Streamflow and Tidal Dynamics in the Lower Pee Dee Basin: Hurricane Impacts

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Abstract. Over past years, extreme tropical storm events along the North and South Carolina coasts—and subsequent river flooding—have warranted the need for a better understanding of the hydrologic response to these events to protect life, property, businesses, and natural and cultural resources. Our focus in this study is the Pee Dee and Waccamaw River systems, which ultimately flow into Winyah Bay near Georgetown, South Carolina. River flows, coupled with the tidal nature of these freshwater systems, are complex and difficult to predict. The objective of the work is to analyze publicly available data from gauging stations along those river system as measured during Hurricanes Matthew and Florence and Tropical Storm Bertha—three uniquely different storm systems that produced varying rainfall depth, duration, and intensity across the Pee Dee Basin. The most important factor in tidal river analysis is the location of the stagnation point, where downstream river flow exactly balances upstream tidal flow. River flow only controls water level upstream of a tidal stagnation point, while ocean tide controls the water level downstream of a tidal stagnation point. An analysis of major flooding following Hurricanes Matthew, Florence, and Tropical Storm Bertha was used to determine the river flows associated with tidal stagnation at each stream gauge active during these storms. A major limitation of the analysis was a lack of flow data for the tidal channels in Georgetown County, which resulted in uncertainty in the flow associated with stagnation and uncertainty in the role played by each of the creeks that connect the Pee Dee and Waccamaw Rivers. Ignorance of the roles of these creeks most limited understanding of the relative importance of Pee Dee and Waccamaw flow to cause stagnation near Pawleys Island and Hagley gauges on the Waccamaw River and the Socastee gauge on the Atlantic Intracoastal Waterway.

INTRODUCTION

In a previous issue of this journal, we discussed the impact of flooding associated with Hurricane Florence on eastern Georgetown County (Williams, Hitchcock, et al. 2019). A combination of floodplain storage and tidal channel hydraulics were responsible for mitigating flooding of that storm. Observations of several homeowners along the Waccamaw River near Hagley Landing (USGS Gauge 02110815 “Waccamaw River Near Hagley Landing, Near Pawleys Island, SC”) indicated that flooding following Hurricane Matthew was higher than it was following Hurricane Florence. We confirmed the homeowners’ observations with gauge records from the Hagley Landing Gauge. The highest water level associated with Hurricane Florence was 5.23 ft (NAVD88), while the highest water level following Hurricane Matthew was slightly higher at 5.68 ft. Why did smaller flows associated with Matthew cause a

higher stage at Hagley Landing? In this paper, we will more closely examine the response of the tidal rivers to determine how tidal influences interact with differing hurricane impacts. In a companion paper, we will examine the role of forested wetlands and the unique geomorphology of the lower Pee Dee Basin in floodplain storage and flood wave attenuation.

Like many coastal counties, Georgetown County, South Carolina, is subject to flooding from three separate processes: flash flooding, riverine flooding, and tidal flooding. Flash flooding occurs when the rate of precipitation exceeds the rate water can infiltrate into the soil to an extent runoff water causes damage to life or property. The scientific principles of flash flooding have been known since Horton (1940) defined infiltration rate and capacity. Riverine flooding is related to flash flooding as runoff water accumulated in larger rivers. The scientific basis for understanding river flooding also dates to the middle of the twentieth century (Chow 1959; Langbein

and Leopold 1964; Henderson 1966), while the explanation of ocean tidal fluctuation dates to the late nineteenth and early twentieth centuries (Darwin 1901; Doodson 1921). Tidal modeling on the continental shelves and estuaries became possible with satellite altimetry data and high-speed computing (Oey et al. 2007; Geleynse et al. 2011; Kim 2013). However, the large rivers in Georgetown County are tidal freshwater rivers that require an understanding of both riverine flow and tidal dynamics, which have only recently been studied (Ensign et al. 2012).

Land-falling tropical cyclones (hurricane, typhoon, or tropical storm) differ widely in size, wind speed, and rainfall but often produce all three types of coastal flooding. The amount and intensity of rainfall from tropical systems may produce surface runoff from even forested land (Bonell 1993) and can result in extreme flash flooding, as experienced in South Carolina in 2015 (Mizzell et al. 2016). In addition to the extreme rainfall in 2015, hurricanes Matthew (2016) and Florence (2018) also generated rainfall exceeding 24" in areas of North and South Carolina (Griffin et al. 2019). In addition to flash flooding, these storms resulted in extreme river flooding. Tidal surges may also be associated with tropical cyclones. In this paper, we will focus on the role of tropical cyclones on river and tidal flooding of the Pee Dee Basin, which empties to the Atlantic Ocean through Winyah Bay in Georgetown County.

BASIN DESCRIPTION

The Pee Dee Basin extends from the eastern continental divide in north-central North Carolina ($36^{\circ}4'N$, $81^{\circ}36'W$)

to the mouth of Winyah Bay in northeastern South Carolina ($33^{\circ}1'N$, $79^{\circ}6'W$) (Figure 1). Long-term data on flow into the Winyah Bay estuary and tidal river system is measured at six USGS streamflow gauging locations (USGS "Current Water Data") that measure a combined 15,032 sq. mi. The Great Pee Dee is the largest sub-watershed, and flow is measured at the USGS Station 02131010 "Pee Dee below Pee Dee," draining 8,850 sq. mi. The Lynches River is measured at the USGS Station 02132000 "Lynches River at Effingham SC" and drains 1,030 sq. mi. The Little Pee Dee River, including the Lumber River basin in North Carolina, is measured at the USGS Station 02135000 "Little Pee Dee River at Galivants Ferry, SC" and drains 2,790 sq. mi. The Waccamaw River is measured at Station 02110500 "Waccamaw River Near Longs, SC" and drains 1,110 sq. mi. The Black River is measured at Station 02136000 "Black River at Kingstree, SC" and drains 1,252 sq. mi. Since 2007, flow has also been measured on the Waccamaw at Station 02110704 "Waccamaw River at Conway Marina at Conway, SC" and Station 02135200 "Pee Dee River at Hwy 701 Near Bucksport, SC." These last two gauges are in the tidal sections of each river and add an additional 508 sq. mi. of measured watershed, with 02110704 measuring 1,440 sq. mi. and 02135200 measuring 14,100 sq. mi. Finally, in 2017, Station 02136030 "Black River near Andrews, SC" was added with a drainage area of 1,560 sq. mi. This station measures stage; flow is also measured, but only when the station does not have tidal fluctuation. In addition to these, several other gauges, some short-term and stage only, were used for this and the companion paper. They are listed in Table 1 and are shown in Figure 2.

Figure 1. Location of the Pee Dee Basin in counties of North and South Carolina, showing locations of hurricane tracks and position of long-term stream gauges (blue dots): (left to right) Black, Lynches, Great Pee Dee, Little Pee Dee, Waccamaw Rivers.

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Table 1. Summary of gauge locations used in this paper. Gauge numbers 3–10 are part of the Pee Dee system, numbers 11–16 are on the Waccamaw River system, and numbers 19–22 are on the Black River system with numbers increasing downstream. The Atlantic Intracoastal Waterway (AIWW) connects the Waccamaw River near Bucksport at Socastee, South Carolina (17) to the ocean through Little River (18).

USGS number	Shortened USGS location name	Datum adjustment (ft)	Gauge number shown in Figure 2	Data types
				Long term > 50 years Medium < 20 years Short < 10 years Temporary < 1 year
02131000	At Pee Dee	23.54	3	Stage, Flow, long-term
02131010	Below Pee Dee	14.29	4	Stage, Flow, long-term
335413079261000	Pee Dee at Hwy 378	0	5	Stage, temporary
02132000	Lynches Effingham	58.49	6	Stage, Flow, long-term
02135000	Little Pee Dee	23.95	7	Stage, Flow, long-term
335025079265600	Lynches Johnsonville	0	8	Stage, Temporary
02135200	Bucksport Pee Dee	−8.92	9	Stage, Flow, Tidal flow, medium term
02136350	Georgetown	0	10	Stage, short-term
02110500	Longs Waccamaw	5.28	11	Stage, Flow, long-term
02110550	Above Conway	0	12	Stage, Flow, Tidal flow, medium term
0211070	Conway	−5.06	13	Stage, Flow, Tidal flow, medium term
02110802	Bucksport Waccamaw	−14.36	14	Stage, medium term
021108125	Pawleys	0**	15	Stage, medium term
02110815	Hagley	−15.15*	16	Stage, Medium term
02110715	AIWW Socastee	0	17	Stage, Medium term
02110777	AIWW Little River	−11.72	18	Stage, Medium term
02136000	Black, Kingstree	24.66	19	Stage, Flow, long-term
02136030	Black, Andrews	−17.23	20	Stage, Flow, short-term
333250079240400	Black, Browns Ferry	0	21	Stage, Temporary
SCGE025843	Black, Plantersville	0	22	Stage, Temporary

*Adjustment is questionable; tide levels suggest number may be −15.43.

**Data for Matthew and Florence corrected by −4.5 ft.

Table 2. Distribution of peak flow (cubic feet per second, cfs) values with date of storm and dates of peaks, among sub-watersheds of the Pee Dee Basin following Hurricane Matthew (10/8/2016), Hurricane Florence (9/18/2018), and Tropical Storm Bertha (5/27/2020).

Storm	Matthew Date 10/8		Florence Date 9/18		T.S Bertha Date 5/27		Annual average flow
	Peak	Date	Peak	Date	Peak	Date	
Black River at Kingstree 02136000 (19)	20,600	10/10	9,100	9/19	16,300	5/31	935
Lynches River at Effingham 02132000 (6)	9,670	10/10	8,630	9/22	10,200	6/2	996
Great Pee Dee River Below Pee Dee 02131010 (4)	32,000	10/13	139,000	9/21	75,200	5/27	7,927
Little Pee Dee River at Galivants Ferry 02135000 (7)	59,100	10/12	64,500	9/21	15,700	6/2	2,962
Waccamaw River at Conway 02110500 (13)	22,400	10/18	49,000	9/26	11,700	6/8	2,180
Pee Dee River at Bucksport 02135200 (9)	129,000	10/16	137,000	9/26	102,000	6/5	9,934

Figure 2. USGS map of gauge locations (gray circles with black centered triangle) used in this paper. Gauge numbers refer to descriptions listed in Table 1. Ocean tide gauges are blue circles; Oyster Creek is on the inset due to scale limitation.

TROPICAL CYCLONE DESCRIPTIONS

In this paper we will focus on three tropical cyclones that produced large flooding events (Figure 1). These three storms (Hurricanes Matthew and Florence and Tropical Storm Bertha) were chosen for analysis because they each produced large peak flows ($> 100,000$ cfs) within the Winyah Bay estuary/tidal river system (Table 2). These three storms also resulted in differing flows in the five tributary river systems.

The track of Hurricane Matthew (October 6–8, 2016) paralleled the coast of South Carolina, briefly coming onshore near McClellanville, moved back over the ocean near Winyah Bay, and then traveled northeastward before dissipating over the Atlantic (Stewart 2016). Rainfall from Matthew resulted in up to 24" of rain in a band along the lower coastal plains of North and South Carolina (Griffin et al. 2019). Hurricane Matthew followed the remnants of Hurricane Hermine (August 27–September 8) and Tropical Storm Julia (September 13–18), which both produced rainfall in the Pee Dee Basin. Total rainfall for September 2016 in the Pee Dee Basin peaked over 27" in North Myrtle Beach, South Carolina, and Plymouth, North Carolina.

Although Hurricane Florence (Stewart and Berg 2018) had weakened to a Category 2 storm before it reached Wrightsville Beach of North Carolina, its slow progress and meandering track (Figure 1) resulted in historic rainfall and flooding in the Pee Dee Basin (Griffin et al. 2019, Williams,

Hitchcock, et al. 2019). Hurricane Florence produced heavy rainfall throughout the entire Pee Dee Basin and resulted in large or record flows in all tributaries except the Black River (Table 1).

Tropical Storm Bertha (May 27–28, 2020) was a minimal storm that formed off Charleston, South Carolina, moved onshore near McClellanville, was downgraded to a tropical depression east of Columbia, and became extratropical in North Carolina as it moved northerward to the Great Lakes (Figure 1). Despite being a minimal tropical cyclone, it resulted in a large flood on the Great Pee Dee, and on the Lynches it produced the greatest peak flow of all three storms (Table 2). Flooding with Bertha was exaggerated by heavy rainfall earlier in May in the Great Pee Dee Basin (NOAA "Advanced hydrologic prediction service").

Each of these tropical cyclones provides a unique example of the types of impacts that might be expected in the Pee Dee Basin. Hurricane Matthew followed a very common track by moving generally parallel to the coast; for comparison, Hurricanes Irma (2017) and Dorian (2019) followed similar paths. This track resulted in the heaviest rainfall and greatest flow in the Waccamaw and Little Pee Dee Rivers. Tropical Storm Bertha landfall was near Bulls Bay, South Carolina (Figure 1), and it then traveled north, passing west of the Pee Dee Basin, with the greatest rain and flow in the Great Pee Dee, Lynches, and Black River Basins. The unusual track

of Hurricane Florence and the slow movement of the storm resulted in major or record flooding in all tributaries except the Black and Lynches Rivers (Table 2).

TIDAL RIVER CHARACTERISTICS

In the mid-eighteenth century, Bernoulli and Euler first described how movement of water can be described by a series of differential equations of conservation of mass, energy, and momentum, often called the Euler equation (Anderson 2016). Deep water waves transfer momentum with no change in mass and minimal loss of energy and are often called Kelvin waves; Lord Kelvin combined planetary motion, Newton's theories of gravitation, and the Euler equation to describe tides on a spherical planet covered in deep water. Those equations were soon modified to explain the distribution of tides on the oceans of the earth (Darwin 1901) and the oceans used by the British Navy (Doodson 1921). As the tide moves across the shallower water of the continental shelves, the wave loses energy through bottom friction and requires solutions of both the transfer of momentum and the loss of energy. The assumptions needed for analytic solutions of deep water were not met and numerical approximations, using high-speed computers, were needed to explain tidal motion onto the continental shelves (Blumberg and Mellor 1987). As the tide moves into a narrow bay or estuary, one must also account for the change in the mass of water, requiring solutions of equations for changes in momentum, energy, and mass simultaneously. Solutions to such problems can only be approximated by more complicated numerical models (Oey et al. 2007; Geleynse et al. 2011; Kim 2013),

which must be parameterized uniquely for each specific bay or estuary.

In order to make more general predictions, Savenije (1992, 2001) utilized Langbein's (1963) empirical findings; estuary width, and cross-sectional-area declined exponentially with distance from the ocean. He made the assumption that estuaries were "funnel-shaped" and developed equations of tidal flow within the estuary, which could be solved analytically. Savenije (2015) applied his equations to several real estuaries to argue that his analytic solutions could be used in real world situations.

Unidirectional flow in open channels can be generally described by assuming no change in water mass or momentum and a uniform loss of energy associated with bottom friction; for example, with Manning's equation (Henderson 1966). Momentum is generally assumed constant except in a detailed analysis where rapid acceleration of flow occurs, such as scour around bridge piers, erosion and deposition around meanders, or where tributaries join a river at a large angle. These assumptions cannot be made where the river is influenced by a downstream tide; as tidal momentum decelerates flow during rising tides (Ensign et al. 2015).

Previous work can be summarized in Figure 3. As the ocean rises, a wave propagates into the estuary and the volume of water in the estuary increases as the face of the wave moves upstream. The increase of volume, often called the tidal prism because it decreases in both width and depth upstream, must be filled by water entering the estuary. The momentum carried by the rising tide causes three reactions. At the estuary mouth, it accelerates ocean water into the

Figure 3. Schematic of a tide in an estuary. The upper left represents the stage and velocity of the tide for an entire cycle at the ocean end of the estuary. Water levels are represented at three times of rising tide in the top, upper right; the side, lower right; and the end, lower left views. The term ωt indicates a repeating time series equal to the tidal wavelength.

estuary (Q_o in Figure 3). It also decelerates and halts the downstream flow of the previous falling tide. Finally, some momentum is dissipated into the estuary bottom and sides. Savenije's (2015) equations describe these processes sufficiently closely so they can be used to understand tides in many alluvial estuaries. While the tide is rising, the river is also flowing into the upstream end of the estuary (Q_r Figure 3). Horrevoets et al. (2004) examined how Q_o and Q_r interact during a tidal cycle.

Conceptually, the interaction of Q_o and Q_r is quite simple, although the mathematical description and numerical modeling are complex. Q_o is controlled by the momentum of the tide, which is determined by the tidal range in the ocean and the geometry of the estuary. During the rising tide, ocean momentum creates an upstream velocity and results in upstream flow Q_o . Estuary geometry and friction determine the energy loss as the tide flows into the estuary. Above the estuary, flow of large rivers, Q_r , will change little during a single tidal cycle, and river momentum can be considered constant. For each tide, upstream and downstream momentum become equal at some point in the estuary or the tidal river. At that point there will be no flow, and the water-surface elevation will be minimum and level. This is called the point of stagnation since flow halts there. The point of stagnation is vital to understanding and predicting flooding of a tidal river. The maximum water level downstream of the stagnation point is controlled entirely by the ocean tide, so traditional river-flood modeling will be erroneous there. Likewise, the maximum water level above the stagnation point is determined by river flow.

Knowing the position of the stagnation point is vital to understanding and predicting water levels in tidal rivers. Although stagnation occurs at a specific location for a single tide and river flow, it is spatially variable, being controlled by a variation of both the tidal range and the quantity of river flow. A large tidal range will result in a stagnation point farther upstream, while greater river flow will result in a stagnation point farther downstream. Alternatively, at a particular point in the river, stagnation can be associated with a particular river flow and tidal range. This alternative view of stagnation can be used to understand the factors important to flooding at points along the river/estuary.

The goal of this paper is to describe the flooding within the tidal sections of the Waccamaw, Pee Dee, and Black Rivers in relation to the ocean tide level and varying freshwater inputs. We used publicly available data to estimate the position of the point of stagnation within the tidal river system in relation to river flow rates and tidal stage. From estimates of the position of the stagnation point, we can

estimate regions where flooding is more likely caused by tidal height or when river flooding will be more important.

METHODS

Collection of data for all three tropical cyclones was as described in (Williams, Hitchcock, et al. 2019). Data were collected from all available USGS Gauges (USGS "Current Water Data") and NOAA tide gauges (NOAA "Water levels-Station selection") at Oyster Creek (8662245) and Springmaid Pier (8661070). All gauge locations are depicted in Figure 2 and summarized in Table 1. Data were collected for a 30-day period that included each storm: Bertha (May 20–June 20, 2020), Florence (September 10–October 10, 2018), and Matthew (September 25–November 5, 2016). Data collection for Hurricane Matthew was extended to include the end of the hydrograph of the Little Pee Dee River. Stage elevations were converted to the NAVD88 datum for all gauge data not already in that datum. Adjustments are listed in Table 1 and were calculated as described in Williams, Hitchcock, et al. (2019). Likewise, flow records were downloaded for each station where flow data were collected.

Data analysis consisted of assembling all stage data into a single sheet, assembling flow data, resampling at 30-minute intervals for Hurricanes Matthew and Florence, and resampling all USGS data to 1-hour intervals. Since NOAA tide data was recorded in either 6-minute or hourly intervals, depending on the station, data comparisons required using hourly flow data for comparisons to tide height. Stage data for an entire 30-day period from all stations were graphed and tidal signatures were inspected to estimate river flows that were associated with the stagnation at that point. Gauges that record tidally corrected flow and bidirectional velocity (Table 1: 9, 12, 13) allow direct measurement of flow associated with the cessation of bidirectional flow, indicating stagnation at the gauge site. At each of these gauges, the average daily flow that corresponded to stagnation could be determined.

The gauges at Conway (12) and Above Conway (13) provided the opportunity to test the theoretical concept of a minimum water level at the point of stagnation. For each rising tide, the water-surface slope will decrease in the upstream direction (we defined downstream as toward the ocean), downstream of the point of stagnation. Likewise, upstream of the point of stagnation, flow will always be downstream and the water-surface slope, although fluctuating with the tide, will always be directed downstream. Along the Waccamaw River, we used gauges at Longs (11), Above Conway (12), Conway (13), and Bucksport (14) to examine the water-surface slope during the tidal cycle when

the stagnation point was near the Above Conway (12) and Conway (13) gauge locations. We found that flow stagnation did occur on the same cycle as when the water-level slope to the next downstream gauge remained positive (positive defined as toward the ocean) throughout the tidal cycle.

Tidal stage elevation graphs were then examined for the other tidal, stage-only stations to estimate flows associated with stagnation at those locations within the Waccamaw and Black Rivers and the Atlantic Intracoastal Waterway (AIWW). The Pee Dee River near Bucksport (9) was the only gauge on the tidal Pee Dee system. The gauges at Pawleys (15), Hagley (16), and Georgetown (10) receive flow from both Pee Dee and Waccamaw Rivers. The Black River was not included in the evaluation of the Bay. The Andrews gauge (19) has only been active since 2017 and the two temporary gauges (20, 21) were only active during Florence. Flow of the Black River during both Hurricane Florence and Tropical Storm Bertha was less than 5% of the flow into the bay.

Since water-surface slope was used to estimate the presence of tidal stagnation, it was critical that the datum estimate was consistent between gauges. The converted stage at Hagley (16) showed consistently higher elevations than Georgetown (10) and Pawley (15), which both had NAVD88 data published by USGS. Since elevations at Hagley were higher for both high and low tides, we suspected that the -15.15-ft correction (Williams, Hitchcock, et al. 2019) applied to the Hagley gauge was incorrect. We altered the datum for the Hagley gauge by linear interpolation of the NAVD88 elevations of the Georgetown (10) and Pawleys (16), based on the length of the river between the three gauges. Stage data for all three gauges were examined over 38 tidal cycles, from 7 days of low flow prior to Tropical Storm Bertha and 12 days prior to Hurricane Florence. A predicted average height at Hagley was interpolated based on Hagley (16) being 5.1 miles from Pawleys (15) and 7.1 miles from Georgetown (10). That predicted average elevation at Hagley (16) was compared to the measured average elevation for the same period. The difference between predicted and actual means was 0.38 ft and a correction of -15.53 ft was used to correct to the NAVD88 datum.

RESULTS

STAGNATION AT MEASURED GAUGE LOCATIONS

On the Waccamaw River, five gauges recorded stage from Longs (11) to Bucksport (14). The gauges at Conway (13) and Above Conway (12) recorded stage, discharge, velocity, and tidally corrected discharge. Low initial flow before Hurricane Florence provided the opportunity to estimate stagnation at both stations, while Tropical Storm Bertha allowed an estimation at Conway (Table 3). From September 10 to 12, 2018, the point of stagnation is upstream of the Above Conway gauge (Figure 4). During these days, river flow

generally averages 116–118 cfs. On September 13, average flow increased to 132 cfs, and for the next three tides, it showed near-stagnation at this gauge, while on September 14, flow became unidirectional, with a daily average flow of 332 cfs. Thus, we can determine that the point of stagnation is at the Above Conway gauge with a flow in the Waccamaw River of about 140 cfs. By inspecting the flow records of the Conway (13) gauge and the Bucksport gauge on the Pee Dee (9), we determined stagnation for those points (Table 4).

STAGNATION AT STAGE-ONLY GAUGES

Only the three tidal gauges listed above have flow records where the stagnation point can be directly estimated. However, water-surface slope can be calculated from stage values along the river channel. Figure 5 shows the water-surface elevation for Conway and Above Conway for September 12–15, 2018, to correspond with the period when the stagnation point was located near the Above Conway gauge, shown in Figure 4. In Figure 5, there is a clear upstream gradient from Conway on September 12 and 13, while it disappears completely on the second tide of September 14. These data confirmed the idea that one can estimate the flow corresponding to stagnation at gauges with only stage data. Two conditions are necessary: a downstream gauge must have stage data for the same period as the gauge considered, and there must be an upstream gauge where flow has been measured during the period considered.

Those conditions were present to estimate flow associated with stagnation for many gauges that measured only stage (Table 4). The exceptions were as follows. On the Black River there is little data. The gauge at Andrews does not measure flow below a stage of 20 ft (about 2.77 ft NAVD88), which is a flow of about 100 cfs. The two gauges below Andrews were only active after Hurricane Florence and the Black River could only be estimated for those two during Hurricane Florence. Likewise, the gauge at Georgetown (10) was not active during Hurricane Matthew. The gauges at Pawleys (15), Bucksport Waccamaw (14), and AIWW at Socastee (17) are near the point where Bull Creek first connects the Pee Dee and Waccamaw Rivers. Bucksport Waccamaw (14) and AIWW Socastee (17) are upstream of the junction with Bull Creek (Figure 2). This arrangement of channels complicates the estimate of upstream contribution from the Waccamaw and Pee Dee Rivers. The stagnation point moved below Bucksport Waccamaw (14) with flows of 6,300–9,700 cfs in the Waccamaw River. At low flow, the AIWW shows a high tide associated with Little River (18) about an hour before and slightly above the high tide associated with Winyah Bay. It seems that the stagnation points at AIWW Socastee (17) and Pawleys (15) do not occur until there are large flows in the Pee Dee River. The flows of both rivers are presented in Table 4, as we cannot know how much water flows in Bull Creek. It does seem that the Pee Dee flow may be dominant since stagnation occurs with Pee Dee flows of roughly 40,000

Table 3. Distribution of initial flow (cubic feet per second, cfs) values among sub-watersheds of the Pee Dee Basin prior to Hurricane Matthew (9/25/2016), Hurricane Florence (9/10/2018), and Tropical Storm Bertha (5/20/2020).

Storm	Black River at Kingstree 02136000	Lynches River at Effingham 02132000	Great Pee Dee River Below Pee Dee 02131010	Little Pee Dee River at Galivants Ferry 02135000	Waccamaw River at Conway 02110500	Pee Dee at Bucksport 02135200
Matthew	999	775	4160	2090	3840	10100
Florence	57	72	4190	277	50	4440
TS Berth	140	822	6920	2070	368	11000

Figure 4. Flow in the Waccamaw River at Above Conway (gauge 12 in Figure 2) for September 9–14, 2018, prior to Hurricane Florence. Negative values represent upstream flow.

Figure 5. River stage elevations for September 12–15, 2018, associated with the tidal flows presented in Figure 4. Green shading indicates periods when the gradient was upstream, from Conway to Above Conway. These correspond to the periods of upstream flow at the Above Conway Gauge.

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Table 4. Estimated flow (cfs) when the stagnation points corresponded to each gauge location. Mean daily flows were measured at the gauge location or at the nearest upstream gauge. For the Pawleys (15) and AIWW Socastee (17) gauges, upstream flow of both Pee Dee (PD) and Waccamaw (W) are listed separately, as an unknown portion of Pee Dee flow contributes to the Waccamaw River near these gauges. Sites are listed by river from upstream to downstream (Figure 2).

Gauge	Florence		Matthew		Bertha	
Above Conway (12)*	140		< 3000		< 340	
Conway (13)*	610		<3500		600	
Bucksport Waccamaw (14)	6640		9340		6280	
AIWW Socastee (17)	PD 39441	W 21203	PD 47900	W 5970	PD 46600	W 2870
Pawleys (15)	PD 102,900	W 40,600	PD 87,200	W 18,500	PD 88,300	W 6,950
Hagley (16)	170800		143,500		106800	
Georgetown (10)	>185800		ND		109400	
Black River Andrews (20)#	100		ND		100	
Black River Browns Ferry (21)	2900		ND		ND	
Black River Plantersville (22)	3100		ND		ND	
Bucksport Pee Dee (9)*	4088		<10100		<11000	

Sites are listed by river system from upstream to downstream.

*Flow measured at these gauges.

USGS does not measure tidally influenced flows below gauge reading of 20 ft (2.7 ft NAVD88) that corresponds to a flow of about 100 cfs.

ND = no data.

Figure 6. Water levels in the Winyah Bay estuary/tidal river system during the storm surge caused by Hurricane Matthew on October 10, 2016.

cfs at AIWW Socastee (17) and 90,000–100,000 cfs at Pawleys (15), regardless of the flow in the Waccamaw (Table 4).

STORM SURGE

Since the point of stagnation marks the limit of upstream flow at high tide, it should also mark the extent of a tidal surge. Only one of the analyzed storms produced a substantial tidal surge. Hurricane Florence was north and east of Winyah

Bay, resulting in a lowering of tide level, and Tropical Storm Bertha winds were too weak to have more than a minimal impact on tide level. However, Hurricane Matthew produced a peak tide level at Oyster Creek of 7.11 ft versus a predicted level of 1.6 ft (NOAA Tides and Currents “Water levels—station selection”). The tidal surge is depicted in Figure 6, showing hourly water levels at each of the active gauges in the Waccamaw and Pee Dee Rivers. The peak elevation

decreases from 7.11 to 4.9 ft at Bucksport Waccamaw (14). There is no observable surge peak at Conway (13) and very minor, < 0.1 ft, at Bucksport Pee Dee (9). Average daily flow of Waccamaw and Pee Dee was 5,300 cfs. Note that the Waccamaw flow was less than the estimated stagnation flow of the gauge at Bucksport Waccamaw (14), while the Pee Dee flow was slightly more than the stagnation flow estimated at Bucksport Pee Dee (9).

DISCUSSION

The stagnation point could be estimated precisely and repeatably at gauges where bidirectional flow was measured. In an earlier paper (Williams, Amatya, et al. 2019), the Pee Dee River at Bucksport (9) was analyzed to determine flows at stagnation and when tidal fluctuation ceased. During that analysis, the stagnation point occurred there with a tidally corrected average flow of 4,290 cfs (measured in July 2016). The stagnation for Hurricane Florence at this gauge occurred with an average daily flow of 4,088 cfs (Table 4), remarkably close to the previous estimate. The gauge at Conway (13) showed stagnation during Hurricane Florence and Tropical Storm Bertha. The values of stagnation also agreed very well at that gauge, both rounding to 600 cfs. Although those storms varied, with very different maximum flow rates in the Waccamaw River, stagnation occurred at Conway when flow reached about 600 cfs following both storms.

Locating stagnation point by examining water-surface slope downstream of a gauge is not as reliable, but it did show similar trends of the stagnation point moving downstream with increased river flows. There was considerable variation at the Hagley (16) and Georgetown (10) gauges. Hoitink and Jay (2016) state water levels near the “head of the tide” will be higher during periods of lower tidal range. Since the Springmaid Pier tide gauge was damaged during Hurricane Matthew, comparisons have been made using the Oyster Creek gauge. At that gauge, tidal ranges were 5.96 ft, 3.29 ft, and 5.29 ft for Matthew, Florence, and Bertha, respectively. While it may seem that the low tidal range during Florence may be responsible for the stagnation being associated with higher river flows, a comparison of the range at Springmaid Pier for Florence (5.49 ft) and Bertha (5.30 ft) does not show the lower range during Florence. The Oyster Creek gauge is at the rear of the North Inlet Marsh system, 2.8 miles from the ocean, and may not always reflect the ocean tides. During the four tides when the Florence stagnation points were estimated, average high tides were identical between Oyster Creek and Springmaid Pier at 3.07 ft. The average low tides were about 2 ft different, -0.22 ft at Oyster Creek and -2.23 ft at Springmaid Pier. It appears that we cannot evaluate any influence in the effect of the ocean tide due to the large errors associated with estimating the stagnation point based solely on the downstream slope.

Downstream water-level slope determines the rate of unidirectional flow, yet in the bidirectional flow of the tidal channel, momentum must also be considered (Ensign et al. 2015). The role of momentum can be clearly seen in the relationship of downstream slope to water flow from the May 20 Conway Gauge (13) records prior to Tropical Storm Bertha (Figure 7).

The water level of the Waccamaw River at Conway (the green line) had a mean height of 2 feet, a semidiurnal tide with a range of roughly 6 inches and a period of 12 hours and 30 minutes. If we look at the slope or the difference in water-level elevation (orange line) between Conway (13) and Bucksport (14), across 17.7 river miles, it varies from -0.4 to 1.4 ft, or slopes of -0.42 ft and +1.5 ft / 10,000 ft. Upstream flow peaked at 230 cfs at 0000 hours and 175 cfs at 1330 hours. Downstream flow peaked at 1,030 cfs at 0945 hours and 1,130 cfs at 2015 hours. The role of momentum is very clear in that peak flow occurs roughly 2.5 hours after the greatest slope, and the slope is negative for nearly 3 hours before the upstream flow begins. It is likely that much of the variation in Table 4 is due to the error associated with estimating flow in a tidal river considering only water-surface slopes. However, for most of the tidal rivers in Georgetown County, stage elevations are all that has been recorded. Although the quantities are approximate, a relatively clear estimation can be made on river flows associated with flow stagnation at those points within the tidal channels of the Winyah Bay system (Figure 8).

The Winyah Bay estuary/tidal river system is highly complex (Figure 9), but a central tidal flow can be traced up the Waccamaw River to just upstream of the Above Conway gauge (12). The height of the tide only controls water elevation of this gauge if the river flow is less than about 140 cfs. Downstream at Conway (13), the tidal channel is larger and will control the water level up to a river flow of about 600 cfs. Flow was not measured below Conway (13), and flow at stagnation can only be estimated from the flow at the Conway (13) gauge. For Bucksport Waccamaw (14), there are two values in the 6,500–7,000 cfs range and one near 10,000 cfs.

The tidal system becomes complex downstream from the Bucksport Waccamaw (14) gauge (Figure 9). Between Bucksport Pee Dee (9) and Georgetown (10), the Pee Dee River connects to the Waccamaw in four significant channels (Figure 9). There is a direct channel to the upper end of Winyah Bay at Georgetown (42.8 miles), a channel through Schooner Creek to the Waccamaw River (38.2 miles), a channel in Thoroughfare Creek to the Waccamaw River (38.8 miles), and a final channel through Bull Creek (49.2 miles). Bull Creek joins the Waccamaw River between the Bucksport Waccamaw (14) and Pawleys (15) gauges, while the other creeks join the Waccamaw River between Hagley (17) and Pawleys (15). Examination of Hurricane Florence

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Figure 7. Relationships of water surface, flow, and downstream water-surface elevation change (head difference). Water-surface slope to the Bucksport gauge = 1.07×10^{-5} for ` ft of head difference. Note the scale for head difference and Conway water level (orange) is offset from the scale for flow (blue). Positive numbers indicate downstream flow and water-surface slope, as opposed to the velocity sign in Figure 3.

Figure 8. Section of map shown in Figure 2 with gauge numbers and approximate flow at stagnation for the tidal rivers of the Winyah Bay estuary/tidal river system. Values near each gauge represent measured flow (9, 12, 13) or our approximation of the river flow that causes tidal stagnation at that point. Values at Socastee (17) and Pawleys (15) are less reliable due to a difficulty in partitioning the flow of the Pee Dee River through Bull Creek.

Figure 9. Distribution of channels connecting Pee Dee River to Waccamaw River. Blue lines were added, as streams in the images used in the Google Earth view varied from black to grey-brown. The blue coloration was carefully applied to cover only the water surface in the high-resolution image to represent the true width of each channel.

Table 5. Water-surface gradients when tidal stagnation occurred at AIWW Socastee and Pawleys following Hurricane Florence, Hurricane Matthew, and Tropical Storm Bertha. All elevations are NAVD88.

Flow at Buckspport Pee Dee (9)	Station	Florence Stage (ft)	Matthew Stage (ft)	Bertha Stage (ft)
40,000 cfs	Buckspport PD (9)	7.80	7.95	7.80
	Buckspport W (14)	4.24	4.25	3.08
	AIWW Socastee (17)	3.44	4.09	2.71
	Pawleys (15)	3.44*	3.69*	3.52*
95,000 cfs	Buckspport PD (9)	12.5	11.98	11.86
	Buckspport W (14)	7.22	6.14	5.86
	AIWW Socastee (17)	6.72	5.67	5.42
	Pawleys (15)	3.88	4.42	3.48

(Williams, Hitchcock, et al. 2019) showed that, at low flow, Buckspport Pee Dee (9) and Buckspport Waccamaw (14) have nearly identical tidal signatures and are almost the same distance from the ocean. Buckspport Waccamaw (14) is 39.4 river miles from the ocean, similar to the distance via either Schooner or Thoroughfare Creeks. Apparently, these two creeks are the primary tidal channels connecting the Pee Dee River to Winyah Bay.

The flow associated with stagnation at both Pawleys (15) and the AIWW Socastee (17) suggest that Bull Creek influences the height of the Waccamaw when the Pee Dee flow exceeds 40,000–50,000 cfs to create a stagnation point at Socastee on the AIWW, and a Pee Dee flow of 85,000–100,000 cfs produces a stagnation point at Pawleys (15). Flow in the Waccamaw was highly variable when these gauges showed

stagnation, suggesting some compensation of Waccamaw and Bull Creek flows when stagnation occurred at Socastee (17) or Pawleys (15).

It seems, if the Waccamaw stagnation point is located downstream of the junction with Bull Creek, then the water level is determined by the flow of the Waccamaw and Bull Creek. With a flow of about 40,000 cfs at Buckspport Pee Dee (9), flow in Bull Creek raised the water level to produce a stagnation point in the AIWW near Socastee with Waccamaw flows of 3,000–20,000 cfs. A similar situation may also occur at Pawleys (15) when the flow at Buckspport Pee Dee (9) reaches 90,000 cfs. Inspection of the flow and stage records of those stations tends to confirm that hypothesis (Table 5). At 40,000 cfs there is a clear gradient to AIWW Socastee (17), and at 95,000 cfs there is clear gradient to both AIWW

Socastee (17) and Pawleys (15). It seems that flow in the Waccamaw tends to divert more flow toward Pawleys (15), but it has less impact on water level.

CONCLUSIONS

The point of tidal stagnation determines whether the water level is controlled by the height of the tide or river discharge. We estimated a tidal stagnation point associated with flows in the Waccamaw, Pee Dee, and Black Rivers. The flow associated with a stagnation point increased from 100 cfs to over 100,000 cfs along the Waccamaw River. We also found that water-surface elevation of a tidal surge was limited to the portion of the river below the stagnation point. That conclusion was based on only one occurrence of tidal surge during Hurricane Matthew.

The determination of a stagnation point at gauges where flow was not recorded showed larger variability, as tidal flow is a function of both water-surface slope and the momentum of the flow (the latter of which may not be reflected by water-surface slope). Estimating the stagnation condition was only available at one point in the Pee Dee system and the distribution of flow in the channels connecting the Pee Dee to the Waccamaw was unknown. Data from AIWW Socastee (17) and Pawleys (14) suggest that the distribution of flow in these creeks may change dramatically between low and high flow of the Pee Dee.

Why was the water level near Hagley Landing higher after Hurricane Matthew than after Hurricane Florence? The main reason appears to be a variation of the point of stagnation near the Hagley gauge due to differing tidal range occurring in each storm. That conclusion is somewhat limited, since Hurricane Matthew damaged the tide gauge with the most accurate estimation of the ocean height, and there was no gauge at Georgetown (10) during that storm. Therefore, the estimation of the stagnation point at Hagley Landing was less reliable during Hurricane Matthew.

The major finding of this paper is that the capacity the tidal channel varies over five orders of magnitude between the nontidal river and the upper end of the estuary. Only very large floods can influence the water level of the river where these large tidal flows are present. Understanding the role of tidal flows and the variation in the point of stagnation where river flow is balanced by tidal flow will be critical to proper modeling of the flooding potential in such systems.

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