High Water Levels Generated by Rivers, Tides and Storm Surges in the Anacostia River Upper Estuary

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2. Abstract

The purpose of this study is to evaluate the separate and combined effects of urbanization, storm surge and sea level rise on flood hazards along the Anacostia River. Before people began modifying the Anacostia River and Estuary, it had marshlands, floodplains, and wetlands that responded to changing sea, sediment, and river levels. Morphological changes (river channelization and wetland removal) and hydrological changes (urbanization and climate) in the Anacostia watershed and estuary may have significantly impacted tidal propagation, and natural channel adjustments. The growth of cities around the estuary has also increased urbanization-driven runoff, increasing stream discharge. Additionally, flood management infrastructure, such as levees and concrete barriers, contain high flows, increasing flood velocities and have prevented floodplain deposition and other adjustments to changing conditions. Analyses were completed to test the following hypotheses: 1. The historical width distribution of the Anacostia River is more consistent with the theoretical width distribution than the present day width distribution. 2. The water surface elevations on both ends of the Anacostia system have increased over time due to urbanization and climate change (sea level rise). 3. The water level data indicates that extreme high water levels are more probable at the upstream end due to river flooding than the river mouth due to high tides. The initial morphology of the Anacostia River-Estuary system and the Port Tobacco River-Estuary system was compared to a theoretical model developed by Bolla Pittaluga et al. (2015) that predicts the width of the estuary along the longitudinal direction of the river given channel widths at the two ends of the system. This is done to determine the effects of sea level rise when rivers are unmodified, compared to the heavily modified Anacostia River. Time series data of stream discharge, tidal stage, and water chemistry was considered to evaluate changes during flood and storm surge events. Water level elevation time series for the river and tidal input for the Anacostia River from October 2019 to October 2020 was analyzed to identify trends in water levels at both ends of the Anacostia system. Finally, water elevation and specific conductance data were converted into elevation (NAVD88) and plotted to evaluate changes in river outflow versus tidal inflow during multiple extreme events. The Anacostia River-Estuary system has been significantly modified. Understanding how these modifications result in hazardous conditions will be useful for preparing for future extreme events.

3. Introduction

3a. Background

The Anacostia Watershed

The Anacostia River watershed (456 km^2) spans Montgomery and Prince Georges counties in Maryland and the eastern half of the District of Columbia and is home to over 800,000 people (Figure 1; AWRP, 2019). The watershed contains 25 major and medium-sized tributaries that form 476 km of channel length (AWRP, 2019). The two largest tributaries (Northeast Branch and Northwest Branch) join at the head of the upper estuary in Bladensburg, Maryland (Figure 1). Downstream of the confluence, the channel is tidally- influenced and it flows 13.5 km southwest into the District of Columbia where it joins the Potomac River-Estuary (AWRP, 2019; Figure 1). The tidally-influenced section of river has a low and variable gradient. The lowest gradients occur at incoming high tides. Furthermore, storm surges can push Potomac River-Estuary water into the lower Anacostia River.

Climate change, sea-level rise, urbanization, stream channelization, estuarine channel straightening, and dredging of the Bladensburg harbor all affect water levels and inundation in the Anacostia River-Estuary system. Urbanization (impervious surfaces and storm sewers) within the watershed has increased stormwater runoff, decreasing hydrograph duration and increasing peak discharge. In response to flooding problems, the lower portions of the Anacostia River channels were straightened

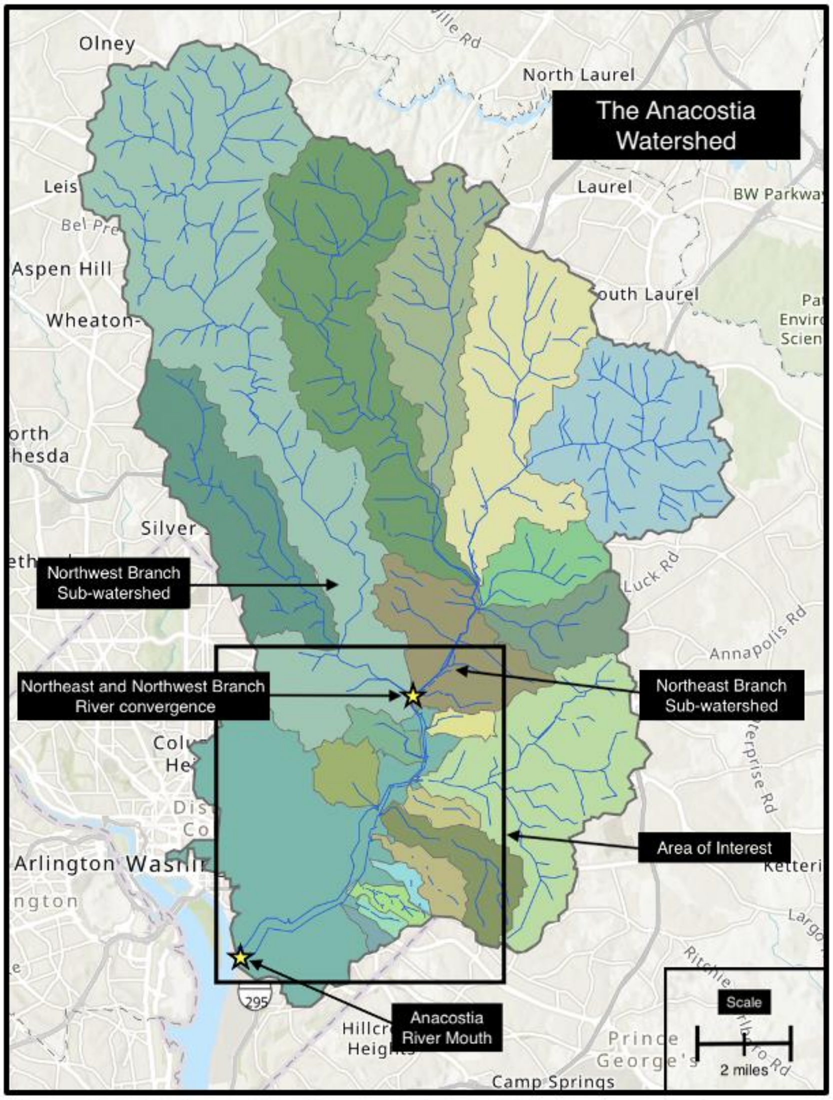


Figure 1: The Anacostia Watershed spans from eastern Montgomery County and western Prince Georges County in Maryland to the eastern half of the District of Columbia. The area of interest shown in the figure above includes the Northwest Branch and Northeast branch sub-watersheds and the Northwest and Northeast Branch River convergence through the the Anacostia River mouth (AWRP, 2019). The Northwest Branch and Northeast Branch River convergence and the Anacostia River mouth are shown in many of the other figures for reference.

and channelized to contain the 100-year flood. Downstream sections of the Anacostia River are characterized as “flashy” meaning it rises quickly in response to rainfall.

The Anacostia River has undergone numerous channelization projects throughout history that have affected the hydrologic regime and natural landscape of the river. Urbanization of the watershed has increased the amount of impermeable surfaces, which has increased flooding hazards along the Anacostia River upper estuary (USACE, 2018). The close proximity to the Chesapeake Bay means the Anacostia River water levels are also effected by the tidal cycle on a daily basis. It has been suggested high water levels in the Anacostia River have resulted from the combined effects of urbanization, tidal patterns, sea level rise and storm surges. In the following sections, additional detail is provided on each of these variables.

Urbanization of the Anacostia River Watershed

In the late 1700s, the lower Anacostia River and estuary contained meandering channels bounded by floodplains and freshwater tidal marshes, (Figure 2). By 1790, the town of Bladensburg was known for its water port located along the Anacostia (NCPC, 2008). Ships brought in supplies and carried out agricultural products from the many plantations and farms in this region. Some of the wetlands surrounding the river were drained and used for grazing dairy cattle and as cropland. Soil eroded from cropland in the watershed was transported and deposited in the upper estuary. Almost half a century later, this sedimentation from farms caused the Bladensburg Port to close in 1840. Sedimentation in the upper estuary affected wetland function and the increasingly shallow upper part of the Anacostia Estuary became unusable for navigation (NCPC, 2008). Other major ports, such as Port Tobacco, also filled with sediment, cutting off transportation routes. This caused the rapid decline of some of these towns (Port Tobacco was once Charles County seat and a major city in Maryland, in 2020, 13 people lived there).

Figure 2: A - The topographic map from 1791 (Hawkins, 1791), shows the topography of the District of Columbia surrounded by the Potomac River, on the left, and the Anacostia River, on the right. B - The satellite image is present-day District of Columbia and shows the current shape of the mouth of the Anacostia River as it flows into the Potomac River for comparison with the shape of the rivers as they appeared in 1791 (Google Earth).

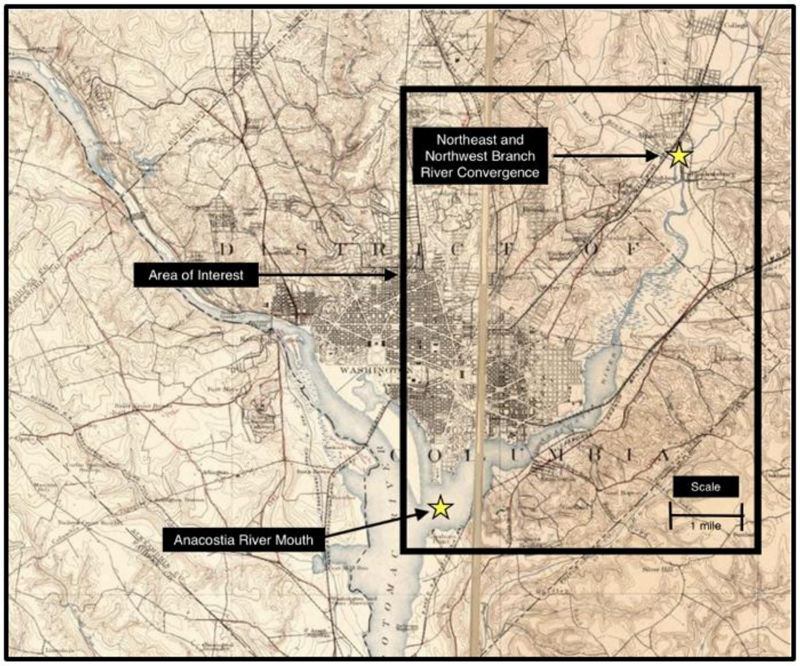


Figure 3: The map above, dated 1895, shows the Anacostia River before the heavy channelization and dredging projects by the USACE that took place in the early 1900s. At that time, the estuary had many acres of wetlands and marshes, as indicated by the blue symbols located adjacent to the river, that assisted with flood control (USGS, 1895).

In the early 1900s, the US Army Corps of Engineers (USACE) began the channelizing the upper estuary with the intent of aiding navigation and controlling flooding (Figure 3). From 1902 to 1920, the USACE dredged the Anacostia from the upper estuary to the Navy Yard (NCPC, 2008). According to the USACE, their actions from 1900 to 1960 destroyed 30,000 linear meters of aquatic habitat and approximately 2,600 acres of wetlands (NCPC, 2008). By 1987, the total percentage of destroyed tidal wetlands and freshwater wetlands was 98 percent and 75 percent, respectively (NCPC, 2008). The combination of channel straightening, dredging, and destruction of the wetlands contributed to increased probability of severe floods along the Anacostia River. In 1933, tidal storm surge produced by an unnamed hurricane caused the Anacostia River to spill over the seawall and into the District of Columbia. During this storm, the maximum discharge from the Northeast Branch was 10,500 cubic feet per second (cfs) and from the Northwest Branch, 8,000 cfs, and the conjunction discharge was estimated to be approximately 15,000 cfs (NCPC, 2008). The average discharge rate for the Northeast Branch and Northwest Branch, for the month of August, are 65 cfs and 38 cfs. Other notable storms in 1936 and 1942 caused severe flooding along the Anacostia River. The

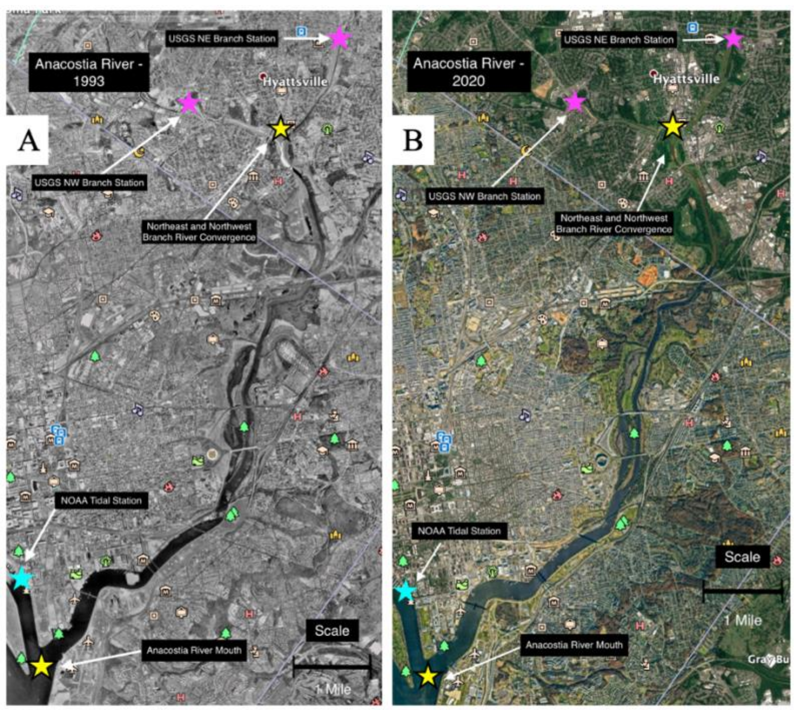


Figure 4: The satellite image, A, shows the Anacostia River in 1993 and satellite image, B, shows the same portion of the Anacostia River in 2020. In 1993, the USACE began wetland restoration projects along the Anacostia River motivated by severe flooding along the river (Google Earth). In the 2020 image, these projects appear on either sides of the river and are concentrated the middle of the image.

severe flooding events highlighted the need for better flood management and resulted in the Flood Control Act of 1950. In 1993, USACE began wetland restoration projects along the Anacostia River (Figures 3 and 4). Despite their efforts, severe flooding events continued to occur, such as the 2003 flood from Hurricane Isabel. This event caused damage to more than 65 buildings and caused two sewage treatment plants to lose power and overflow 96 million gallons of sewage into the river (NCPC, 2008). In the Northeast Branch sub-watershed, 85 percent of the mainstem of the river has been channelized and levees were constructed by USACE as local flood risk management (USACE, 2018). The USACE has continued to work on various restoration projects in an effort to reduce flooding along the Anacostia River and in riverfront towns, such as Bladensburg, but flooding events continue to occur.

3b. Flooding Scenarios

River-Estuary Transitions

The main area of focus of this project is the Anacostia River-Estuary, created by upstream inputs from the Anacostia River and tidal inputs from the Potomac Estuary (Figure 5). Above the transition zone, water flux is in the downstream direction. In the upper estuary the water level is dominated by freshwater downstream flow, but also has tidal influence (Dalrymple et al., 1992). The complicated interactions between river and tidal currents in the transition zone is influenced by the net momentum of the river discharge and the tidal flow. Water and momentum flux changes during a tidal cycle and more significantly during extreme events (river floods and tidal surges). As tides propagate further upstream, tidal amplitudes decrease becoming similar to the downstream river discharge meaning that the tide heights are the same height as downstream water heights (Yankovsky et al., 2012). This area of interaction is defined as a transition zone, shown by the blue box in Figure 5. In transition zones, the flow dynamics of the tides moving upstream are important to consider. The hydrodynamic conditions imposed by a changing sea level cause rivers to flow at a slower pace during high tides. Waves with a tidal component are initially symmetric, but as they move upstream they become asymmetric if river discharges are significant (Blanton et al., 2002). The shift from symmetric to asymmetric tides aids in the generation of overtides (Lanzoni and Seminara, 1998). Overtides are a higher frequency secondary tide, impacting the speed and strength in which tides return to the ocean, a process known as ebb. According to Torres-Garcia (2014), overtides in areas where floods are common, can result in strong short-lasting floods and a weak, but longer-lasting ebb. Variations in momentum balance scenarios can shift the location of the transition zone along the river channel (Torres-Garcia, 2014). In transition

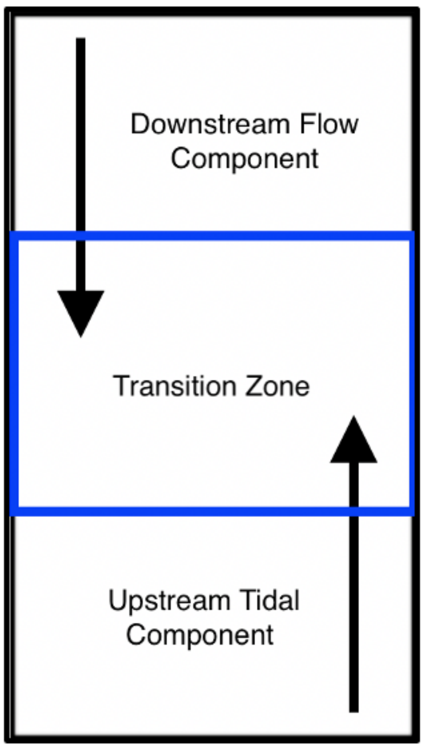


Figure 5: The transition zone is the area in a river where the downstream flow component and upstream tidal component meet, as demonstrated in the schematic above. There are many factors that can impact the position of the transition zone and can result in complicated scenarios as discussed in the text.

zones, multiple momentum balance scenarios are possible (Torres-Garcia, 2014). A steady state results when both the river discharge and the tide current are stable. A high discharge and high momentum flux caused by major storm and river flooding events can result in river-dominated conditions, which can push the tidally-influenced water levels back towards the tidal inlet. High tidal levels, such as occurring during storm surge tides, result in tidally-dominated conditions that push upstream, although river discharge is still present. All three of these scenarios are possible in the Anacostia River transition zone.

The system will return to equilibrium when both ends of the system are essentially the same elevation, however it will change slightly because of the daily tidal patterns. It will remain in equilibrium, changing slightly with the high and low tides, until an outside event adds water to either end of the system. This will then change where the transition zone is based on which end of the system is higher in water elevation. In the event of a high precipitation event at the upstream end of the system, a plume of freshwater will form as water enters the system via runoff or direct entrance. The flux of freshwater precipitation that enters the river travels downstream and eventually out of the system. This can result in a decrease in water elevation at the downstream end of the system as the plume of freshwater pushes the tides out of the system. When the plume moves down the system, the transition zone shifts further down the river. After the plume of freshwater has moved out of the system, the tides return back into the system and increase the water elevation at the downstream, shifting the transition zone back upstream. In the event of a storm surge event at the downstream end of the system, the tidal patterns will add height based on the size of the incoming storm surge. The new elevation of the downstream component will impact the elevation gradient in the river, ultimately moving the transition zone further upstream, resulting in more apparent tidal influences where they normally are not as dominant.

3c. Factors Influencing High Water Levels

Watershed Runoff and Stream Discharge: Upstream Controls

Runoff is a measure of the amount of precipitation that is delivered to a stream. During storm events in urban watersheds, much of this runoff is due to precipitation rates in excess of infiltration rates, primarily from impermeable and low permeability surfaces. This runoff is conveyed quickly to stream channels through storm drain systems (USGS, 2017). Urbanization of the Anacostia Watershed has increased the amount of impervious surfaces, increasing runoff and peak discharges. As a consequence of storm runoff, river water levels and discharge rapidly rise. River flow depths (gage height in gaged watersheds), discharge, and velocity affect downstream transition zone processes. In the Anacostia Watershed, there are two main sub-watersheds that contribute to the discharge into the main Anacostia River. These are the Northeast Branch sub-watershed and the Northwest Branch sub-watershed (USACE, 2018). Seventy-four percent of the Northeast Branch sub-watershed has been classified as developed (~37% impervious cover). In the Northwest Branch, 58% of the sub-watershed is developed, with ~26% impervious surface cover (USACE, 2018). According to the USACE, the Northeast and Northwest sub-watersheds are approaching maximum development potential (USACE, 2018). Over time, this increase in impervious surfaces and storm sewers has resulted in larger annual peak discharges (Figure 6, USGS data). Although an increase in flood peak discharge usually causes an increase in maximum water level, dredging and straightening of the channel decreased the bed elevation in the lower portion of the river, which also increased bed gradient. The time series of annual maximum discharge at Northwest Branch and Northeast Branch Anacostia is shown below. Discharge for both rivers has been increasing since the late 1930's at the same rate (within a few hundredths), in Figure 6.

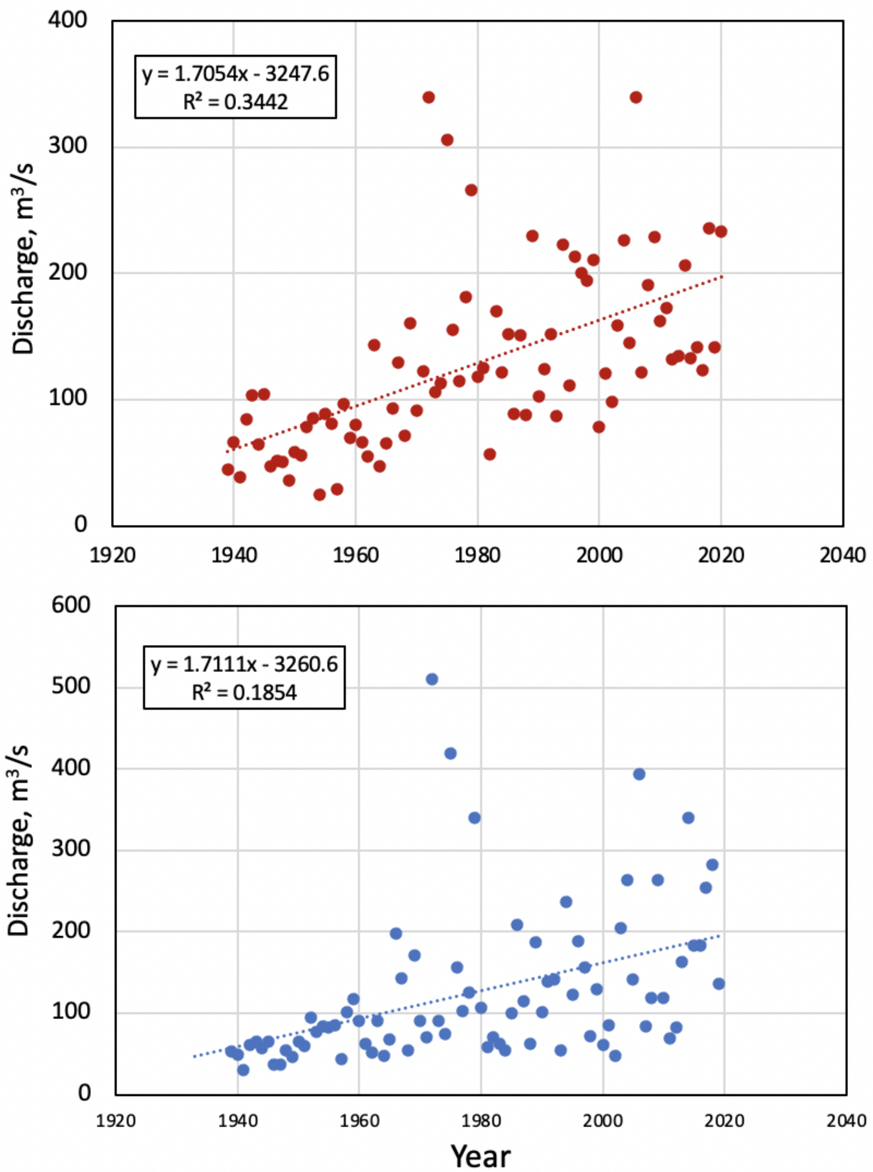


Figure 6. Annual maximum discharge for the Northeast Branch Anacostia (top) and the Northwest Branch Anacostia (bottom). Since 1940, mean annual discharge for both rivers have increased an average of 1.7 m^3/s per year. (Graphs from Prestegaard, personal comm.)

Tidal Levels and Sea Level Rise

The Anacostia River water levels are also influenced by daily tide patterns and sea level rise. A majority of coastal areas experience two high tides and two low tides every day. The time scale for tides is based on a 24-hour solar day, which is equivalent to 24 hours and 50 minutes. High tides occur every 12 hours and 25 minutes, and low tides occur 6 hours and 12.5 minutes after peak high tide (Ross, 1995). The tides propagate up from the Atlantic Ocean into the Chesapeake Bay, and into the Potomac River, which partially branches off into the Anacostia River. Tides at the mouth of the Anacostia typically have a range of three feet between peak high tide and peak low tide. As the tide moves in, water levels within the river rise, shifting the momentum balance further up the river (Torres-Garcia, 2014). As the tides return to the ocean, the momentum balance shifts back down the river. The momentum balance rotation will follow the same pattern over time. Another tidal factor needing to be considered when studying tidal flooding is storm surge. Storm surge tides accompany tropical storms, hurricanes or other intense storms that bring high winds pushing water into the coast (Rahmstorf, 2017). Water levels in tidally-dominated rivers can rise rapidly as a result of storm surges, and in combination with high downstream discharge can create dangerous situations for coastal cities (Rahmstorf, 2017). The sea level trend for Washington DC shows a 3.43 mm/year increase from 1924 to 2020, which is equivalent to a 1.13 ft increase over the past century (NOAA, 2020). Sea level rise impacts the water levels in tidal rivers and shifts the transition zone further inland up the river. The wetlands that used to surround the Anacostia River provided a natural barrier against flooding (NCPC, 2008). In addition, the straightening of the river allows tides to propagate upstream easier than if the river was still meandering. The combination of channelization and sea level rise creates a higher risk of tidal flooding in coastal cities, such as Washington DC, Alexandria VA and Bladensburg MD.

Channelization of the lower portions of Northeast and Northwest branches of the Anacostia has resulted in deeper and straighter rivers, which are efficient in transporting water and sediment. Due to the channelization of the upstream portion of the estuary, the tidal influence and tidal amplitude is able to extend further up the river. As a result, the transition zone, the region where the tidal influence and downstream freshwater flow meet, has shifted further up the river as sea water levels continue to rise. These changes in tidal wave transmission, base level, along with the increases in river discharge have resulted in modifications that can increase high water levels at both the terrestrial and Potomac estuary ends of the Anacostia estuary. Due to the increasingly flashy hydrological system along with channelization and degradation of the fringing marshes, the location of the transition zone has extended further up the river past the Bladensburg harbor.

4. Questions and Hypotheses

For this project, there are two main concepts being evaluated: the changing equilibrium flow conditions of the Anacostia River and the probability of extreme scenarios. The Anacostia River has two inputs impacting the conditions within the river, therefore analyzing the changes of those inputs and how the river shape has changed over time will be important. In addition, flooding events have become a prevalent issue in the areas surrounding the Anacostia.

Questions:

1. Comparison with Theory - How does the current distribution of the width (shape) of the river compare to theoretical distribution?
2. Time Series Changes - What are the long term changes in water surface elevation at both ends of the systems?
3. Extremes – What are the probability of extreme water levels at both ends of the systems?

Hypotheses:

1. The historical Anacostia River width is more consistent with the theoretical width distribution than the present day measured width.
2. The water surface elevations on both ends of the Anacostia system have increased over time due to urbanization and climate change (sea level rise).
3. Water level data indicates that extreme high-water levels are more probable at the upstream end due to river flooding than the river mouth due to high tides.

5. Methodology

5a. Estuarine Morphology: Measurements and Theory

Urbanization and channelization of the Anacostia River have changed river elevations and flood confinement, which have affected the river-estuary system. The morphology of an estuary is determined by the type of tides, adjustments to both river and tidal inputs, and human modifications (e.g., channelization). Modifications of tidal inlets, river cross sections, and marsh modification can all affect the incursion of tidal flows into the estuary. Marshes can attenuate tidal amplitudes; removal of these marshes allow upstream propagation of tides within these systems.

Estuaries have been divided into two main classes based on the interactions of the tides with the shape of the estuary: hypersynchronous and hyposynchronous. A hypersynchronous estuary inlet begins with a funnel shape at the mouth converging to a much smaller river (Dalrymple and Choi, 2007). The funnel shape causes the tidal influence to increase in range due to the decrease in width. Hyposynchronous estuaries occur when the bottom friction offsets the convergent shape, causing tidal range to decrease as the tides propagate upstream (Dalrymple and Choi, 2007). An "ideal estuary" shows neither of these two effects and the tidal range propagates almost unchanged upstream. This means the tidal amplitude remains the same at the mouth of the estuary and further upstream. Understanding the difference among these behaviors allowed for prediction of tidal behavior in the estuary (Bolla Pittaluga et al., 2015).

I used a theoretical model to predict the equilibrium width distribution within the Anacostia River-Estuary and compared the results to both current and historic widths. Bolla Pittaluga et al. (2015) developed a model to predict the distribution of channel widths in river-influenced tidal estuaries. Their model is based on previous work on tidal estuary widths (Langbein, 1963). They compared the two end-members in tidally-dominated estuaries and river-dominated estuaries, and how the transition zone impacts the equilibrium profile. The equation of Bolla Pittaluga et al., (2015) was adapted from Langbein (1963), where there was no fluvial input (Langbein, 1963). The relationship between tidally dominated estuaries with a river input is represented in Figure 7.

Tides from the Potomac Estuary flow into the mouth of the Anacostia Estuary, then propagate up the channel where they mix with downstream river flow.

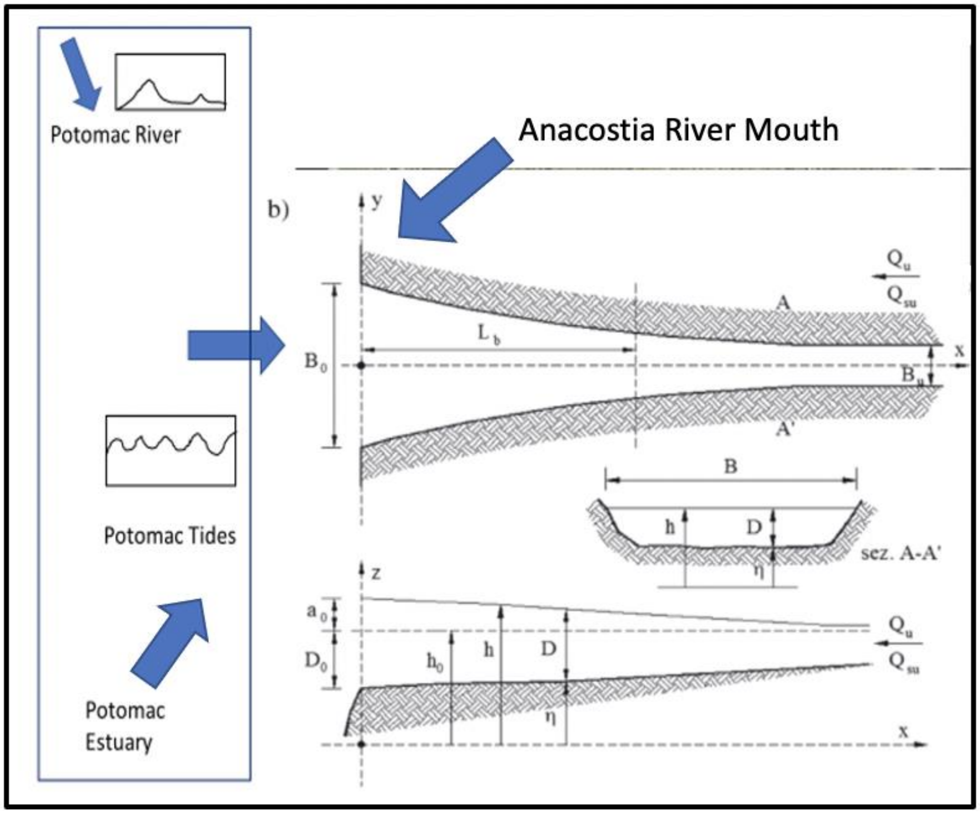


Figure 7: In the diagram by Bolla Pittaluga et al. (2015) shown on the right, the relationship between the length, width and depth of a river in an estuary is modeled. In the modified figure (on the left) tides from the Chesapeake Bay propagate up the Potomac Estuary, then eventually flow into the Anacostia River mouth and up the Anacostia River. The tides flowing in from the Potomac River impact the width and depth of the Anacostia River which in turn affects the distance up the Anacostia River that tides can reach.

Variables in the Bolla Pittaluga et al. (equation 1), are:

- B – channel width
- x – fraction of upstream distance from the estuary mouth
- B_u – upstream river width
- B_0 – estuarine channel width at the inlet
- L_b – channel length between B_u and B_0 (Bolla Pittaluga et al. 2015)

$$B = B_u + (B_0 - B_u) \exp\left(-\frac{x}{L_b}\right)$$

Equation 1

The estuaries selected for this analysis are: Anacostia 1895; Anacostia 2020; and Port Tobacco 2020. By definition, the Anacostia Estuary is an example of a manmade ideal estuary. Over time, it has not been able to adjust as nature would let it due to the urbanization of the surrounding area and therefore, the need to control where it moves. Because of this, it was subjected to many channelization and river straightening events, where marshes and tidal wetlands were removed and the river was dredged. However, all of those events began after 1895. The map of the river in 1895 provides an example for what the Anacostia River looked like before the USACE stepped in, which allowed for a good visual of how the river morphology has changed over time with human inputs.

The Port Tobacco Estuary is an example of a hypersynchronous estuary. The area surrounding Port Tobacco is far less urbanized than the area surrounding the Anacostia Estuary, containing mostly rural farmland, few roads, and building structures. Due to the lower population surrounding the river, the estuary remained mostly unchanged by human action unlike the Anacostia Estuary. Because of this, the estuary has been allowed to change shape, size, depth, etc., naturally. However, Port Tobacco was affected by sedimentation which likely severely narrowed the upper estuary width. By using the Port Tobacco Estuary and the Anacostia Estuary, the differences in morphologies between heavily urbanized and non-urbanized estuaries and how they changed over time were able to be observed.

To apply equation 1 to the Anacostia River and Port Tobacco, I completed the following steps:

Steps in Anacostia morphologic evaluations:

1. From the 1895 historic map of the Anacostia River (earliest available) (Figure 3), determine the total length, L, of the river in kilometers (km).
2. Convert measured length from km to meters (m).
3. Measure upstream, B_u and outlet, B_0, width on the 1895 map (values in m).
4. Use measured L, Bu, Bo in the Bolla Pittaluga et al. (2015) equation to predict estuary widths at 200 m increments.
5. On the 1895 map, measure the actual width, in 200 m increments and compare to the theoretical width calculation.
6. Plot the theoretical width calculations versus measured values.
7. Repeat steps 1-6 using values from the current Anacostia River (Figure 4B), and Port Tobacco. Acquire width versus distance data for 2020 from Google Earth images.
8. Once the theoretical and actual calculations for width are completed on both 1895 map and 2020 map, plot both the actual and theoretical shapes on one graph to illustrate both relationships with theory and changes from 1895 to the present.
9. Plot the theoretical measurements versus actual measurements and performed a linear regression, calculating the slope, intercept, and R^2 value. This evaluates systematic variations.
10. Calculate predicted – observed.

Steps in Port Tobacco morphological evaluations:

1. Using Google Earth, determine the available length, L, of the river in kilometers (km) of the current Port Tobacco River.
2. Convert measured length from km to meters (m).

3. Measure B_u and B_0 in m on the google earth map.
4. Use measured L, Bu, Bo in the Bolla Pittaluga et al. (2015), equation to predict estuary widths at 200 m increments.
5. Once both the theoretical width measurements and the actual width measurements are complete, plot them on a graph to illustrate the changes in morphological width throughout the river.
6. Plot the theoretical measurements versus actual measurements and perform a linear regression, calculating the slope, intercept, and R^2 value. This evaluates systematic variations.
7. Calculate predicted – observed.

5b. Analyzing Time Series Data

Used to evaluate long term trends and annual variations in tides and river elevations.

To quantify the long-term changes in water surface elevations at the two ends of the system, the river and tides, USGS Water Station data were used. Streamflow data for the upstream end of the system was available for the two stations maintained by the United States Geological Survey (USGS) located on the Northeast Branch and Northwest Branch of the Anacostia, just upstream of where the two rivers converge. At these stations, the USGS monitors discharge (cfs), gage height (ft), temperature (^oC) and specific conductance (µs/cm at 25 ^oC). For this study, only gage height data was used. The first site was USGS 01649500 Northeast Branch Anacostia River at Riverdale, MD, and that gage collected data every 5 minutes. The second site was USGS 01651000 Northwest Branch Anacostia River near Hyattsville, MD, and that gage collected data every 15 minutes. The downstream site, representing the tidal component of the study, was located at Buzzard Point, USGS 01651827 Anacostia River NR Buzzard Point at Washington DC, where data are collected every 15 minutes. This station also collected discharge (cfs), gage height (ft), temperature (^oC) and specific conductance (µs/cm at 25 degrees Celsius) data. The USGS compiles the date, gage height and discharge of the annual maximum discharge into a data series. Data are given in gage height, which was converted to NAVD88 elevations using the datum elevation.

For the annual analysis, data from October 1, 2019 to October 1, 2020 was used. This period includes a major flood, which occurred on September 10, 2020. The following steps were included in the data analysis:

Steps for annual distribution of River Input Trend:
1. Download instantaneous data from October 1, 2019 to October 1, 2020 data from both USGS sites.
2. Convert gage height data to same elevation reference frame as water level – (NAVD88).
3. Plot converted gage height data from both USGS sites on separate graphs.
4. For each graph, determine overall trend of the data over the past year.

Steps for annual distribution of Tidal Input Trend:
1. Download instantaneous data from October 1, 2019 to October 1, 2020 water data from the USGS Buzzard Point station.
2. Convert gage height data to same elevation reference frame as water level – (NAVD88).

3. Plot water level data onto graph.
4. For each graph, determine overall trend of the data over the past year.

5c. Probability of Extremes

High water events are occurring more frequently at both ends of the Anacostia River System. Understanding how the water levels change in response to storm events is important in mitigating and predicting the effects of flooding. Streamflow data was downloaded from USGS for the following dates in 2020: Storm 1 - August 4-8, Storm 2 - September 3-4, Storm 3 - September 10, Storm 4 - October 12, Storm 5 - November 11-12. These storm events were chosen in collaboration with Alex Bollinger, who chose those dates within 2020 because they were in the top 90^{th} percentile of water level. These storm events were chosen because they provided a variety of different magnitude storm events, different storm durations, and occurred during different months of the hurricane season (June-November). During hurricane season, larger storm events are more likely to occur, bringing the possibility of large storm surge events from the tidal end and large precipitation events at the river end of the system. Three components were analyzed for each storm event: water elevation, specific conductance, and elevation gradient. The water elevation was used to demonstrate the difference in elevations at both ends of the system. Specific conductance was used to demonstrate the influx of freshwater caused by upstream precipitation, and the time it took for the plume to move down the river and out of the system. The elevation gradient of the river was used to show the slope of the river from the Northwest Branch station to the Buzzard Point station, and from the Northeast Branch station to the Buzzard Point station. The slope helped to determine where the transition zone shifts within the river as the elevation changes, and to determine which end of the system dominates during a specific storm event.

To complete this analysis, gage height and specific conductance data from the USGS Northwest Branch, Northeast Branch, and Buzzard Point stations was downloaded for the chosen dates. The gage height data for every station was converted into the same elevation reference frame – NAVD88.

The steps below were followed to complete these analyses for each selected storm event:

Steps for Storm Data Analyses:

1. Using water data collected at USGS Stations: Northwest Branch, Northeast Branch, and Buzzard Point, pick a date where a storm event occurred.
2. Download all available data from each site for a few days before the storm event and a few days after.
3. For Water Elevation vs Time Analysis:
   a. Convert the gage height data from feet to meters.
   b. For Northeast and Northwest Branches, add 0.29 m to converted height to account for the higher upstream elevation (NAVD88).
   c. For the Northeast Branch, sort the data so that the data collected is collected every 15 minutes, or every third data point.
   d. Plot water elevations for all three stations vs the date/time on a graph in excel.
4. For Specific Conductance Analysis:

   a. For the Northeast Branch, sort the data so that the data collected is collected every 15 minutes, or every third data point.
   b. Plot the specific conductance data for all three stations vs the date/time on a graph in excel.
5. For Elevation Gradient Analysis:
   a. Measure the distance from the Buzzard Point station to the Northeast Branch station and the Northwest Branch station in meters.
   b. Subtract the Buzzard Point water elevation data from the Northeast Branch water elevation data. Repeat step for the Northwest Branch station.
   c. Take the calculated differences and divide by the total length to get the slope from the Northeast Branch to Buzzard Point and Northwest Branch to Buzzard Point.
   d. Plot the calculated slopes vs date/time to get the elevation gradient over time.
6. Repeat steps 1-5 for each storm event chosen.

6. Results

6a. Estuarine Morphology

Estuary width distributions for the 1895 and 2020 Anacostia and the 2020 Port Tobacco Estuaries were measured and compared with theory (Bolla Pittaluga et al. 2015). The 2020 images are shown in Figure 8, the main parameters used in the Bolla Pittaluga model are in Table 1.

Table I – Measurements of L, B_u and B_o for Bolla Pittaluga et al. (2015) Equation

	L (m)	B_u (m)	B_o (m)
1895 Anacostia Map	13500	50	1150
2020 Anacostia Image	13230	50	470
2020 Port Tobacco Image	7810	30	2470

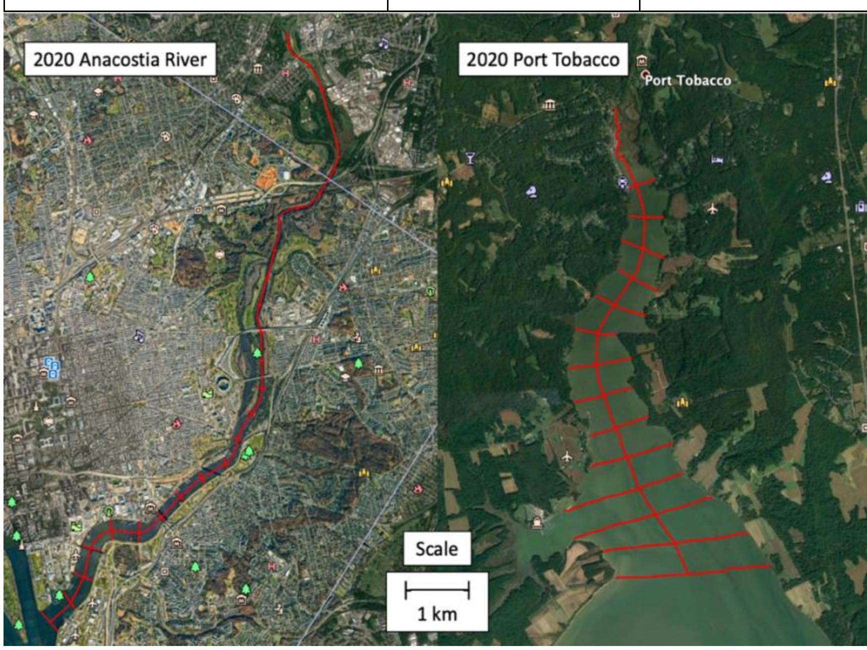


Figure 8. 2020 Anacostia Estuary (left), 2020 Port Tobacco Estuary (right) Images, accessed through Google Earth. These images show the width measurements using the line tool on Google Earth for the estuary methodology. (Both images shown on the same scale).

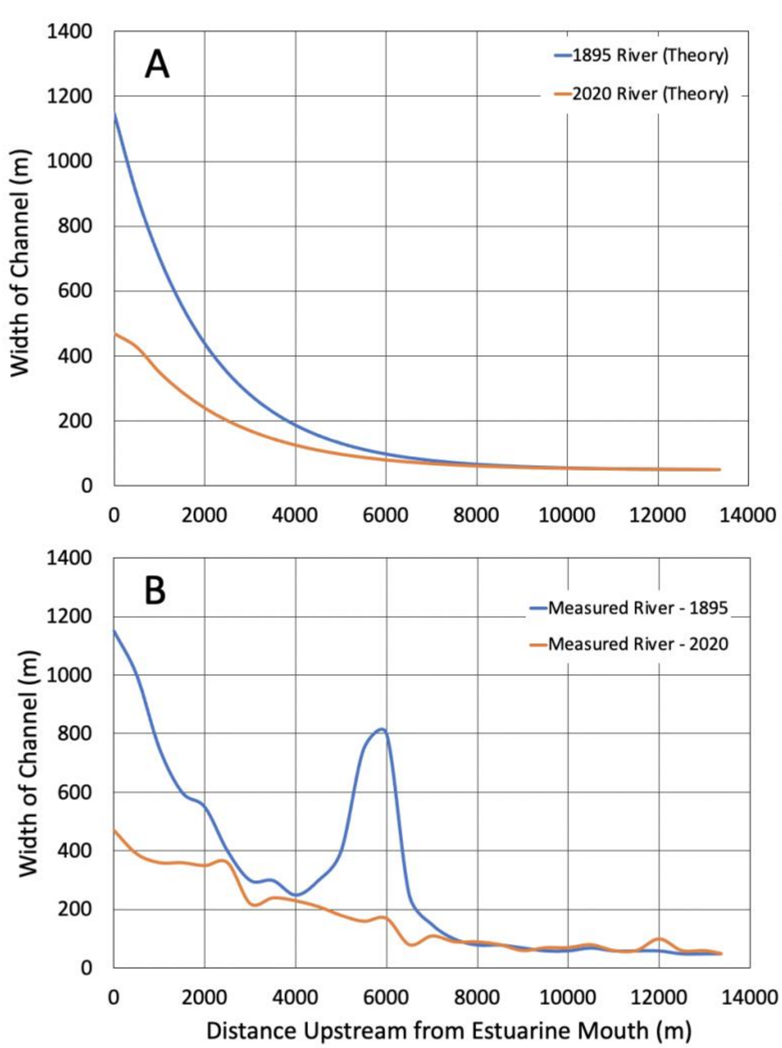


Figure 9. A: Theoretical Anacostia River 1895 vs 2020, B: Measured Anacostia River 1895 vs 2020. Graph A shows the application of the Bolla Pittaluga et al. (2015) equation on widths for the 1895 and 2020 Anacostia Estuaries. Graph B shows the actual width measurements off of the maps for the 1895 and 2020 Anacostia Estuaries.

Anacostia Estuary Width Distributions

Measurements for L, Bu and Bo, were taken from the 1895 Anacostia River Map and the June 11, 2020 Anacostia River Map, provided in Table I. These measurements were used in the Bolla Pittaluga et al. (2015) equation to produce the theoretical width distribution of the Anacostia Estuary for both 1895 and 2020. The width of the 1895 Anacostia Estuary was measured at 500 m intervals and the width of the 2020 Anacostia Estuary was measured at 200 m intervals. Graphs of the theoretical and measured values are shown in Figure 9. Both are plotted as distance upstream from the tidal inlet to show the difference in the river width going upstream. The mouth of the 1895 river is wider than the 2020 river by 680 meters, however the upstream end of the river is equal in width to one another. However, 4000 m up the river, after almost being the same width as the measured river in 2020, the 1895 river widens again to a maximum width of 800 m and while the 2020 river has a width of 98.9 m and continued to decrease. This suggested that most major modification of the river was done on the lower half of the Anacostia

River between 1895 and 2020. The notable change in shape of the estuary from 1895 to 2020 also suggested modification of the river over the last century and a half, which was demonstrated by the USACE actions from 1900 to present day.

Figure 10 compares the theoretical width to the measured width for the 1895 and 2020 Anacostia River, the 2020 Port Tobacco River, and the regression analyses completed for each river. The regression analysis of predicted to measured values was completed to determine differences between predicted and observed values for both sets of measured Anacostia Estuary width values and the 2020 Port Tobacco width values.

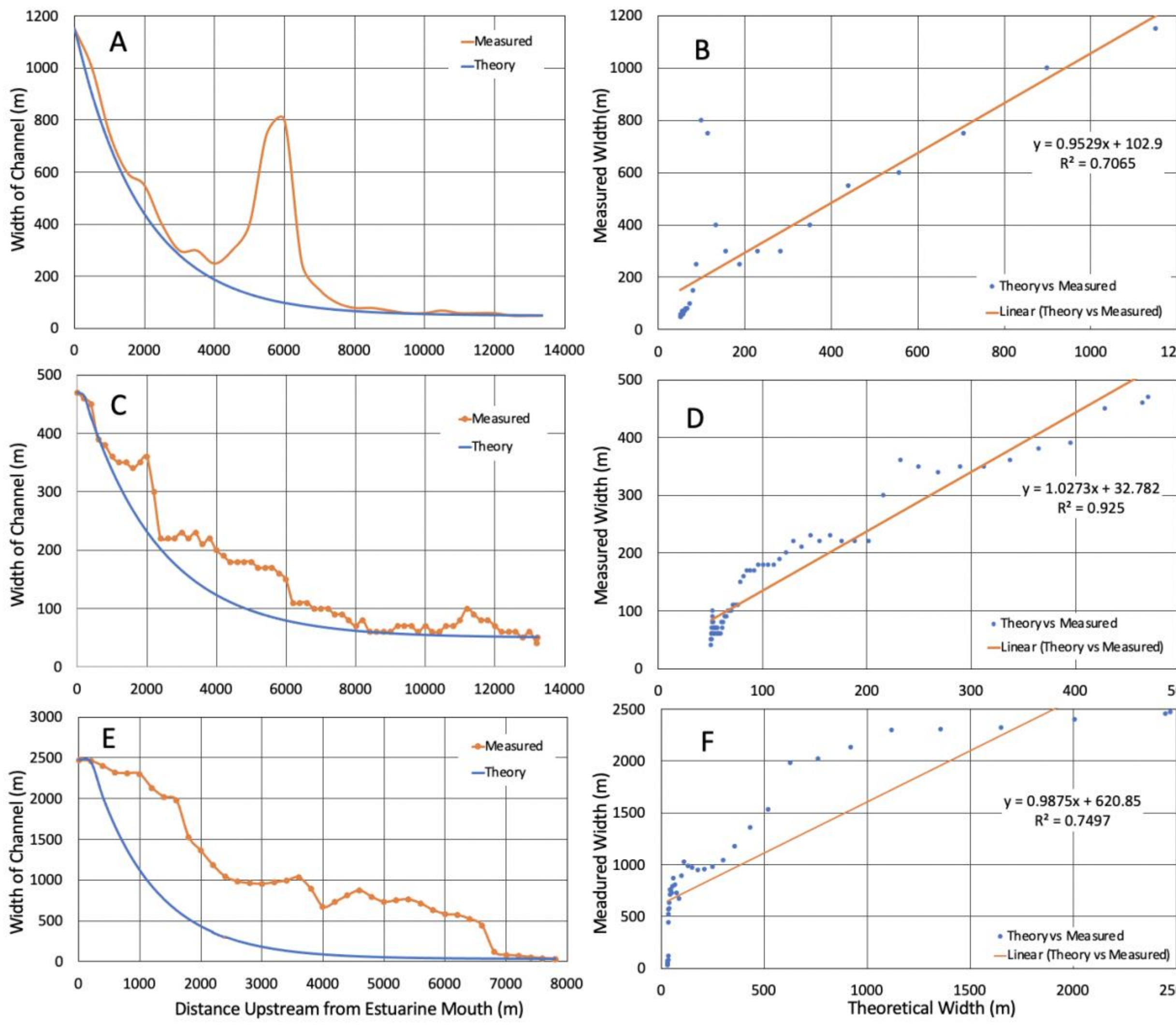


Figure 10. A: 1895 Anacostia River Theory vs Measured, B: 1895 Anacostia River Regression Analysis – Theory vs Measured, C: 2020 Anacostia River Theory vs Measured, D: 2020 Anacostia River Regression Analysis – Theory vs Measured, E: 2020 Port Tobacco Theory vs Measured, F: 2020 Port Tobacco Regression Analysis – Theory vs Measured. The graphs on the left show the compared theoretical and measured widths for each river of interest. The graphs on the right show the regression analyses completed to compare the theoretical widths to the measured widths for each river of interest.

Table II: Regression Analysis of Anacostia and Port Tobacco Width Predictions

Site	Slope	Intercept	R^2
Anacostia Estuary 1895	0.953	102.9	0.707
Anacostia Estuary 2020	1.027	32.78	0.925
Port Tobacco 2020	0.988	620.9	0.75

Values of regression slope, intercept, and R^2 values are shown in Table II. All of the calculated slopes are positive, but the intercept values were different, indicating systematic offsets. For the Anacostia River, in 1895 the intercept is 102.9 compared to the 2020 river which has an intercept of 32.8. This difference can be attributed to the large widening in the middle of the Anacostia River in 1895, which is no longer there in 2020. However, Port Tobacco had an intercept of 620.9, which is due to the procreation of marshes downstream, further impacting the length of the entire system. After the regression analysis was completed, an R^2 value of 0.9627 was calculated. This value shows that the measured widths of the 2020 river are much closer to the theoretical widths of the 2020 river, indicating that the estuary is in equilibrium.

Port Tobacco Width Distributions

Measurements for L, Bu and Bo, were then taken from the 2020 Port Tobacco Map and the same methodology was repeated using the Bolla Pittaluga et al, (2015) equation. The Port Tobacco Estuary was selected because it is located along the Potomac River, further down towards the Chesapeake Bay. Based on its characteristics, the Port Tobacco Estuary was classified as a hypersynchronous estuary, where the width of the mouth of the estuary is much larger, narrowing down into a funnel shape. Port Tobacco has a history of harbor siltation, like the Anacostia. Unlike the Anacostia, the watershed has not been urbanized. From the end of the funnel, the Port Tobacco Estuary decreased in size drastically to a small river. In addition, in Figure 10, which shows the measured Port Tobacco widths compared to the theoretical widths, that the measured widths are much larger than any of the theoretical widths until the estuary narrows down to the small river. This suggests that the main estuary length was shorter than expected, however the direct cause for that is unknown at the moment. In Figure 10, the Port Tobacco Estuary measured and theoretical widths were plotted to see the similarity between the two. The measured Port Tobacco Estuary was much wider than the theoretical widths, which suggested that the estuary shape been significantly modified, most likely but siltation and progradation of the freshwater tidal marshes at the terrestrial end. The area surrounding the Port Tobacco Estuary is a well-known example of the consequences of agricultural erosion (Gottschalk, 1945). Descriptions of Port Tobacco prior to 1800 indicate that the original estuary continued upstream of the town. Sediment from agricultural runoff filled the upper portion of this estuary and is now occupied by freshwater tidal wetland. Maps suggested that the initial estuary continued for another 3,000 m upstream of its current location, with input river width about 15-20 m (current width). In Figure 11, the smaller river is what currently exists in place of the much larger estuarine river.

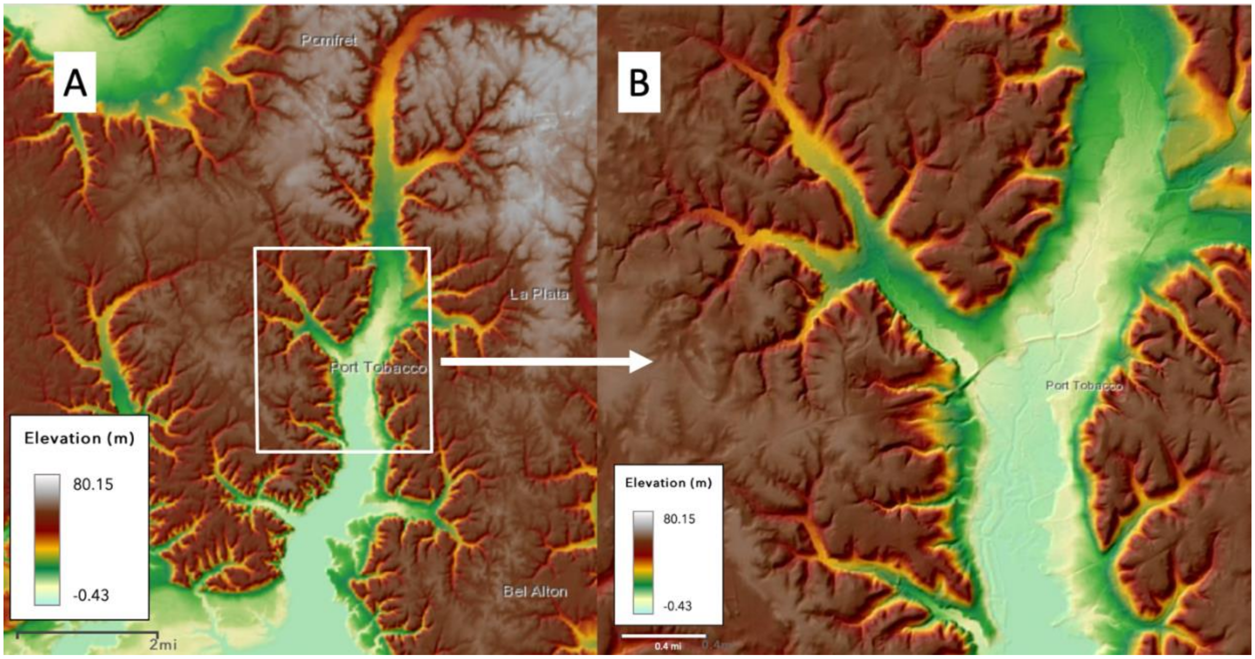


Figure 11. The LiDAR images show the elevation changes surrounding the Port Tobacco Estuary. Image A shows the Port Tobacco Estuary as a whole. Image B shows the zoomed in area of the white box. In Image B, lightest green area represents the area where the water in the Port Tobacco Estuary used to exist, however that area is now composed of tidal wetlands and small freshwater rivers. Image screenshotted and modified from MD iMAP, LiDAR Topography Viewer.

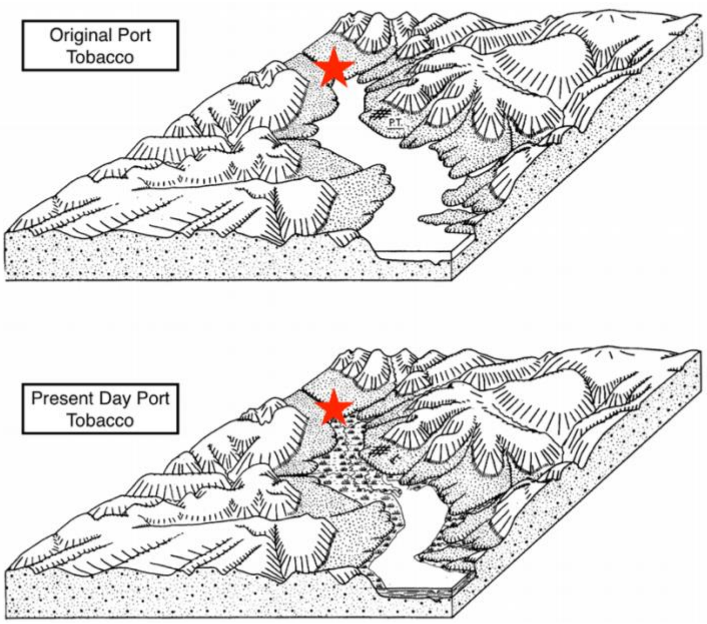


Figure 12. This is a conceptual diagram of how the original Port Tobacco has changed to the present day Port Tobacco. As previously discussed, the Port Tobacco Estuary extended much further inland (indicated by the red star), whereas today the same area is primarily wetlands with small rivers running through. Diagram modified from Gottschalk (1945).

6b. Analyzing Time Series Results

Extremes Over Period of Record:

Annual maximum floods and sea level rise over the period of record were downloaded from the USGS and NOAA. The annual maximum flood represents the peak flood for each year since the late 1930's. There was an increase in annual maximum flood elevation until 1973, then there was a drastic decrease which can be attributed to dredging of the river (Figure 13.). The elevation at the upper end of the river was dropped approximately 2-2.5 meters to manage flooding at the upper end of the system. However, since then, the annual maximum flood elevation has continued to increase, almost reaching flood elevations pre-dredging. At the other end of the system, data collected by NOAA for Washington, DC suggests that the water elevations have also been increasing since mid-1930's as well (Figure 13.).

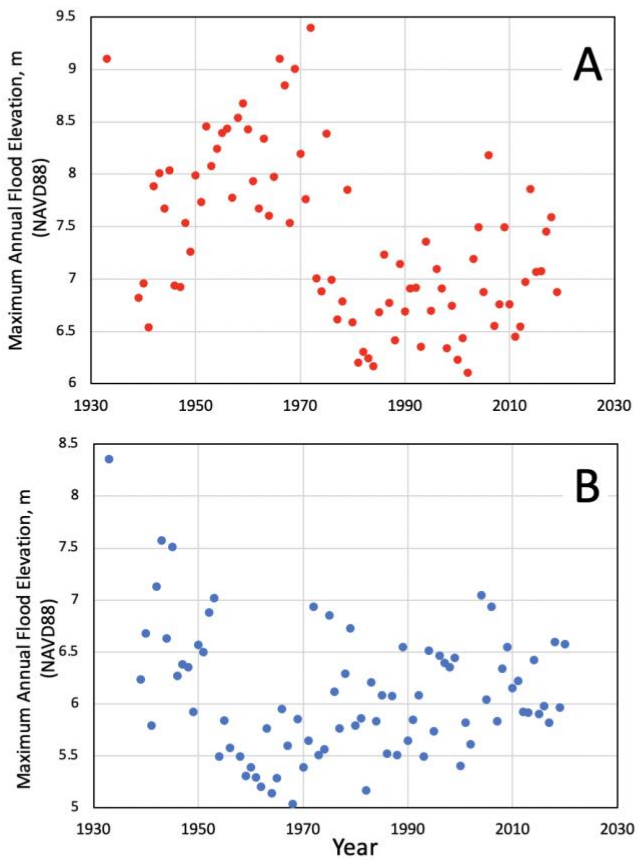


Figure 13. A: Northwest Branch Anacostia River Maximum Annual Flood Elevations in NAVD88 since 1933, B: Northeast Branch Anacostia River Maximum Annual Flood Elevations in NAVD88 since 1933. These images show the observed elevations of Annual Maximum Floods at the gage locations in the Northeast and Northwest Branch Anacostia.

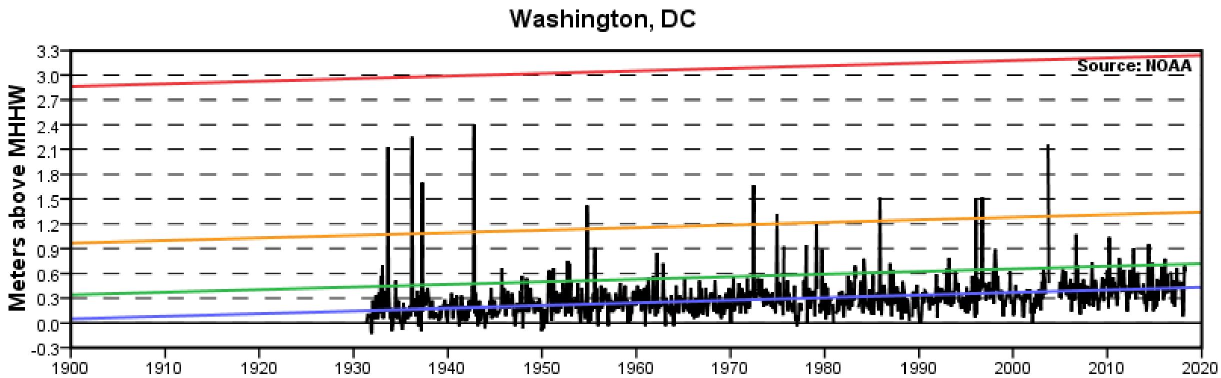


Figure 14. Tidal extremes over period of record and the sea level rise trend for Washington, DC, graph unmodified from NOAA, 2020.

Table III: Top 10 Extreme Tidal Gage Heights over the Period of Record

Dates	Tidal Gage Heights (m)	Northeast Branch Gage Heights (m)	Northwest Branch Gage Heights (m)
August 23, 1933	5.298	8.36	9.09
March 19, 1936	5.419	6.95	6.68
April 28, 1937	4.871	N/A	N/A
October 17, 1942	5.572	8.00	7.57
October 15, 1954	4.597	N/A	N/A
June 24, 1972	4.840	9.36	6.94
November 5, 1985	4.685	N/A	N/A
January 21, 1996	4.671	9.28	6.46
September 9, 1996	4.691	7.09	6.94
September 19, 2003	5.333	N/A	7.24

Table III shows the top 10 extreme gage heights over the period of record for both ends of the Anacostia River-Estuary System in the same elevation reference frame - NAVD88. The dates chosen are the top 10 extreme events on the tidal end. The gage heights for the Northeast and Northwest Branches were then compared to see whether the extreme event was a river flooding event or storm surge event. Three of the ten extreme tidal levels did not have corresponding extreme river gage heights indicating those events were storm surge dominated events only and did not affect the river end of the system. The other seven events had corresponding peak gage heights on the river end, indicating a river flooding event which resulted in extreme water levels at the tidal end of the system. This further supports the concept that the Anacostia Estuary is a river dominated system.

Annual Probability of High Water Levels - Water Year 2020:

The results from analyzing time series of water surface elevation from October 1, 2019 to October 1, 2020 from the Northeast Branch, Northwest Branch and Buzzard Point are provided below. Both water surface elevation data and the exceedance probability are provided for each of the three locations. In Figure 15, graphs A, C and E showed a very small increase over the year at every end of the system, which could be contributed towards October being a one of the peak hurricane months, or trends in seasonal rainfall, however more research would need to be completed in order to find an answer for the slight increase. The probability of the water levels at each station exceeding a certain elevation was calculated for the 2020 water year, in Figure 15, graphs B, D and F and in tables IV and V. For both the Northeast and Northwest Branch, a majority (95%+) of the water elevations collected was in the range of 0-1 m in elevation. Water elevations exceeding 1+ m, 2+ m, and 3+ m was also provided, however events creating water elevations higher than 1+ were relatively rare in the 2020 water year. At the other end of the system, approximately 36.7% of water elevations were actually below zero m, which most likely can be attributed to the daily low tides. The most common water elevations (42.4%) were between 0-0.5 m, and 17.3% of water elevations exceeded 0.5 m. During the data collection period, events that created water elevations greater than 1 m occurred less than 0.28% of the time.

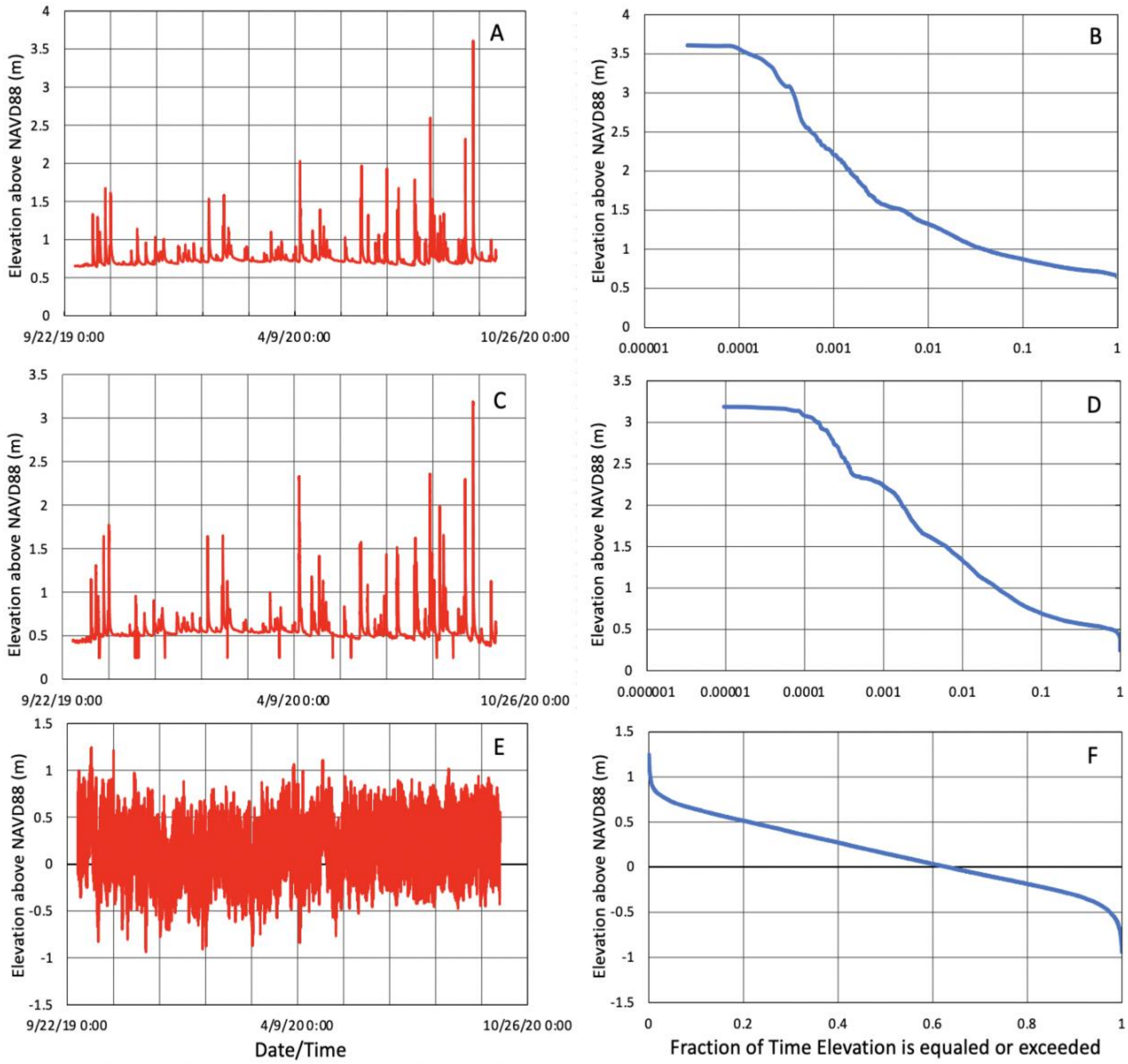


Figure 15. A: Water Surface Elevation Northwest Branch, B: Water Surface Elevation Northeast Branch, C: Water Surface Elevation Buzzard Point, D: Probability of Water Surface Elevation Northwest Branch, E: Probability of Water Surface Elevation Northeast Branch, F: Probability of Water Surface Elevation Buzzard Point. The figures on the left in red represent the water surface elevation for the three stations used for water year 2020. The figures on the right in blue represent the fraction of time water elevation at each station in equaled or exceeded.

Table IV: River Water Elevation – Probability of Exceedance

	3+ Meters	2+ Meters	1+ Meters	0.0+ Meters
Northeast Branch	0.01%	0.17%	2.62%	97.2%
Northwest Branch	0.04%	0.29%	3.98%	95.6%

Table V: Tidal Water Elevation – Probability of Exceedance

	1+ Meters	0.75+ Meters	0.5+ Meters	0.0+ Meters	-1 Meters
Buzzard Point	0.28%	3.16%	17.3%	42.4%	36.7%

Again, these data indicate that it is more probable for the high waters to be at the river end of the system than on the tidal end of the system.

6c. Probability of Extremes: Behavior of Individual Storms

In the previous section, I analyzed peak water surface elevations at the upstream (river) and downstream (tidal) ends of the Anacostia Estuary to determine the magnitude and frequency of major high water events. These data indicate that high flows are more likely to come from the rivers than tides or storm surges. In this section, I examine the behavior of several major floods through the estuary from the water record 2020 season. The storms events analyzed were: August 4-8, September 3-4, September 10, October 12 and November 11-12. The water elevation versus time, specific conductance and elevation gradient over time were analyzed to demonstrate specific characteristics that occur during flooding events.

<u>Water Elevation Over Time:</u>

The water elevation over the duration of the specific storm event was used to demonstrate how the water elevations at either end of the system change during an event. When a precipitation event occurs, water elevation at the upper end of the system increases caused a “flood peak” on the hydrographs. Shortly after that happened, depending on the size of the flood, the river flood momentum lowered the tidal maxima as the flood water moved down and out of the system. In some cases, a small storm surge occurred after the floodwater moved out of the system, which caused post-flood tidal flooding and increased water elevation at the tidal end of the system.

Specific Conductance:

The specific conductance was used to understand how freshwater moves through the Anacostia system and transition reach during storm events. Incoming freshwater caused the dilution of stream baseflow and tidal waters. As the freshwater enters the system, a steep drop on specific conductance occurred at the upstream stations. The freshwater moved through the system, eventually reaching the downstream station which caused a steep drop in specific conductance at the downstream end of the system.

Elevation Gradient Over Time:

The water level elevations and the slope of the river have an inverse relationship. When the tides were highest, the elevation gradient as negative because the downstream end of the system was higher than the upstream end of the system. This meant that tides were pushing the river water back upstream. When the tides were lowest, the elevation gradient was positive because the upstream end of the system was higher than the downstream end of the system. This means that the river water was pushing the tidal water downstream. When the slope was positive (<0), the system was river-dominated, and when the slope was negative (>0), the system was tidally dominated.

Storm 1 - August 4-8, 2020:

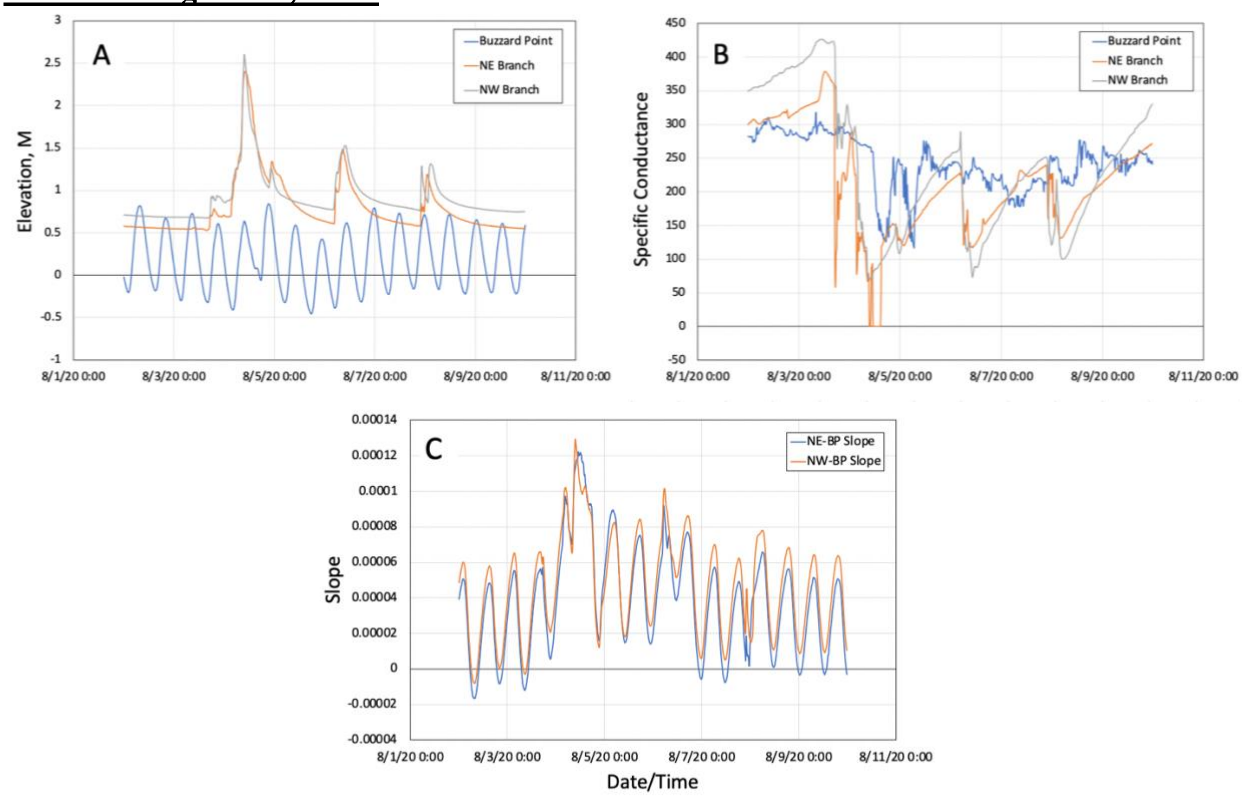


Figure 16. A: Water Elevation versus Time, B: Specific Conductance, C: Elevation Gradient Over Time

Storm 2 - September 3-4, 2020:

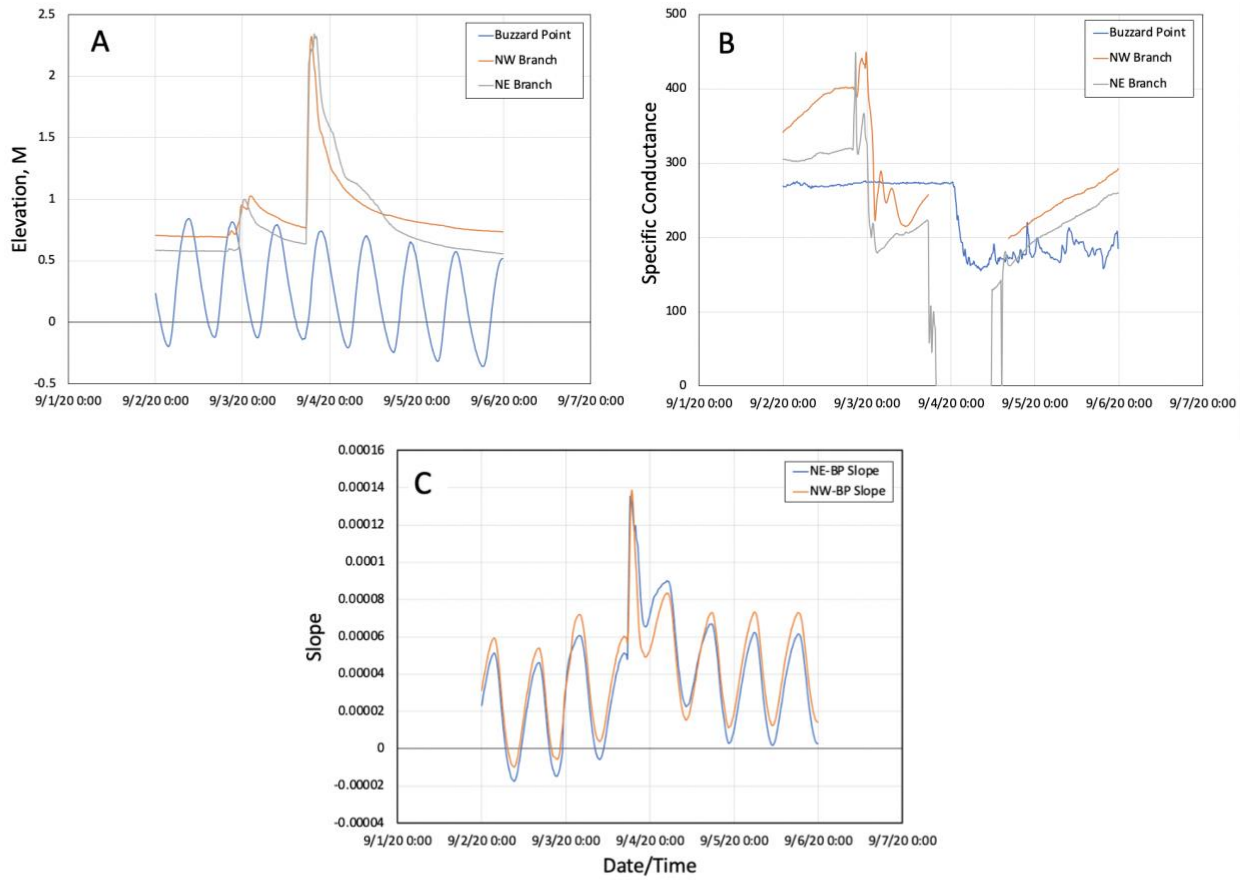
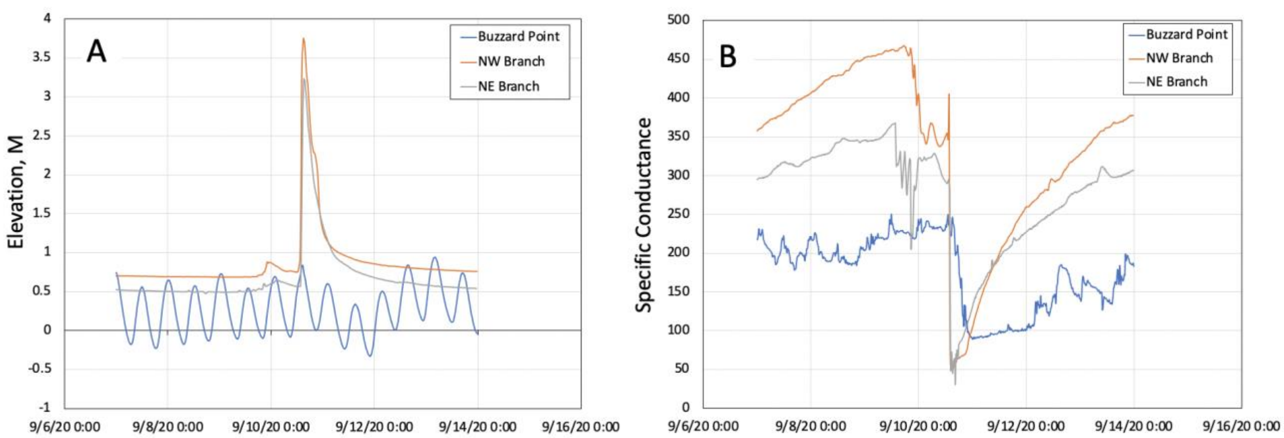


Figure 17. A: Water Elevation versus Time, B: Specific Conductance, C: Elevation Gradient Over Time

Storm 3 - September 10, 2020:



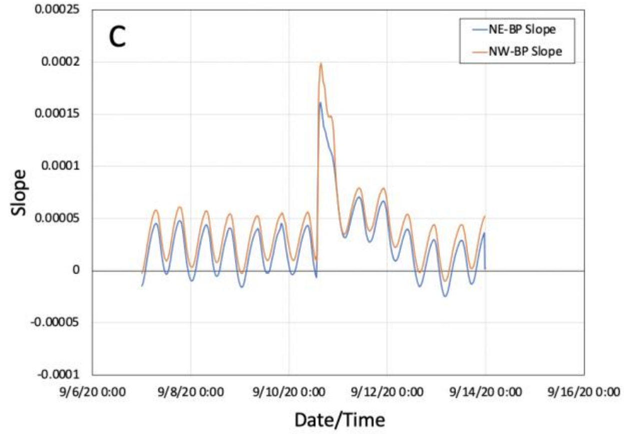


Figure 18. A: Water Elevation versus Time, B: Specific Conductance, C: Elevation Gradient Over Time

<u>Storm 4 - October 12, 2020:</u>

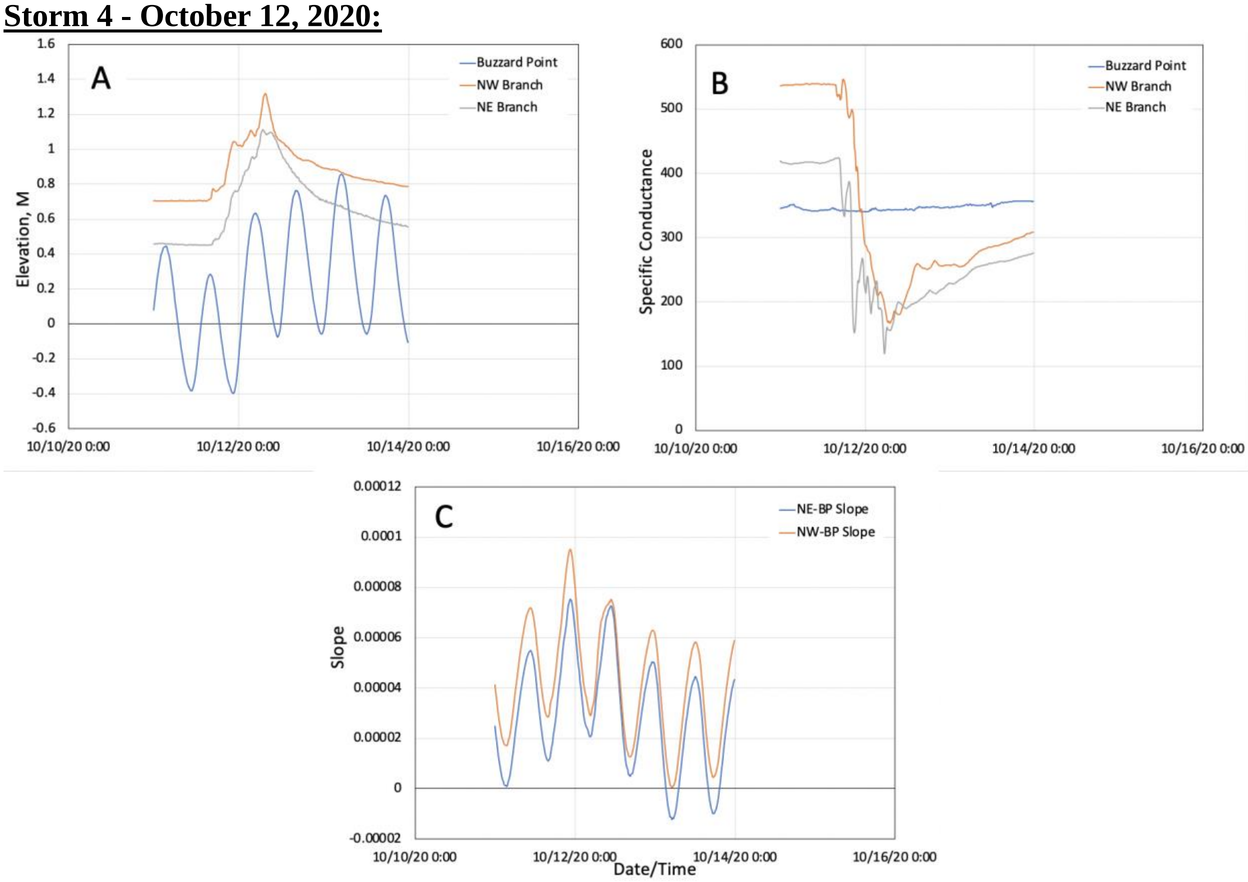


Figure 19. A: Water Elevation versus Time, B: Specific Conductance, C: Elevation Gradient Over Time

Storm 5 - November 11-12:

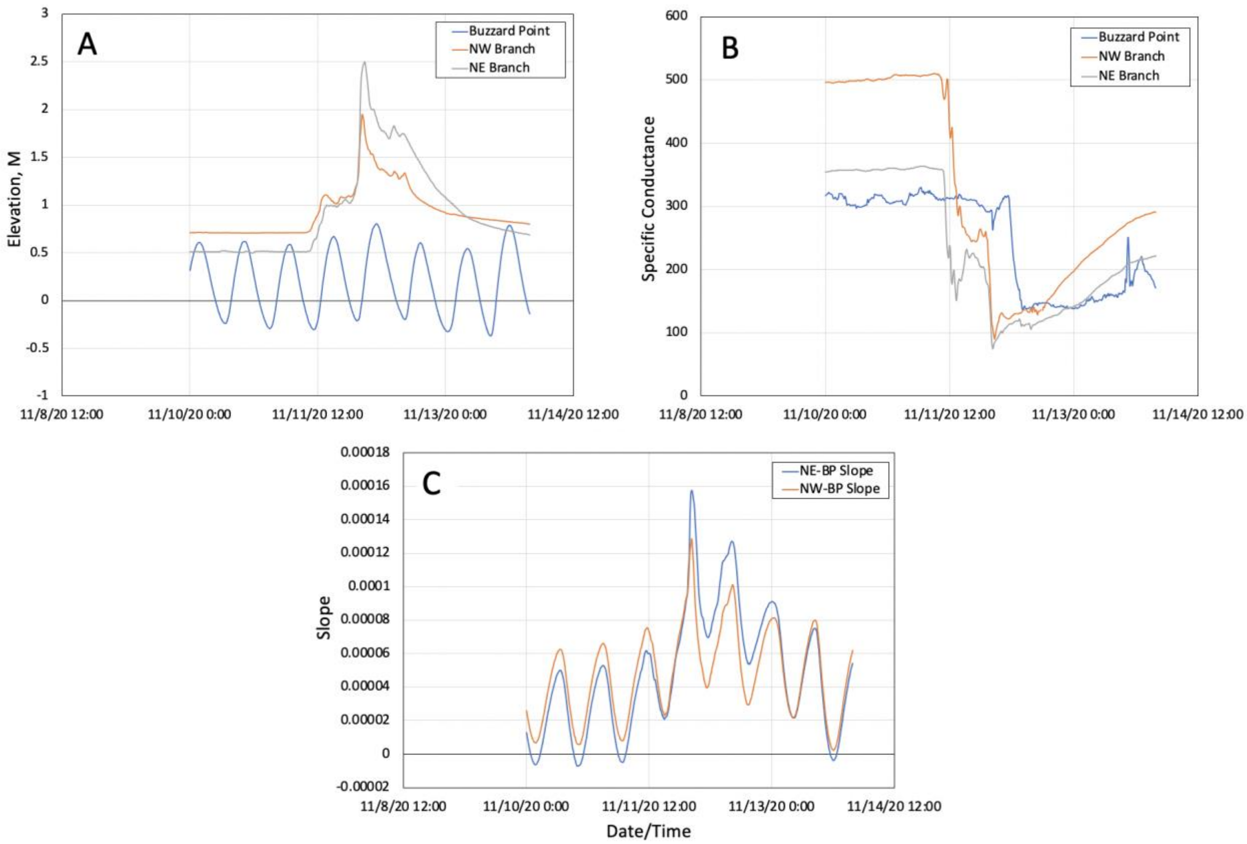


Figure 20. A: Water Elevation versus Time, B: Specific Conductance, C: Elevation Gradient Over Time

Individual Storm Analyses:

Table VI: Elevation Gradient Over Time

	Storm 1	*Storm 2*	*Storm 3*	*Storm 4*	*Storm 5*
NE-BP % of Positive Slope	89.7%	89.1%	80.5%	89.6%	89.8%
NE-BP % of Negative Slope	10.3%	10.9%	19.5%	10.4%	10.2%
NW-BP % of Positive Slope	97.5%	94.0%	95.6%	100%	100%
NW-BP % of Negative Slope	2.5%	6.0%	4.4%	0%	0%

This table describes the percentage of time, before, during, and after each storm event, where the slope was positive and negative from both the Northeast and Northwest Branches down to Buzzard Point. A higher positive percentage indicates that the storm event was river dominated, and a higher negative percentage indicates that the storm was tidally dominated.

In Table VI, the percentage of time the slope was positive and negative, for both the Northeast Branch to Buzzard Point and the Northwest Branch to Buzzard Point, was calculated. For the Northeast Branch to Buzzard Point, approximately ~90% of the time for each storm event, the event was river dominated, while approximately 10% of the time, the event was tidally dominated. Storm event 3, which occurred on September 10th, 2020 was much larger than the other storm events, pushing a greater amount of freshwater out of the system, ultimately resulting in a larger returning storm surge, explaining the approximately ~20% of the event that resulted in a negative slope. For the Northwest Branch to Buzzard Point, for every storm event, more than 94% of each event was river dominated, while less than 6% for each storm was tidally dominated. For events 4 and 5, the slope was positive 100% of the time, meaning it was only a river dominated event. Looking at both the Northeast Branch and Northwest Branch to Buzzard Point, for each event a majority of the time, the events were river dominated, with little tidal influence. This is notable because it shows that the Anacostia River is influenced more frequently and to a higher degree, by precipitation events than tidal events.

7. Discussion of Results

Based on the results produced from analyzing the data sets from USGS, there are two main conclusions that can be made. With regards to the 1895 Anacostia River width compared to the 2020 Anacostia River width, the first conclusion that can be made is that the river width has changed over time. The width traveling further upstream in the 2020 Anacostia River remains more consistent as it moves upstream, whereas the 1895 Anacostia River was much wider at the mouth and then also was wider towards the middle before narrowing abruptly. This suggests a change in the type of estuary; however, it was man-made change opposed to natural change. Because of the history of channelization and river straightening done by the USACE throughout the 1900s, it is likely that the shape of the river would much different than it is in 2020. However, after comparing the Anacostia Estuary to the Port Tobacco Estuary, the Port Tobacco is much larger in width than was predicted from the theoretical width calculations. Based on maps and comparison with theory, Port Tobacco should be a tidally dominated system, Instead, modification by siltation from the river end has resulted in freshwater tidal wetlands dominating the uppermost portions of what used to be the Port Tobacco Estuary, which is supported by the sedimentation hypotheses of freshwater tidal wetlands. Water elevation patterns at either end of the system were impacted by the change in morphology and urbanization of the surrounding watersheds.

The second conclusion that can be made from the data is that the water level elevations at both ends of the system have been increasing since the 1930s, when official data collection began. Physical changes to the river have impacted the annual maximum flood elevations, however despite the attempt to lower water levels, they continue to increase. The annual water data for 2020 showed a slight increase over time, however it was very small. Based on the history of the urbanization of the Anacostia Watershed and the amount of impervious surface on both of the sub-watersheds, the Northeast and Northwest Branch water surface elevation was expected to increase over time.

Further narrowing down the timeline to look at how the Anacostia Estuary reacted to specific events was important in order to understand how extreme events impact both ends of the system. The three components analyzed for each storm event were: water elevation, specific conductance, and elevation gradient, which allowed for a better understanding of how both ends interact with each other. The five events that were analyzed all occurred in late summer through the end of fall, where precipitation events influenced by tropical storms and hurricanes are more likely to occur. During river flooding events, there are two main scenarios that we saw occur. The first scenario that was seen in the data, was a sharp increase in water elevation in the Northwest and Northeast Branches of the Anacostia, with little to no impact of the water elevation at Buzzard Point. This indicates that the storm event primarily occurred at the river end and did not noticeably impact the water elevations at the tidal end of the system. This occurred during storm events 1, 4 and 5. The second scenario that was seen in the data for storm events 2 and 3, was a sharp increase in water elevation in the Northwest and Northeast Branches of the Anacostia, followed by a decrease in tidal elevation at the Buzzard Point station. The decrease in elevation indicates that the plume of freshwater, caused by precipitation, traveling down the Anacostia River was larger enough to push the tidal water out into the Potomac River. At this point, the storm event would’ve been considered a river flooding event and the transition zone shifts down the river, because the water elevation at the upstream end was greater than at the tidal end. However, after the freshwater plume had completely passed through the system, there was a small storm surge back into the Anacostia River as tidal waters were returning into the system. When this happened, the elevation at the tidal end of the system was greater than at the river end of the system, resulting in a tidal flooding event, where the transition zone shifted back upstream. Eventually the system returns to equilibrium, or its “normal” state, where elevations at the river end are slightly higher than the tidal end. Based off of the results in Table VIII, it can be concluded that the Anacostia Estuary is more prone to river flooding than tidal flooding during storm events, however, tidal flooding can still occur.

Conclusions and Broader Impacts

8a. Conclusions

In this study, multiple analyses were completed to determine how the Anacostia Estuary has changed over time and how that relates to the causes of high water levels within the Anacostia Estuary. The following conclusions were made from the results above. The Anacostia Estuary has changed morphological shape due to human impacts, including channelization of the river itself and heavy urbanization of the surrounding area. The first hypothesis stated that the historical Anacostia River width is more consistent with the theoretical width distribution than the present day measured width. After plotting the measured versus theoretical widths for both the historical and present day Anacostia River, the first hypothesis was unsubstantiated. It can be concluded that the present day Anacostia River is more consistent with the theoretical width distribution, than the historical Anacostia River. After analyzing the morphological changes of the Anacostia Estuary, both short term and long term trends were investigated to understand how the water levels were changing. The second hypothesis stated that the water surface elevations on both ends of the Anacostia system have increased over time due to urbanization and climate change (sea level rise). The short and long term trends support rising water elevations at both ends of the Anacostia Estuary. Both river and tidal water elevations are increasing gradually over time and will most likely continue to increase because of the impacts of sea level rise and urbanization. The final conclusion that can be made is that the Anacostia Estuary water levels are primarily controlled by downstream river flow and extreme precipitation events at the upstream river end of the system. The final hypothesis for this project stated that water level data indicates that extreme high-water levels are more probable at the upstream end due to river flooding than the river mouth due to high tides. This final hypothesis was corroborated by the individual storm event analyses, which showed a higher percentage of river dominated events than tidal dominated events.

8b. Broader Impacts

Studying what causes high water levels in the Anacostia River is important in understanding how flooding events in the future could be avoided. Given that sea levels are rising, the downstream end of the system and the surrounding communities will feel the effects of rising tide levels as time progresses. On the upstream end, heavily urbanized communities have contributed to the amount of precipitation runoff that flows into streams and rivers, quickly increasing discharge and water levels. It was concluded that the Anacostia Estuary is a river dominated system, however, with water levels rising on both ends, areas in the middle of system suffer the consequences of increased water levels from both sides. Due to the history of estuary modification, it is known that removing wetlands and marshes also removes flooding barriers, therefore also contributing towards flooding in surrounding communities. Wetland restoration has assisted in floodplain management but will never return to what it once was. Analyzing trends of water levels will allow for surrounding communities to better prepare for flooding events in the future. High water levels generated by rivers, tides and storm surges in the Anacostia River will continue to rise, emphasizing the importance in understanding the root causes, such as urbanization, channelization and sea level rise.

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Honor Pledge

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

Signed: Caerwyn Hartten