and channelization in the Anacostia is a trend also seen in other studies of water balance in urban areas. In a study by Bhaskar and Welty (2012), it was found that when looking only at natural water balance components, there was extra water in many urban watersheds because of a decrease in evapotranspiration. Another study by Stephenson (1994), found that suburban development increased runoff in a watershed by a factor of four compared to an undeveloped watershed that was similar. Impervious cover and channelization in a suburban or urban watershed can cause this increase in runoff. It was also found that 67% of the precipitation is lost to evapotranspiration in both the suburban and undeveloped watershed. The similar evapotranspiration for the suburban watershed was attributed to irrigation for gardens and lawns (Stephenson, 1994). Stephenson (1994) also included a comparison table of annual water balance studies for urban areas, which shows evapotranspiration rates between 17 and 71% and runoff rates between 13 and 76% of the precipitation into the watersheds. For this study the average annual evapotranspiration rate is 59% for the Northeast Branch of the Anacostia and 62% for Zekiah Swamp Run. The evapotranspiration values for both of these sites fit into the range seen from other urban water balance studies. The average runoff values for this study are 41% for the Anacostia and 38% for Zekiah Swamp Run, both of which also fit into the range seen from the other studies.

The discharge probability analyses (flow duration curves) for the paired watershed comparison indicate significant differences at the high and low end of the discharge spectrum between Zekiah Swamp Run and the Anacostia River. The flows are higher in the Anacostia at both the high end and the low end, which ties into the differences in the water balance for the two sites. Low flow is higher in the Anacostia because there is less evapotranspiration and more runoff than Zekiah Swamp Run. At the high end of flows the Anacostia lacks the retention sites that Zekiah Swamp Run has so most of the precipitation turns into runoff. The flows in the middle of the discharge spectrum are very similar for the two sites.

The at-a-Station hydraulic geometry data indicate significant differences in channel hydraulics between the Anacostia and Zekiah Swamp run channels. The hydraulic geometry exponents indicate which hydraulic variable (width, depth, and velocity) adjusts to accommodate an increase in discharge. In a natural coastal plain stream with wide, shallow braided channels the width tends to increase faster than depth and the velocity tends to increase at a slower rate due to the flow resistance (Charlton R., 2008). For Zekiah Swamp Run a natural coastal plain stream the width has the highest exponent, whereas the Anacostia River, which has been altered by urbanization and channelization, has the highest exponent value for velocity. Zekiah Swamp Run has a braided channel morphology that accommodates increases in discharge by occupying multiple channels, thus increasing channel width. The channelized Anacostia River accommodates by increasing depth and velocity. Maximum velocity values in the Anacostia River were almost an order of magnitude higher than values in Zekiah Swamp Run.

A new technique was created to examine the probability distributions of velocity. The probability distributions of velocity were calculated from the discharge probability data and the at-a-station hydraulic geometry equations. This was done by plugging the discharge values from the probability data into the velocity equations calculated from the hydraulic geometry analysis. Flow velocities in the Anacostia are significantly higher than in Zekiah Swamp Run for approximately 20 percent of the time. The velocities are similar between the two streams for low to moderate flows. The velocities for Zekiah Swamp Run rarely get above 0.5 m/s while high values of velocity in the Anacostia River approach 4 m/s.

Changes in the Anacostia watershed hydrology and channel hydraulics that occurred as a consequence of urban development and channelization were evaluated and presented as time series data. Hydrologic data were analyzed across three time periods including 1938 – 1960, 1970 – 1990, and 1994 – 2012, for the Anacostia River. The hydraulic data was also analyzed on a decadal time scale (from the 1940s through the 2000s) with the resulting graphs available in the appendix.

The time series analysis of the Anacostia indicates only minor changes in major hydrologic characteristics (discharge probability, evapotranspiration, and runoff) since 1940. Maximum peak discharge indicates an increasing trend, as do the stream hydraulics. A specific gauge plot, analysis of the changes in height of the water at a certain discharge, was constructed for the Northeast Branch of the Anacostia. This analysis indicates changes in bed elevation through time, and indicates both the major shift due to channelization in the 1960s, but also a recent shift in the bed elevation at the gauge site on the Northeast Branch of the Anacostia, which dropped by approximately 0.6 meters.

The time series water balance data for the Anacostia indicates that evapotranspiration values range from 67.6 to 70.8 cm and runoff values range from 37.2 to 46.0 cm throughout the three time periods. The runoff in the Anacostia has been increasing throughout the time series analysis with it being highest in the 1994-2012 time period. The evapotranspiration however decreased from the 1939-1960 time period to the 1970-1990 time period but then slightly increased again for the 1994-2012 time period. The 1939-1960 time period has the highest evapotranspiration values.

The flow duration curves for the Anacostia time series show that there are some changes in the extreme flows (both very low and very high) but the median values stay relatively similar. Throughout the time periods the high flows are getting higher for the Anacostia. This is possibly due to the decrease in evapotranspiration and the loss of water storage sites that come with urbanization and channelization.

Time series data of at-a-station hydraulic geometry coefficients and exponents indicated a systematic decrease in the width exponent and systematic increase in the velocity exponent. This means the stream is now doing most of its accommodation to higher flows by increasing the stream velocity. This is as expected because the channelization limits the streams ability to widen, like it would have in its natural state.

A lot of research has been done on the hydraulic geometry relationships in different stream types. In his 2007 paper, Dingman compared all the empirically determined exponent values from previous studies. When compared to the studies summarized in the Dingman (2007) paper the values found in this study for the Anacostia fit into the range, as do the depth exponents for all of the sites. However the width and velocity exponent values for the non-urban coastal plain streams do not fit into the range seen in the previous studies. Research that has been done on bifurcated river deltas shows numbers closer to what is seen in the non-urbanized coastal plain streams (Edmonds and Slingerland, 2007; Edmonds et al., 2011). The exponent values from all these previous studies and those from this study can be compared in Table 4.1.

Table 4.1. Hydraulic Geometry Exponent Values from Various Studies (Adapted from Dingman, 2007; Edmonds and Slingerland, 2007; Edmonds et al., 2011).

Location	b	f	h	Source
Mid-West USA	0.26	0.40	0.34	Leopold and Maddock (1953)
Brandywine Creek, PA USA	0.04	0.41	0.55	Wolman (1955)
Ephemeral Streams, Semi-Arid USA	0.25	0.41	0.33	Leopold and Miller (1956)
Rio Manati, Puerto Rico	0.17	0.33	0.49	Lewis (1969)
R. Hodder, UK	0.09	0.36	0.53	Wilcock (1971)
R. Bollin-Dean, UK	0.12	0.40	0.48	Knighton (1975)
R. Ter, UK	0.14	0.42	0.43	Harvey (1975)
New Zealand	0.18	0.31	0.43	Jowett (1998)
Australia	0.11	0.28	0.52	Stewardson (2005)
Laitaure Delta	0.39	0.38	0.23	Andrén (1994)
Volga and Danube Delta	0.50	0.33	0.17	Mikhailov (1970)
Northeast Branch 1984-2012	0.12	0.34	0.53	This Study
Zekiah Swamp Run 1984-2012	0.51	0.37	0.13	This Study
St. Mary's 1984-2012	0.18	0.35	0.48	This Study
St. Clements 1984-2012	0.31	0.32	0.37	This Study
Piscataway 1984-2012	0.38	0.40	0.19	This Study
Northeast Branch 1938-1960	0.25	0.38	0.37	This Study
Northeast Branch 1970-1990	0.14	0.33	0.46	This Study
Northeast Branch 1994-2012	0.12	0.32	0.56	This Study

The velocity distribution analysis shows that velocities in the Anacostia River have increased over time as channelization has progressed upstream. The median and low flow velocities in the Anacostia River have remained similar over time with slight variations but no real pattern related to time. The extreme high velocities however, have been getting higher over time. In addition to the velocities getting higher over time they also appear to be getting more frequent.

Chapter 5: Conclusions and Implications

Most research on the effects of urbanization on a stream has been done in small watersheds that are less than 10 km^2. The Northeast Branch of the Anacostia River is a large, urban, coastal plain watershed located in the Washington DC Metro Area. The purpose of this study was to examine the effects of urbanization and channelization on a large coastal plain watershed. The study found that mean evapotranspiration was higher in Zekiah Swamp Run than in the Northeast Branch of the Anacostia for the period from 1984-2012. For the same period it was found that mean runoff was higher for the Northeast Branch. The time series data for the Northeast Branch of the Anacostia River showed that the mean evapotranspiration was higher prior to channelization. The mean runoff was highest for the most recent time period, 1994-2012. The hydraulic geometry comparison shows that for the period from 1938-1960, Zekiah Swamp Run accommodates to increases in discharge by increasing the width of the channel while the Northest Branch accommodates by increasing the velocity of the streamflow. For the time series of the Anacostia River the stream moves from accommodating by increasing the width to accommodating by increasing the velocities. This means the width exponent decreases across the time period while the velocity exponent increase. The channel hydraulics in the Northeast Branch of the Anacostia have continued to change at the downstream gauge location after the initial channelization in the watershed. This continued change is attributed to ongoing channelization in the upstream portions of the watershed.

The study found that the runoff and velocities in the Anacostia have continued to grow over time. The change in velocity indicates a significant shift in the sediment carrying capacity of the Anacostia River. This is a problem because the high velocities in the Anacostia can convey significant suspended sediment loads downstream. With more suspended sediment loads being carried into the tidal estuary portion of the Anacostia, there has been significant aggradation of sand and finer sediment. Since the water from the Anacostia Watershed eventually travels to the Chesapeake Bay, the increased suspended sediment load will also end up in the Bay. Sediment is one of the major factors polluting and degrading the Chesapeake Bay. The clarity of a water body can be affected by sediment, which can lead to decreases in sunlight reaching the plants in the bay that are used by fish and other animals for habitat. Nutrients, like nitrogen and phosphorous, can also bind to sediment and spread throughout the bay. These nutrients can cause harmful algal blooms that can affect the amount of sunlight reaching the depths of the bay and can also cause dead zones, which rob the water of oxygen.

Concerns about sediment degrading a stream ecosystem lead to restoration practices that channelize an urban stream reach. However, as was found in this study, channelization does not necessarily stop sediment loads in the stream system. This is because despite stabilizing the stream banks, in a system like the Anacostia, channelization also reduces sediment storage sites. This study shows the importance of fully understanding a stream system before attempting an ecosystem restoration. The techniques used in this study are relatively inexpensive ways to examine a watersheds hydrology and hydraulics for gauged watersheds. They can be used to determine what factors are affecting a particular watershed. With the use of these techniques it would be possible for decisions about stream restoration projects to be tailored to the system. This would make for restoration projects that work with the stream instead of ones that fail or cause more problems within the system.

A typical coastal plain watershed, like Zekiah Swamp Run or the historic Northeast Branch of the Anacostia, should have a wide braded channel with intact flood plains and sediment and water storage sites. Instead of the classic channelization approach to restoration, a better approach for coastal plain streams would be to allow for a more natural system and especially increase sediment and water storage sites. It would also be beneficial to widen the stream channel and reconnect the stream to its floodplains. It may not be possible to increase the width of the stream or provide floodplains in areas that are already extremely urban. However, it may be possible to allow for storage areas. Also it is important to take this into account in rapidly urbanizing areas. While an area is still urbanizing it may be possible to limit how close to a stream building can occur, which would allow the streams to remain more natural. The most important factor is to try to understand the hydrology and hydraulics of a stream system before any restoration decisions are made.

Appendix

A.1 Flow Duration Curves for the Time Series Analysis of the Anacostia

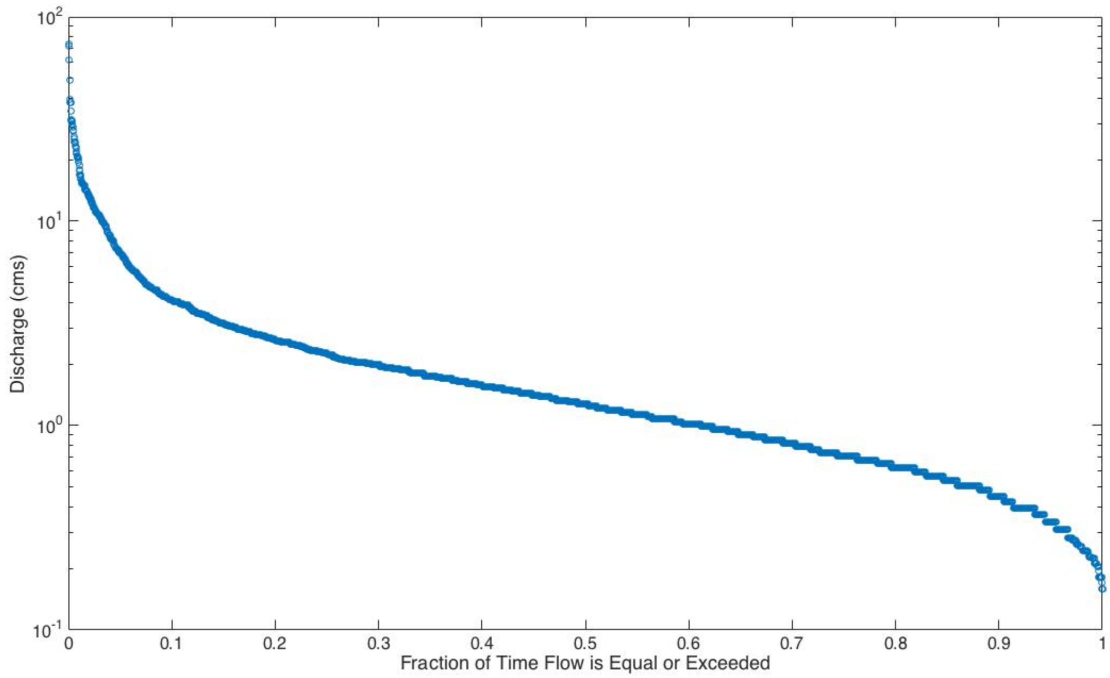


Figure A. 1. Flow Duration Curve for the Northeast Branch of the Anacostia for 1940 – 1949

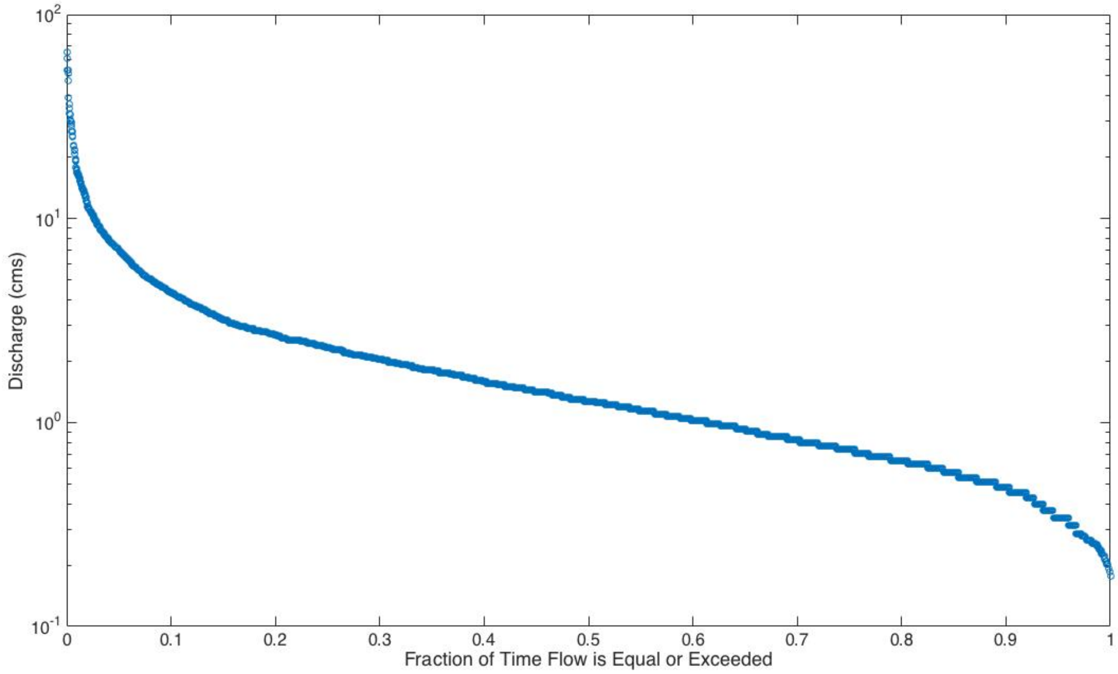


Figure A. 2. Flow Duration Curve for Northeast Branch of the Anacostia for 1950 – 1959

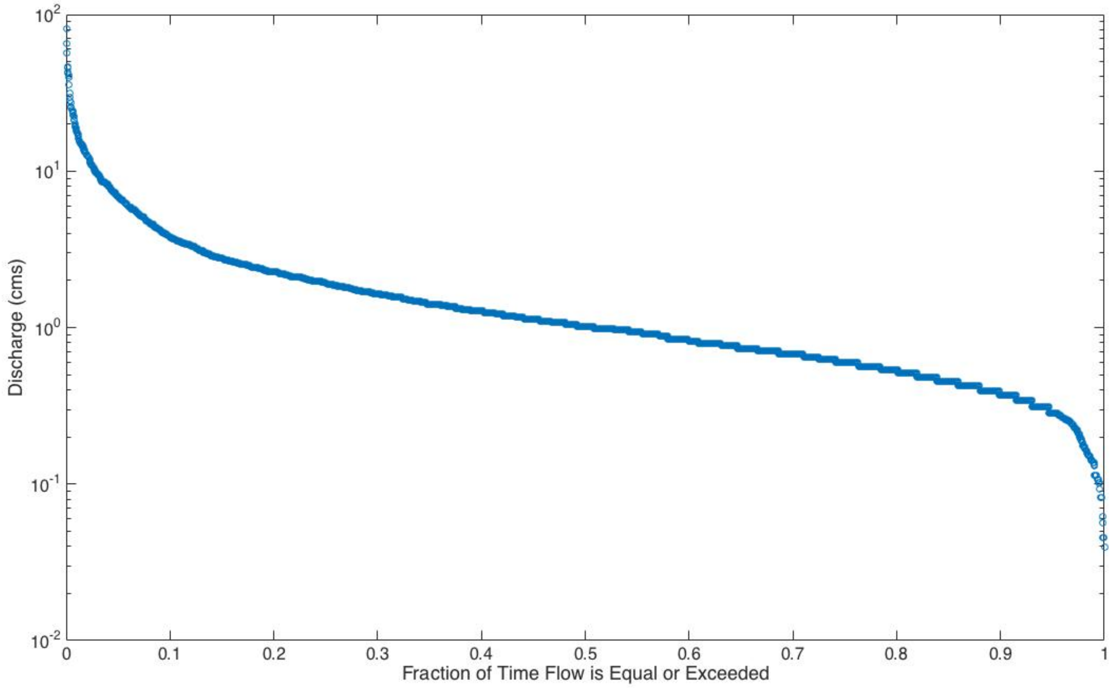


Figure A. 3. Flow Duration Curve for the Northeast Branch of the Anacostia for 1960 - 1969

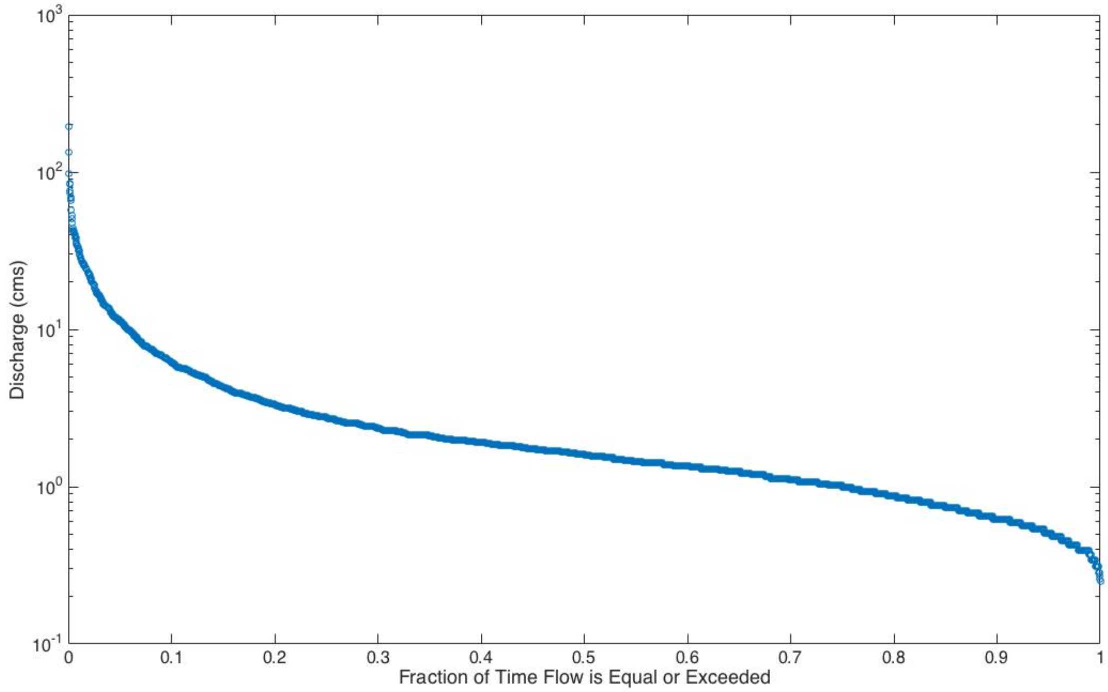


Figure A. 4. Flow Duration Curve for the Northeast Branch of the Anacostia for 1970 - 1979

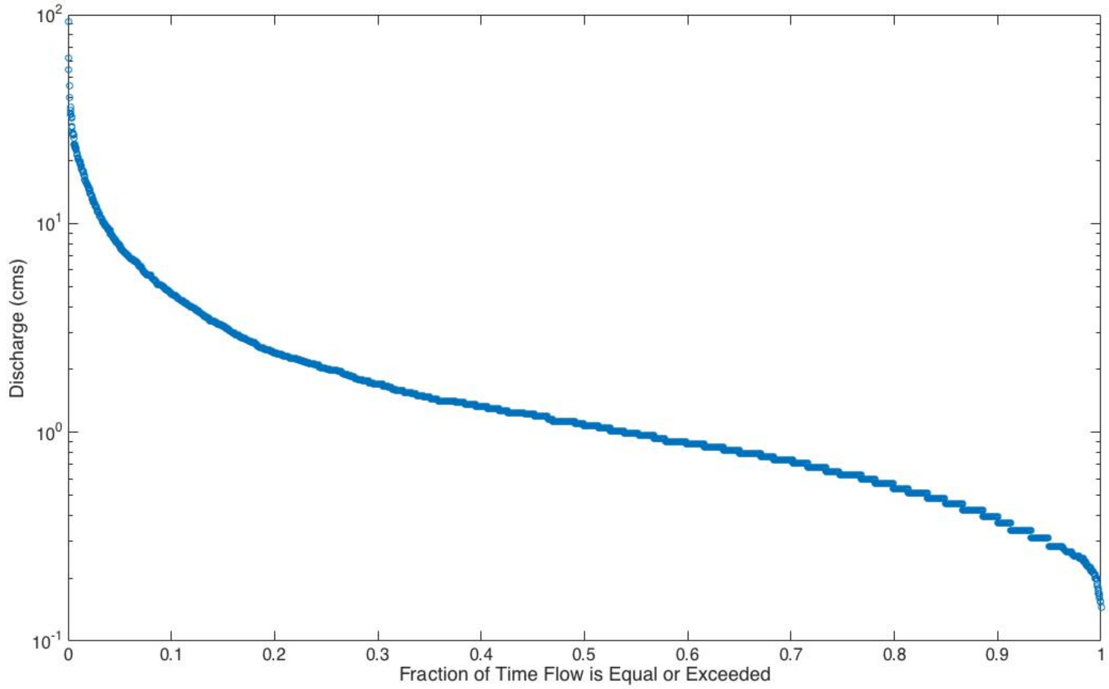


Figure A. 5. Flow Duration Curve for the Northeast Branch of the Anacostia for 1980 - 1989

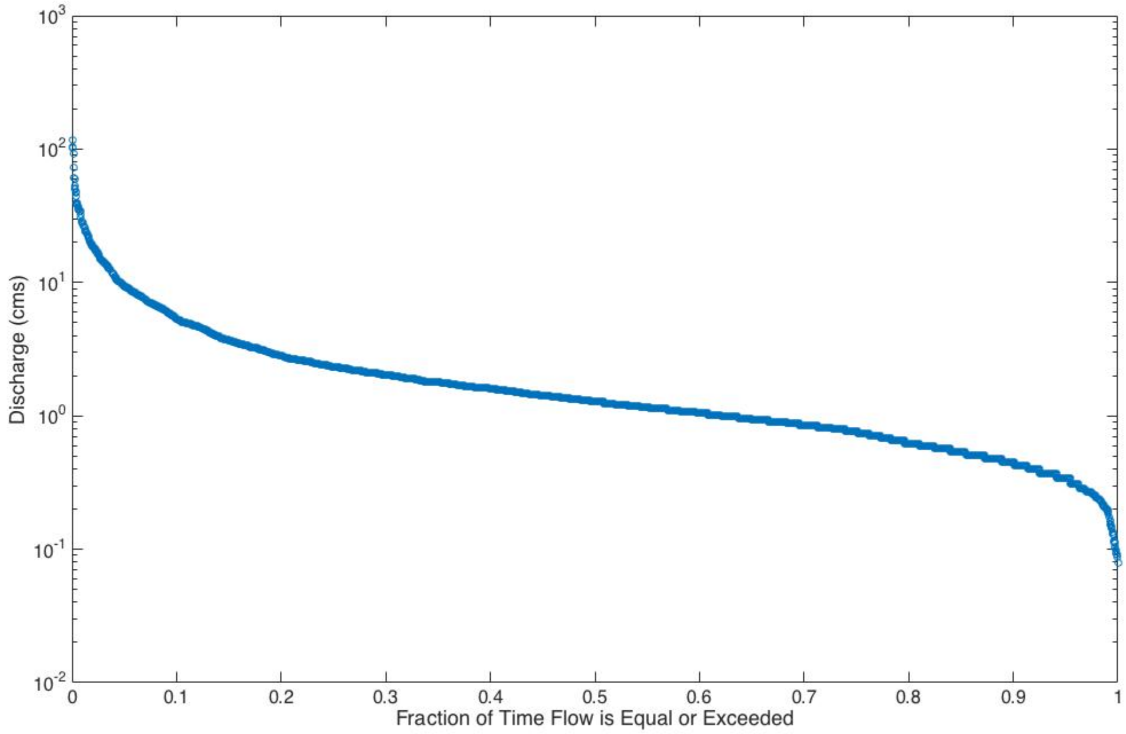


Figure A. 6. Flow Duration Curve for the Northeast Branch of the Anacostia for 1990 - 1999

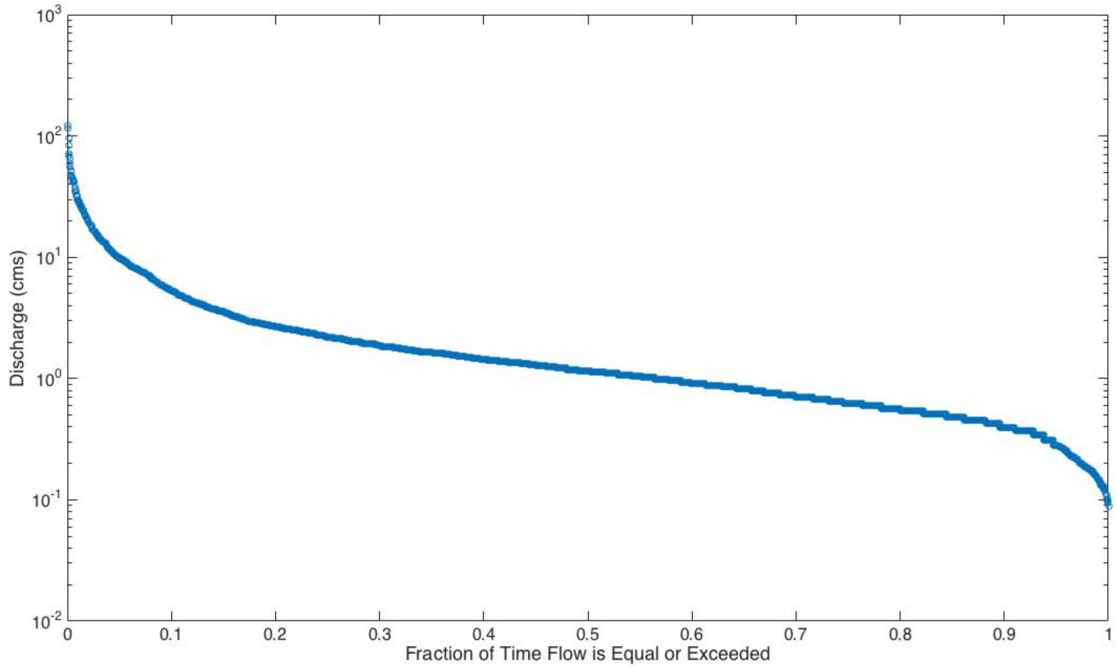


Figure A. 7. Flow Duration Curve for the Northeast Branch of the Anacostia for 2000 – 2009

A.2 Hydraulic Geometry for the Time Series Analysis of the Anacostia

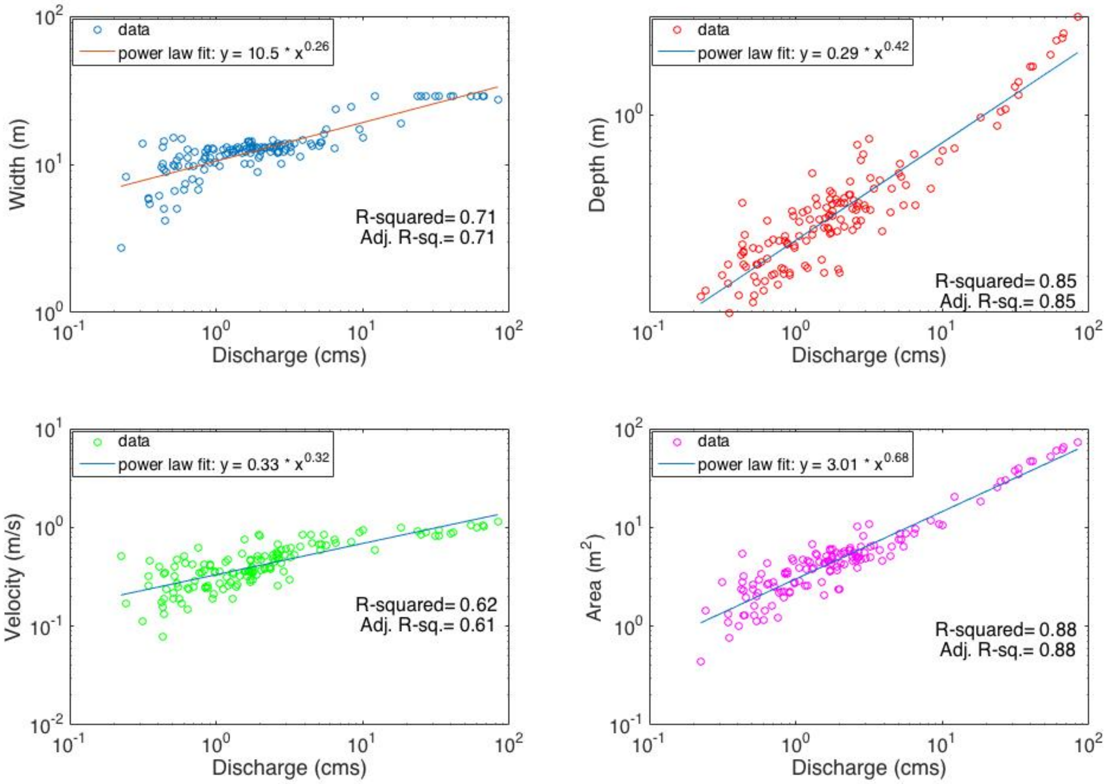


Figure A. 8. Hydraulic Geometry for Northeast Branch of the Anacostia for 1940 – 1949

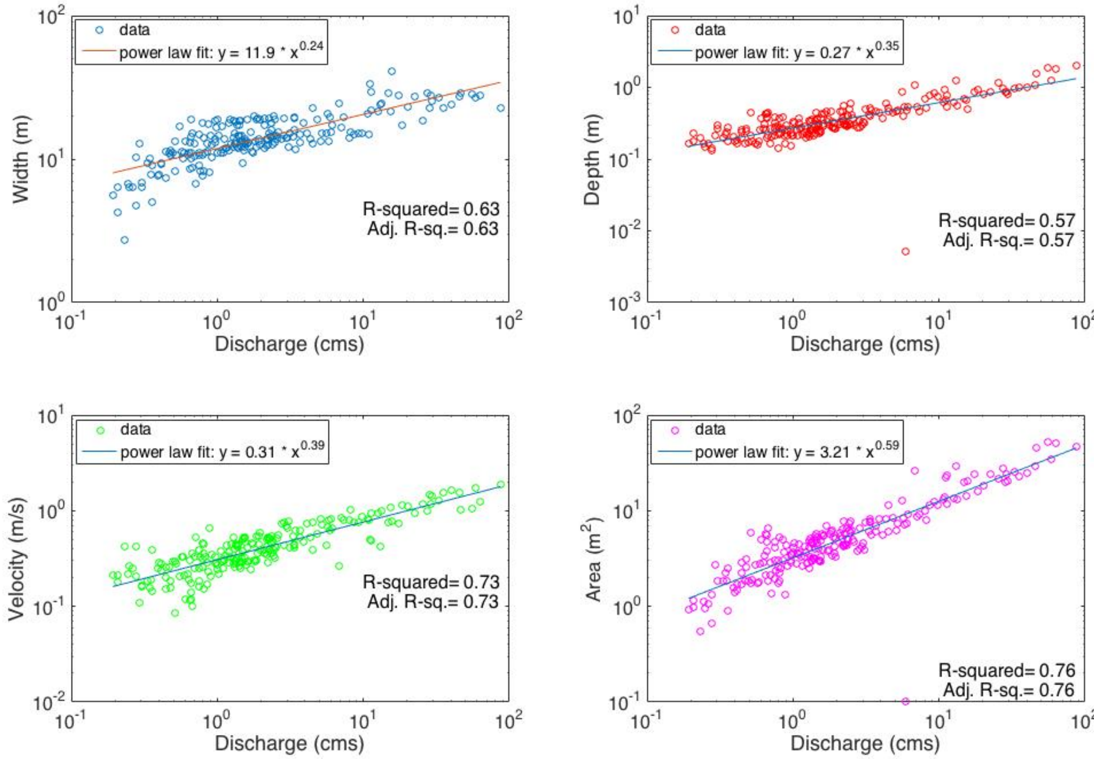


Figure A. 9. Hydraulic Geometry for Northeast Branch of the Anacostia for 1950 – 1959

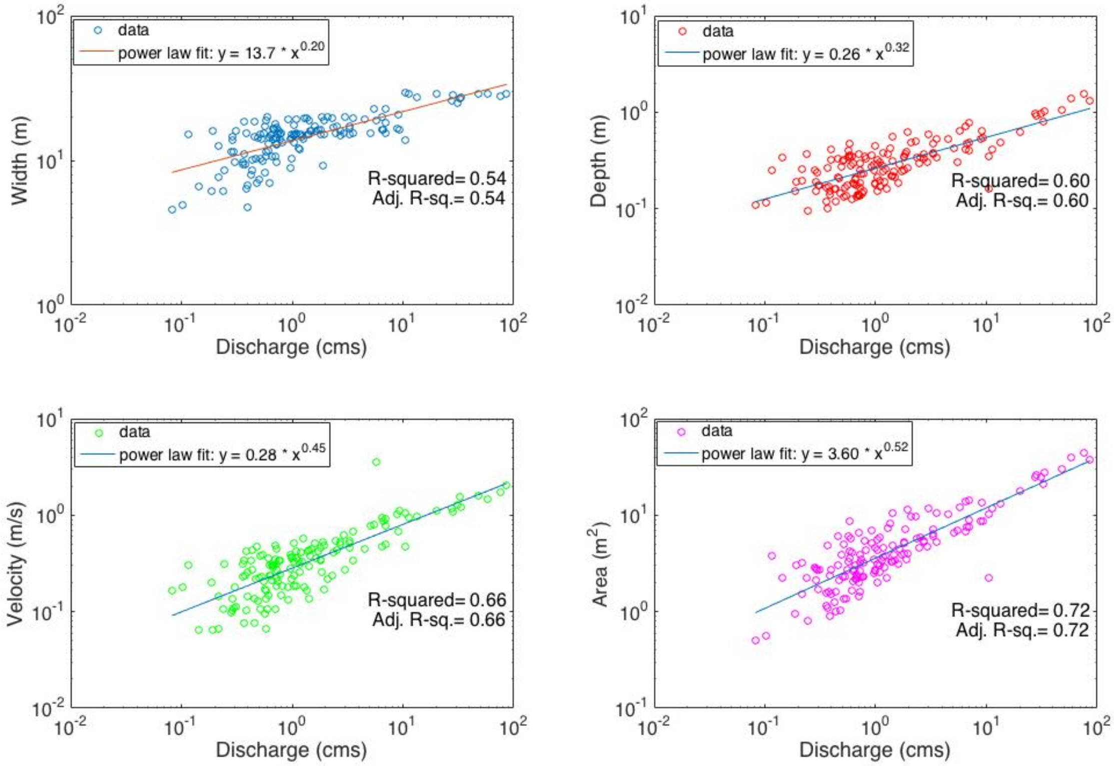


Figure A. 10. Hydraulic Geometry for the Northeast Branch of the Anacostia for 1960 – 1969

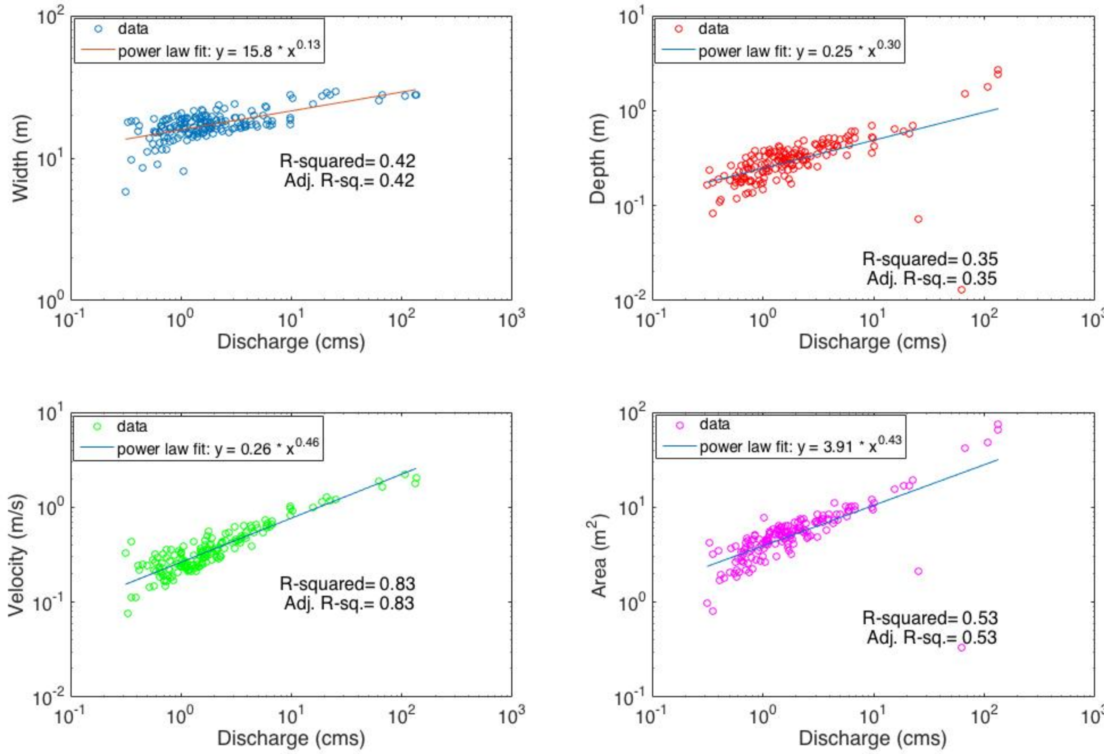


Figure A. 11. Hydraulic Geometry for the Northeast Branch of the Anacostia for 1970 – 1979

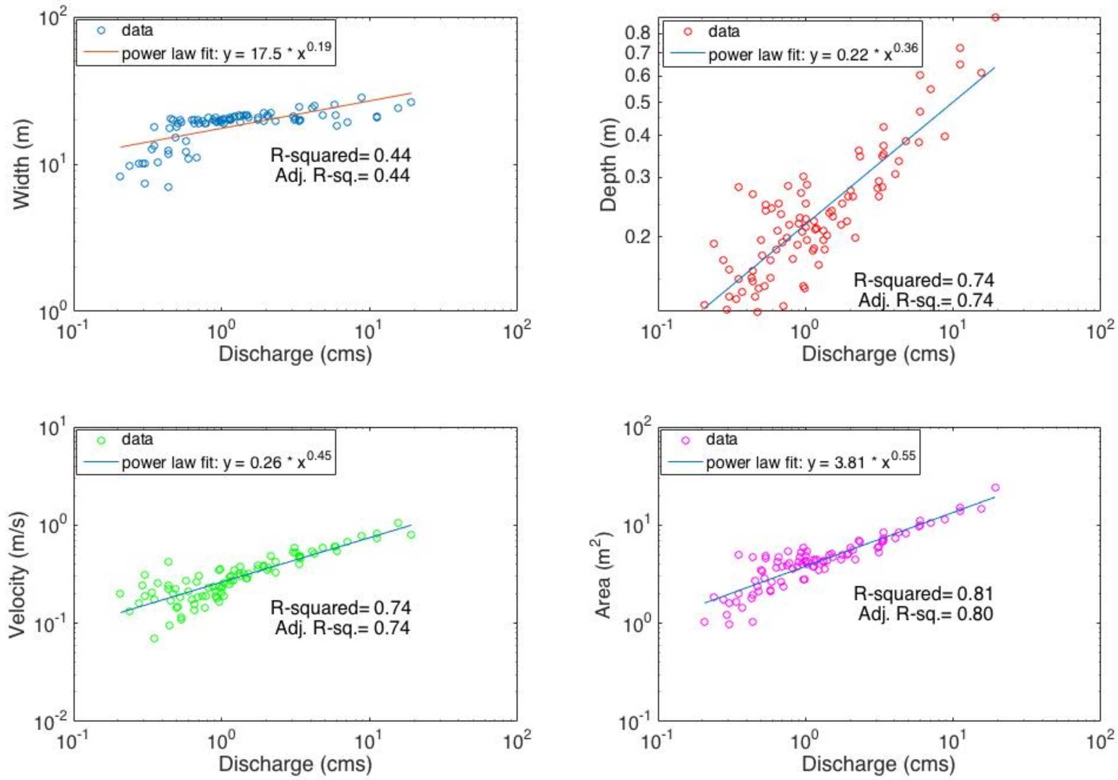


Figure A. 12. Hydraulic Geometry for the Northeast Branch of the Anacostia for 1980 – 1989

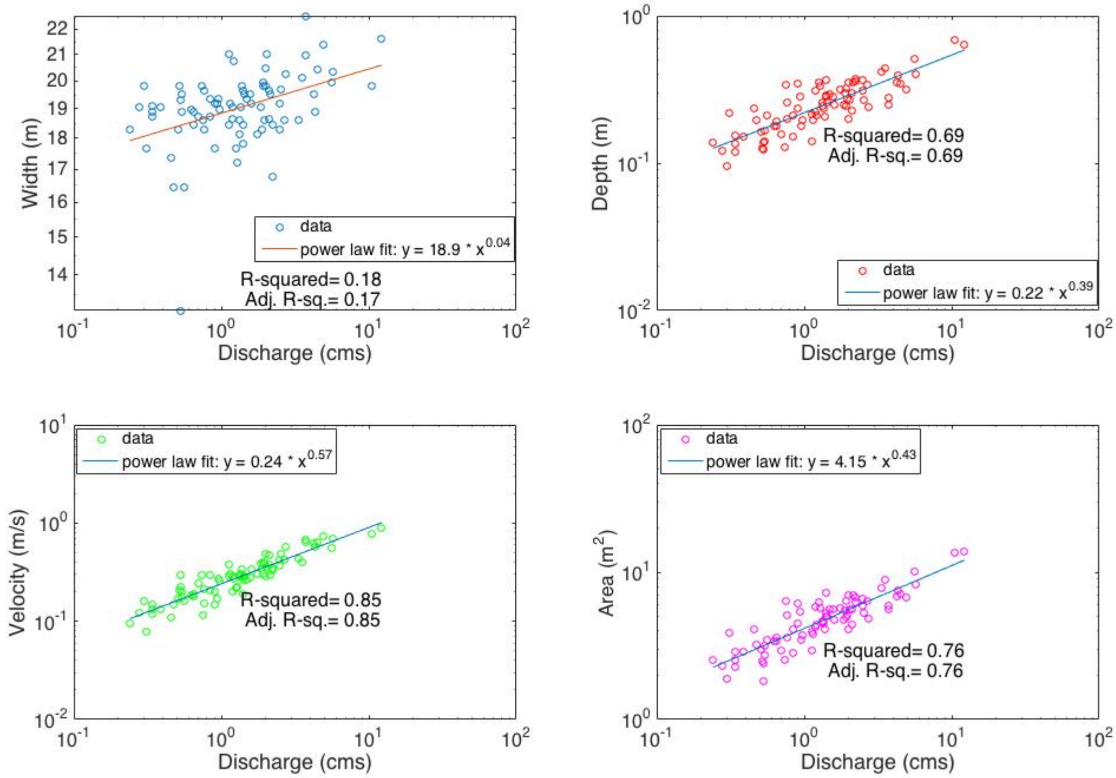


Figure A. 13. Hydraulic Geometry for the Northeast Branch of the Anacostia for 1990 – 1999

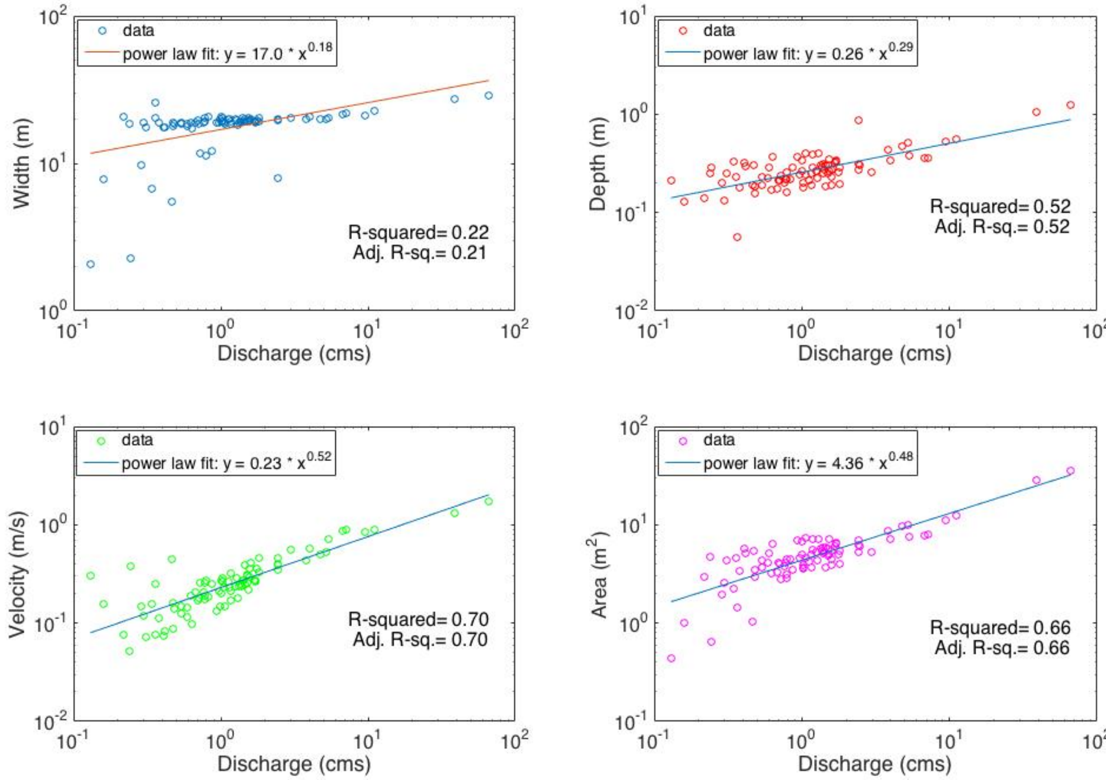


Figure A. 14. Hydraulic Geometry for the Northeast Branch of the Anacostia for 2000 - 2009

A.3 Velocity Distribution Curves for the Time Series Analysis for the Anacostia

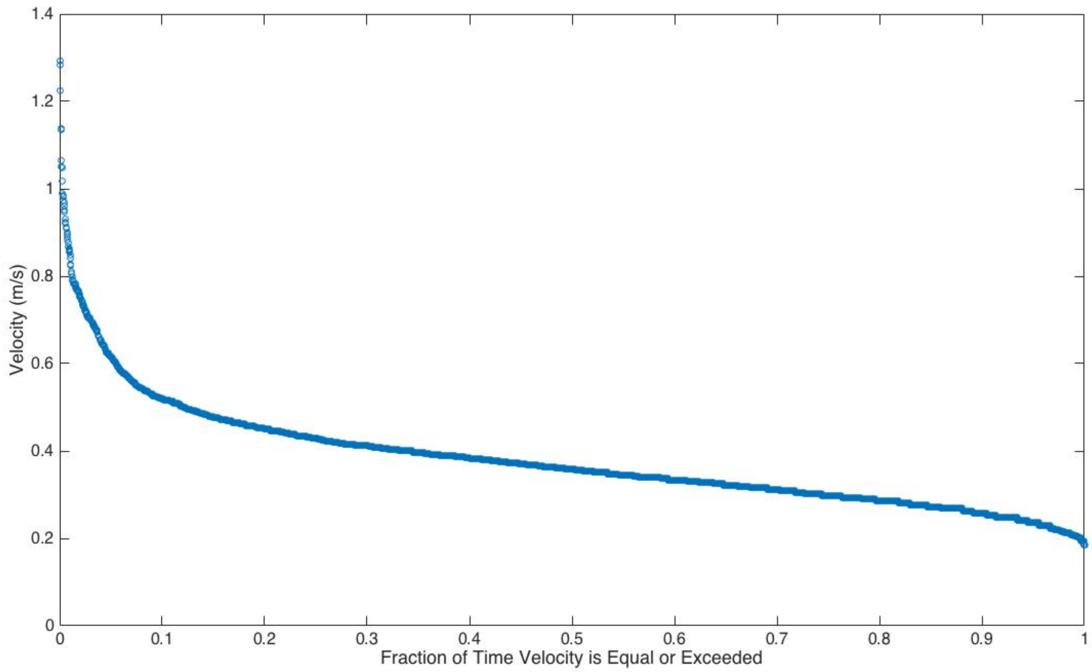


Figure A. 15. Velocity Duration Curve for the Northeast Branch of the Anacostia for 1940 - 1949

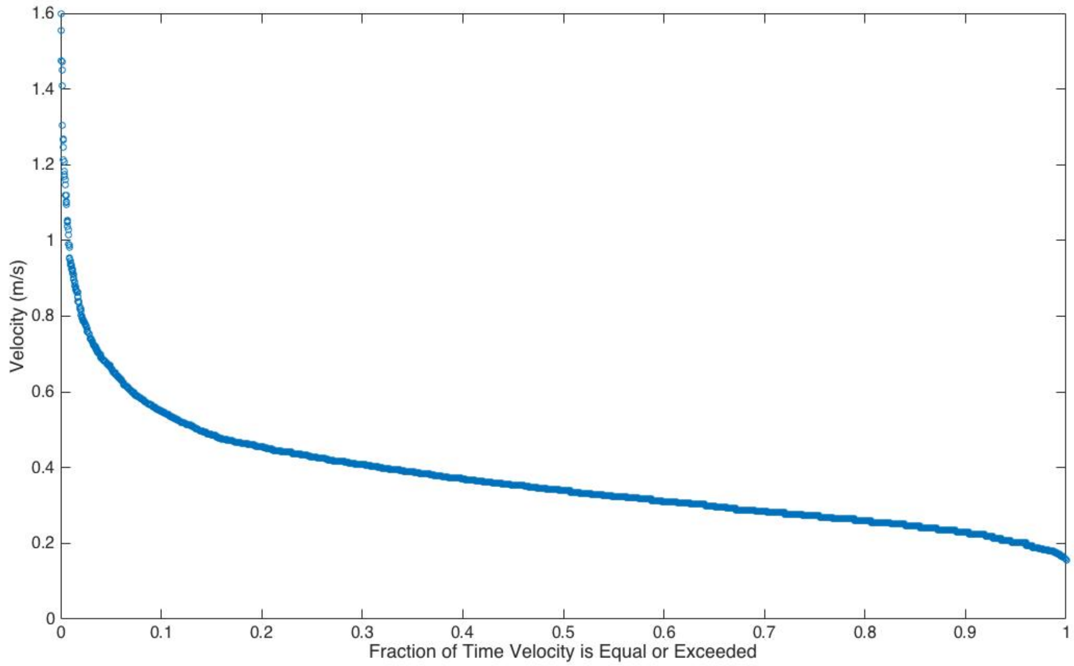


Figure A. 16. Velocity Duration Curve for the Northeast Branch of the Anacostia for 1950 – 1959

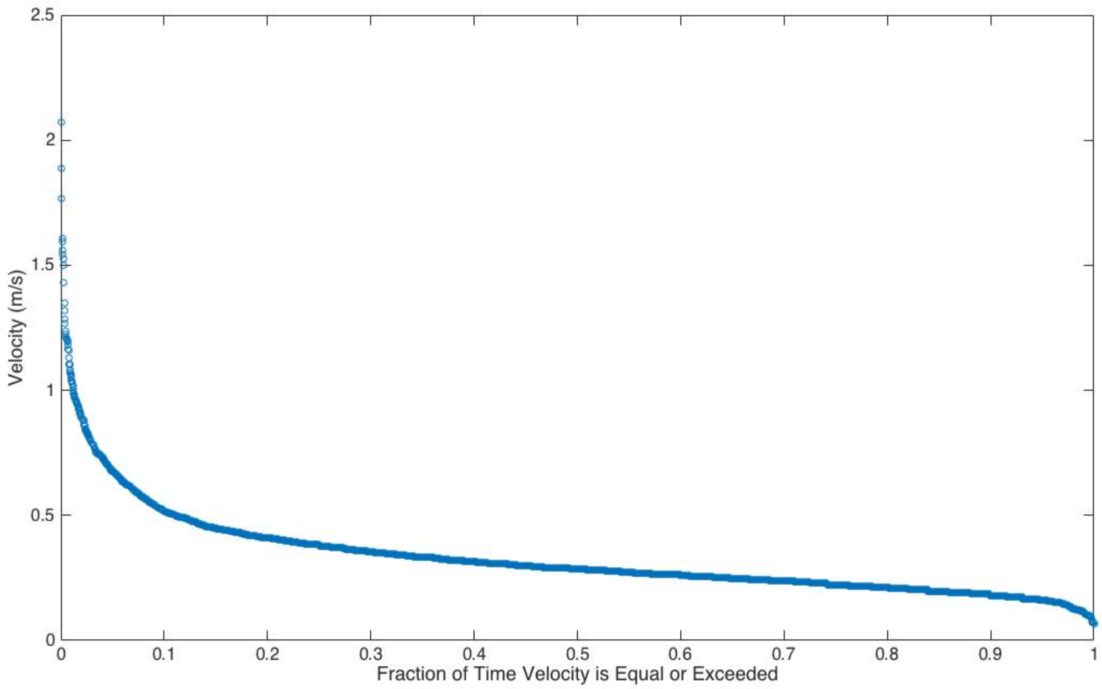


Figure A. 17. Velocity Duration Curve for the Northeast Branch of the Anacostia for 1960 – 1969

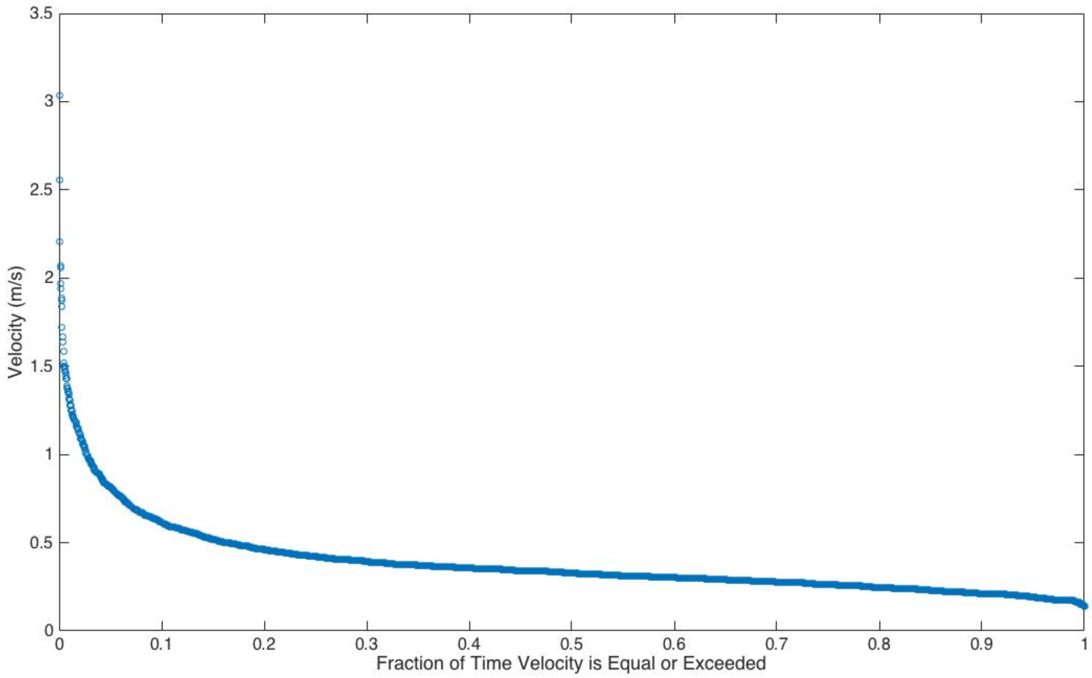


Figure A. 18. Velocity Duration Curve for the Northeast Branch of the Anacostia for 1970 – 1979

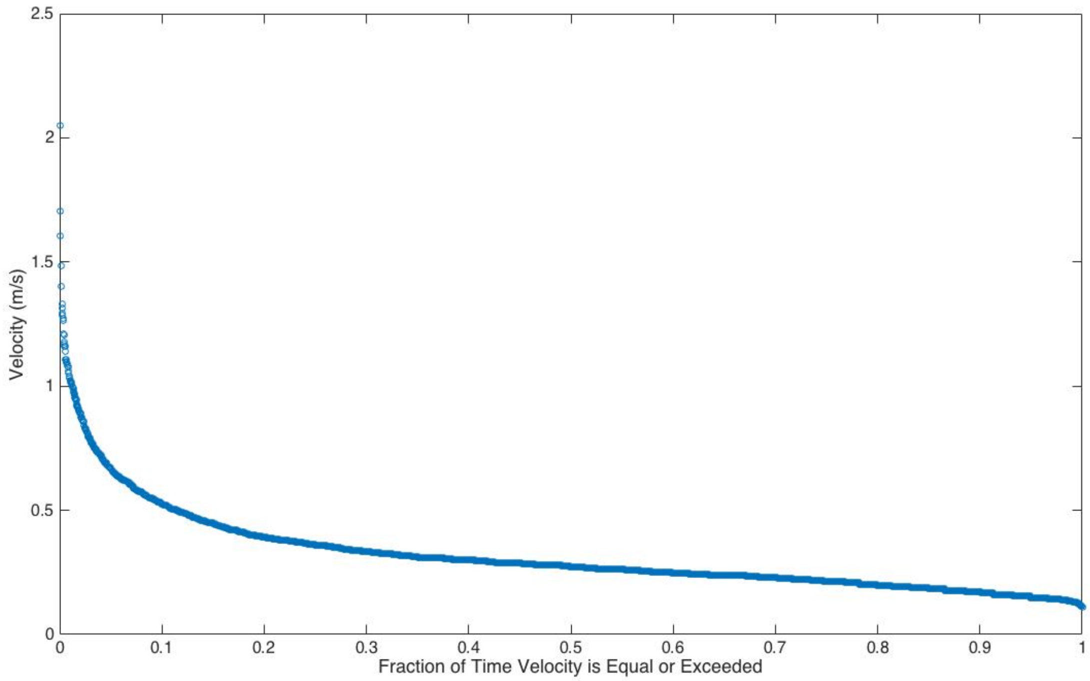


Figure A. 19. Velocity Duration Curve for the Northeast Branch of the Anacostia for 1980 – 1989

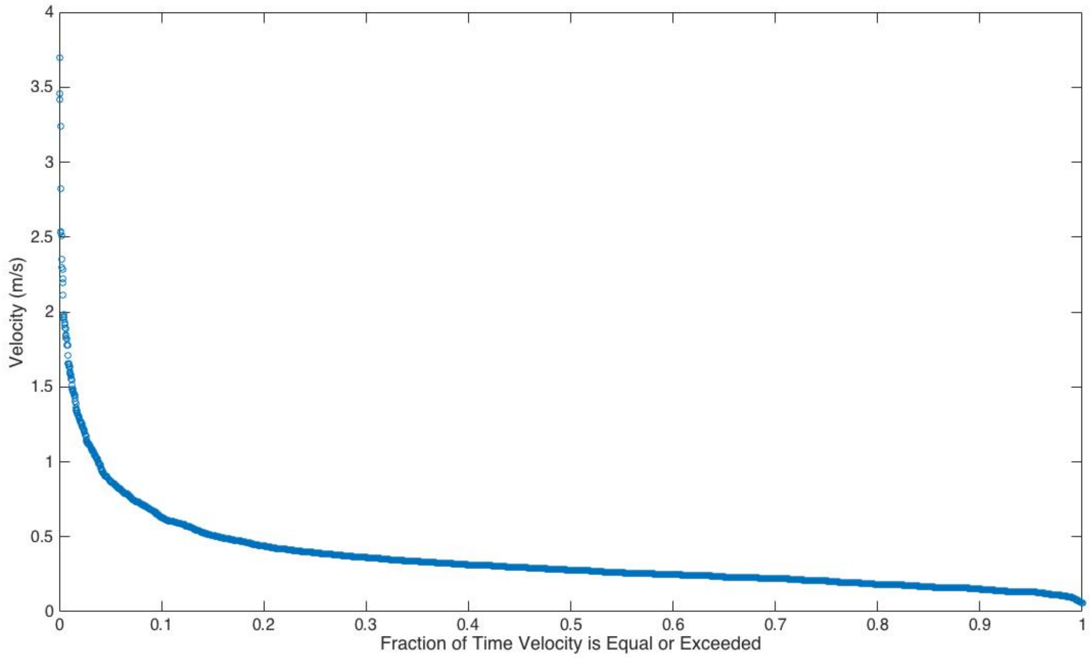


Figure A. 20. Velocity Duration Curve for the Northeast Branch of the Anacostia for 1990 – 1999

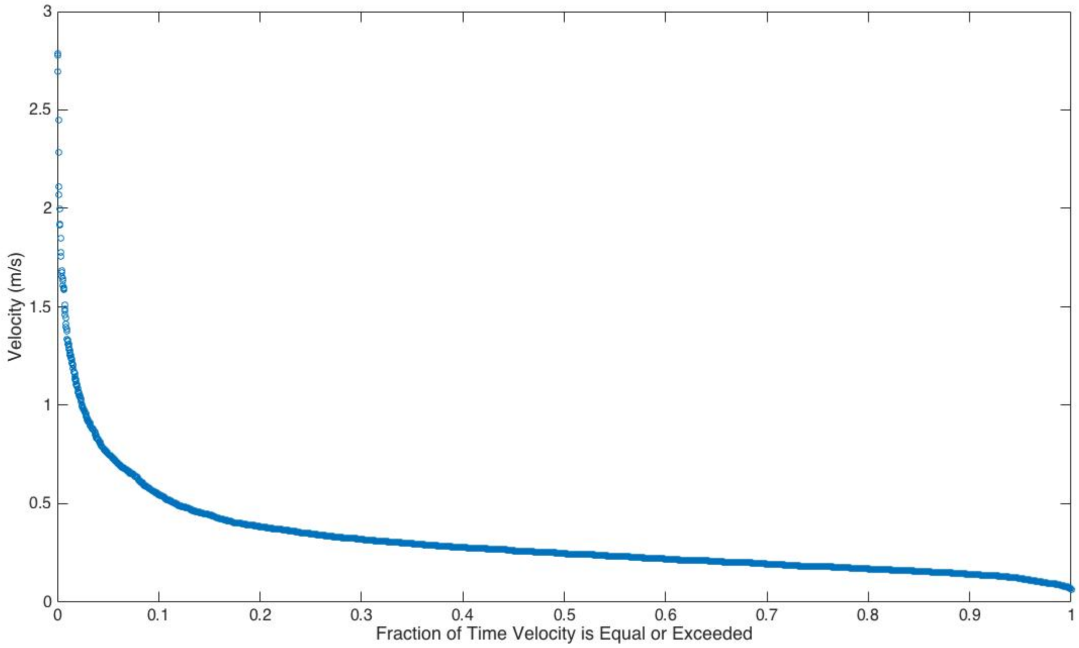


Figure A. 21. Velocity Duration Curve for the Northeast Branch of the Anacostia for 2000 – 2009

Works Cited

"Anacostia Watershed Restoration Partnership History Land Use." *AWRP*. Web. 11 Apr. 2016. <http://www.anacostia.net/history/Landuse.html>

Andrén, H. 1994. *Development of the Laitaure Delta, Swedish Lapland: A Study of Growth Distributary Forms, and Processes*, Ph.D. Thesis, p. 188, Inst. Of Earth Sci. Phys. Geogr., Uppsala Univ., Uppsala, Sweden.

Bhaskar, A.S. and C. Welty. 2012. Water Balances Along an Urban-to-Rural Gradient of Metropolitan Baltimore, 2001-2009. *Environmental & Engineering Geoscience*, v. 18, n. 1, p. 37-50.

Beighley, R.E. and G.E. Moglen. 2002. Trend Assessment in Rainfall-Runoff Behavior in Urbanizing Watersheds. *Journal of Hydrologic Engineering*, v. 7 no. 1, p. 27-34.

Blanchet, Z.D. 2009. Effects of Bar Formation on Channel Stability and Sediment Loads in an Urban Watershed: M.S. Thesis Dissertation, University of Maryland, Department of Geology.

Bravard J.P., Amoros C., Pautou G., Bornette G., Bournaud M., Creuzé des Châtelliers M., Gibert J., Peiry J.L., Perrin J.F., and Tachet H. 1997. River Incision in Southeast France: Morphological Phenomena and Ecological Impacts. *Regulated Rivers: Research and Management*, 13, 75–90.

Brooker, M.P. 1985. The Ecological Effects of Channelization. *The Geographical Journal*, v. 151, n. 1, p. 63-69.

Brown, L.R., Cuffney, T.F., Coles, J.F., Fitzpatrick, F., McMahon, G., Steuer, J., Bell, A.H., and May, J.T. 2009. Urban Streams Across the USA: Lessons Learned from Studies in 9 Metropolitan Areas. *Journal of the North American Benthological Society*, v. 28, n. 4, p. 1051-1069.

Brutsaert, W. *Hydrology: an introduction*. Cambridge University Press, 2005.

Buchanan, T.J. and W.P. Somers. 1969. *Discharge Measurements and Gaging Stations*. Techniques of Water-Resources Investigations of the United States Geological Survey, Chapter A8, Book 3: Applications of Hydraulics. Washington, D.C.: U.S. Geological Survey, 1969.

Charlton, R. *Fundamentals of Fluvial Geomorphology*. Routledge, 2007.

Craig, L.S., M.A. Palmer, D.C. Richardson, S. Filoso, E.S. Bernhardt, B.P. Bledsoe, M.W. Doyle, P.M. Groffman, B.A. Hassett, S.S. Kaushal, P.M. Mayer, S.M. Smith, and P.R. Wilcock. 2008. Stream Restoration Strategies for Reducing River Nitrogen Loads. *Frontiers in Ecology and the Environment*, v. 6.

Dietz, M.E. 2007. Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. *Water, Air, and Soil Pollution*, v. 186, p. 351-363.

Dingman, S.L. *Fluvial Hydrology.* New York, NY: W.H. Freeman and Company, 1984.

Dingman, S.L. 2007. Analytical Derivation of At-a-Station Hydraulic Geometry Relations. *Journal of Hydrology*, v. 334, p. 17-27.

Doyle, M.W., Harbor, J.M., Rich, C.F., and Spacie, A. 2000. Examining the Effects of Urbanization on Streams Using Indicators of Geomorphic Stability. *Physical Geography*, v. 21, n. 2, p. 155-181.

Dunne, T. and L.B. Leopold. *Water in Environmental Planning*. San Francisco: W. H. Freeman, 1978.

Edmonds, D.A. and R.L. Slingerland. 2007. Mechanics of River Mouth Bar Formation: Implications for the Morphodynamics of Delta Distributary Networks. *Journal of Geophysical Research: Earth Surface*, v. 112, n. F2.

Edmonds, D.A., C. Paola, D.C.J.D. Hoyal, and B.A. Sheets. 2011. Quantitative Metrics that Describe River Deltas and Their Channel Networks. *Journal of Geophysical Research*, v. 116, n. F4.

Elliott, J. G., Gellis, A. C., and Aby, S. B. 1999. *Evolution of Arroyos: Incised Channels of the Southwestern United States* (pp. 153-185). Incised River Channels. John Wiley & Sons, New York.

Erskine, W.D. 1999. Oscillatory Response Versus Progressive Degradation of Incised Channels in Southeastern Australia. In: Darby, S.E., Simon, A. (Eds.), Incised River Channels. Wiley, Chiches- ter, UK, pp. 67–95.

Ferguson, R.I. 1986. Hydraulics and Hydraulic Geometry. *Progress in Physical Geography*, v. 10, n. 1, p. 1-31.

Hammer, T.R. 1972. Stream Channel Enlargement Due to Urbanization. *Water Resources Research*, v. 8 no. 6, p. 1530-1540.

Harvey, A.M. 1975. Some Aspects of the Relations Between Channel Characteristics and Riffle Spacing in Meandering Streams. *American Journal of Science*, v. 275, n. 4, p. 470-478.

Harvey, M. D., & Watson, C. C. 1986. Fluvial Processes and Morphological Thresholds in Incised Channel Restoration. *JAWRA Journal of the American Water Resources Association*, *22*(3), 359-368.

Heatherly, T., II, Whiles, M. R., Royer, T.V., David, M.B. 2007. Relationships Between Water Quality, Habitat Quality, and Macroinvertebrate Assemblages in Illinois Streams. *Journal of Environmental Quality*, v. 36, p. 1653-1660.

Henshaw, P.C. and D.B. Booth. 2000. Natural Restabilization of Stream Channels in Urban Watersheds. *Journal of the American Water Resources Association,* v. 36, n. 6, p. 1219-1736.

Jowett, I.G. 1998. Hydraulic Geometry of New Zealand Rivers and its Use as a Preliminary Method of Habitat Assessment. *Regulated Rivers: Research and Management*, v. 14, n. 5, p. 451-466.

Juracek, K.E. and F.A. Fitzpatrick. 2009. Geomorphic Applications of Stream-Gage Information. *River Research and Applications*, v. 25, n. 3, p. 329-347.

Keller, E.A. 1978. Pools, Riffles, and Channelization. *Environmental Geology*, v. 2, n. 2, p. 119-127.

Kirchner, J.W. 2009. Catchments as Simple Dynamical Systems: Catchment Characterization, Rainfall-Runoff Modeling, and Doing Hydrology Backward. *Water Resources Research*, v. 45, n. 2.

Knighton, A.D. 1975. Variations in At-A-Station Hydraulic Geometry. *American Journal of Science*, v. 275, n. 2, p. 186-218.

Konrad, C.P. and D.B. Booth. 2005. Hydrologic Changes in Urban Streams and Their Ecological Significance. *American Fisheries Society Symposium, v.* 47, p. 157-177.

Kroes, D.E. and C.R. Hupp. 2010. The Effects of Channelization on Floodplain Sediment Deposition and Subsidence Along the Pocomoke River, Maryland. *Journal of American Water Resources Association*, v. 46, n. 4, p. 686-699.

Leopold, L. 1968. Hydrology for Urban Land Planning – A Guidebook on the Hydrologic Effects of Urban Land Use. *Geological Survey Circular 554*, p. 18.

Leopold, L. B. 1973. River Channel Change with Time: An Example Address as Retiring President of The Geological Society of America, Minneapolis, Minnesota, November 1972. *Geological Society of America Bulletin*, v. *84*, n. 6, 1845-1860.

Leopold, L.B. and T. Maddock. 1953. The Hydraulic Geometry of Stream Channels and Some Physiographic Implications. *U.S. Geological Survey Professional Paper 252*, p. 57.

Leopold, L.B. and J.P. Miller. 1956. Ephemeral Streams – Hydraulic Factors and Their Relation to the Drainage Net. *US Geological Survey Professional Paper 282A*.

Leopold, L.B., M.G. Wolman, and J.P. Miller. *Fluvial Processes in Geomorphology*. San Francisco, W.H. Freeman, 1964.

Lewis, L.A. 1969. Some Fluvial Geomorphic Characteristics of the Manati Basin, Puerto Rico. *Annals of the Association of American Geographers*, v.59, n. 2, p. 280-293.

Lundberg, D. 2011. Effects of Channel Morphology on Floodplain Inundation and Surface-Groundwater Interactions in an Urban Watershed: M.S. Thesis Dissertation, University of Maryland, Department of Marine and Estuarine Environmental Science.

Maryland Greenways Commission. 2000. Maryland Atlas of Greenways, Water Trails, and Green Infrastructure. Maryland Greenways Commission, MDNR.

Maryland-National Capital Park and Planning Commission. 2002. Prince George's County Approved General Plan. Maryland-National Capital Park and Planning Commission, 82202152405.

Meierdiercks, K.L., J.A. Smith, M.L. Baeck, and A.J. Miller. 2010. Analyses of Urban Drainage Network Structure and Its Impact on Hydrologic Response. *Journal of American Water Resources Association*, v. 46, n. 5, p. 932-943.

Meierdiercks, K.L., J.A. Smith, M.L. Baeck, and A.J. Miller. 2010. Heterogeneity of Hydrologic Response in Urban Watersheds. Jou*rnal of American Water Resources Association*, v. 46, n. 6, p. 1221-1237.

Meyer, J. L. 1990. A Blackwater Perspective on Riverine Ecosystems. *BioScience*, 643-651.

MDNR. 2005. Characterization of the Anacostia River Watershed in Prince George's County, Maryland: Maryland Department of Natural Resources, DNR-14-1209-0021.

Mikhailov, V.N. 1970. Hydrologic-Morphometric Characteristics of Delta Branches. *Studies and Reports in Hydrology*, v. 9, p. 146-158.

Millar, R.G. 2004. Theoretical Regime Equations for Mobile Gravel-Bed Rivers with Stable Banks. *Geomorphology*, v. 64, p. 207-220.

Miller, C.V., A.L. Gutiérrez, B.L. Feit Majedi, and G.D. Foster. 2007. Water Quality in the Upper Anacostia River, Maryland: Continuous and Discrete Monitoring with Simulations to Estimate Concentrations and Yields, 2003-05. *U.S. Geological Survey Scientific Investigations Report 2007-5142*, p. 43.

Milly, P.C.D. 1994. Climate, soil water storage, and the average annual water balance. *Water Resources Research*, v. 30, n. 7, p. 2143-2156.

Miltner, R.J., White, D., and Yoder, C. 2004. The Biotic Integrity of Streams in Urban and Suburbanizing Landscapes. *Landscape and Urban Planning*, v. 69, p. 87-100.

Noe, G. B. and Hupp. C. R. 2005. Carbon, Nitrogen, and Phosphorus Accumulation in Floodplains of Atlantic Coastal Plain Rivers, USA. *Ecological Applications*, v. 15, p. 1178–90.

Occhi, M. 2010. Hydrograph Separation Analyses to Determine Runoff Sources in a Large, Urban Watershed: M.S. Thesis Dissertation, University of Maryland, Department of Geology.

Olson, S.A., and J.M. Norris. 2007. U.S. Geological Survey Streamgaging...from the National Streamflow Information Program. *U.S. Geological Survey Fact Sheet 2005–3131*, p. 4.

Patton, P. C., & Schumm, S. A. 1975. Gully Erosion, Northwestern Colorado: A Threshold Phenomenon. *Geology*, v. 3, n. 2, 88-90.

Paul, M. J., and J. L. Meyer. 2001. Streams in the Urban Landscape. *Annual Review of Ecology, Evolution, and Systematics*, v. 32, p. 333-65.

Rantz, S.E. 1971. Suggested Criteria for Hydrologic Design of Storm-Drainage Facilities in the San Francisco Bay Region, California. *U.S. Geological Survey Open File Report 71-341*.

Rantz, S.E., et. al. 1982. Measurement and Computation of Streamflow: Volume 1. Measurement of Stage and Discharge. *U.S. Geological Survey Water-Supply Paper 2175.*

Sauer, V.B. and R.W. Meyer. 1992. Determination of Error in Individual Discharge Measurements. *U.S. Geological Survey Open File Report 92-144.*

Schueler, T.R., L. Fraley-McNeal, K. Cappiella. 2009. Is Impervious Cover Still Important? Review of Recent Research. *Journal of Hydrologic Engineering*, v. 14, n. 4, p. 309-315.

Schumm, S. A., and Hadley, R. F. 1957. Arroyos and the Semiarid Cycle of Erosion [Wyoming and New Mexico]. *American Journal of Science*, v. 255, n. 3, 161-174.

Simon, A. □1989□. The Discharge of Sediment in Channelized Alluvial Streams. *Water Resour. Bull.,* 25□6□, 1177–1188.

Simon, A., & Darby, S. E. 1999. The nature and significance of incised river channels. *Incised River Channels: Processes, Forms, Engineering and Management. John Wiley & Sons, Chichester*, 3-18.

Simon, A., Curini, A., Darby, S. E., and Langendoen, E. J. 1999. *Streambank Mechanics and the Role of Bank and Near-Bank Processes in Incised Channels* (pp. 193-217). John Wiley and Sons, Chichester, UK.

Stephenson, D. 1994. Comparison of the Water Balance for an Undeveloped and a Suburban Catchment. *Hydrological Sciences Journal*, v. 39, n. 4, p. 295-307.

Stewardson, M. 2005. Hydraulic Geometry of Stream Reaches. *Journal of Hydrology*, v. 306, n. 1, p. 97-111.

Thorne, C. R. □1999□. Chapter 5: Bank Processes and Channel Evolution in the Incised Rivers of North-Central Mississippi. *Incised river channels*, S. E. Darby and A. Simon, eds., Wiley, Chichester, England, 97 – 122.

Thornthwaite, C.W. and Mather J.R. 1955. The Water Balance. *Laboratory of Climatology, Publication No. 8*, Centerton, NJ.

Thornthwaite, C.W. and Mather J.R. 1957. Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance. *Laboratory of Climatology, Publication No. 10*, Centerton, NJ.

Tockner, K. and Stanfod, J.A. 2002. Review of Riverine Flood Plains: Present State and Future Trends. Environmental Conservation, v. 29, n. 3, p. 308-330.

"Water Resources of the United States." *USGS*. Web. 21 Oct. 2012. <http://water.usgs.gov/>.

Wilcock, D.N. 1971.Investigation into the Relations Between Bedload Transport and Channel Shape. *Bulletin of the Geological Society of America*, v. 82, n. 8, p. 2159-2176.

Wolman, M.G. 1955. The Natural Channel of Brandywine Creek, Pennsylvania. *US*

Geological Survey Professional Paper 271.

Wolman, M.G. 1967. A Cycle of Sedimentation and Erosion in Urban River Channels. *Geografiska Annaler*, v. 49A, p. 385-395.

Zhang, L., W.R. Dawes, and G.R. Walker. 2001. Response of Mean Annual Evapotranspiration to Vegetation Changes at Catchment Scale. *Water Resources Research*, v. 37, n. 3, p. 701-708.