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Geomorphic impacts of Hurricane Florence on the lower Neuse River: Portents and particulars

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ABSTRACT

In September 2018 Hurricane Florence had severe impacts on the lower Neuse River and Neuse estuary, North Carolina, despite the fact that it was a minor storm in terms of traditional indicators of storm intensity. The storm was consistent with recent trends and predictions of tropical cyclone activity driven by Anthropocene climate warming. However, its impacts in the Neuse area were also conditioned by idiosyncratic aspects of the geographic setting and the synoptic situation. Geomorphic changes examined here include erosion of estuarine shoreline bluffs, geomorphic transformations of small freshwater swamps, and effects on the river and floodplain upstream of the estuary. The shoreline changes caused by Florence were unique with respect to previous tropical cyclones and ongoing episodic erosion, due to the extraordinarily high and unusually long duration of storm surge. Transformations of the "ravine swamps"—mainly associated with deposition of >0.6 m of sand on organic muck and open water surfaces—were similarly unprecedented. Despite high river discharges (third highest on record) and the high storm surge, fluvial impacts in the lower river and fluvial-estuarine transition zone were minimal. This is attributable to the morphology of the channel-floodplain system, adapted to Holocene sea-level rise and preserved by wetlands protection programs. The large area of the storm, slow forward movement, and extreme rainfall of Florence are likely indicative of a "new normal" with respect to tropical cyclones in the region. However, the geomorphic impacts in the lower Neuse were largely determined by particulars of the Neuse estuary and Florence's storm track. An exception is the limited impacts on the lower fluvial portion of the river and the fluvial-estuarine transition zone, where there exists a complex mosaic of channels and flowing wetlands capable of accommodating extreme discharges.

1. Introduction

The steady accumulation of heat in the ocean and general warming of the atmosphere in the Anthropocene has created a climate conducive to stronger and more numerous tropical cyclones. Studies of the impacts of tropical cyclones on land have focused on the effects of high winds, wave attack, and coastal storm surges. Additionally, evidence exists that these storms are moving more slowly and expanding their areal coverage as they make landfall. This can result in extensive precipitation and extreme stream flows in the lower portions of river basins, high and long-lasting storm surges in estuaries well inland from the ocean, and exposure to winds of >11 m s^{-1} (25 mph) for extended periods. These extraordinary rainfall-producing tropical cyclones may represent a "new normal" in the era of Anthropogenic warming (e.g., Easterling et al., 2017; Kunkel and Champion, 2019; Paerl et al., 2019). This study examines the geomorphic impacts of one such storm (Hurricane Florence, 2018) on the lower Neuse River and estuary in North Carolina in this context. Specifically, the goal is to ascertain to what extent the geomorphic impacts are more-or-less typical of those associated with previous tropical cyclones, those that are primarily associated with larger, slower moving storms (and thus potentially portents of future storm impacts), and those that are controlled mainly by the geographical contingencies of the lower Neuse area and the synoptics of Florence.

The paper starts by discussing several slow-moving, extensive storms that affected the Carolinas in 2015–2019 and the apparent role of recent global warming in determining their characteristics and behavior. The general hydrologic and geomorphic impacts of these tropical cyclones are described and compared and contrasted with the typical impacts of previous tropical cyclones in the region. Specific examples from Hurricane Florence (2018) in the Neuse River and estuary of North Carolina are then analyzed. These impacts are then examined in terms of their relationships to geographical contingencies of the lower Neuse, specific characteristics of Florence, and the effects of larger, slower storms.

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2. The storms of 2015–2019

2.1. Hurricanes Matthew and Florence

The largest floods ever recorded in many locations in eastern North and South Carolina (Fig. 1) occurred in conjunction with Hurricanes Florence in 2018, Matthew in 2016, and Floyd in 1999, and a tropical cyclone-influenced October 2015 storm. In northeastern SC and eastern NC, at many locations the three hurricanes represent, in one order or another, the three largest floods and/or precipitation totals ever recorded. Note that the focus here is on their effects in the Carolinas, and on geomorphic impacts. Both storms had severe impacts on humans and their property and infrastructure, as well as on ecological systems and water quality. Matthew did its worst damage in the Caribbean (especially Haiti), while Florence mainly affected the Carolinas.

Matthew and Florence were not particularly powerful storms in many respects when they reached the Carolinas. Matthew's landfall on 8 October 2016 near McClellanville, SC was the first October hurricane since Hazel in 1954 to make landfall north of Florida—it was Matthew's fourth landfall, having previously come ashore in Haiti, Cuba, and the Bahamas. According to the National Hurricane Center's (NHC) report (Stewart, 2017), the northwest edge of the large eyewall extended well inland and brought hurricane-force wind gusts and heavy rains to coastal regions of the Carolinas. As Matthew moved ENE to the south of eastern NC early on 9 October, a combination of the cyclone undergoing extratropical transition and an increasing pressure gradient from an approaching cold front caused sustained hurricane-force winds over the NC Outer Banks and significant sound-side storm-surge flooding.

At NC sites the minimum pressure and winds were not extraordinary for hurricanes. Minimum sea-level pressures from Jacksonville along the coast up to Pamlico Sound ranged from 983.4 to 995.2 mb, maximum sustained winds from 13.4 to 21.1 m s^{-1} (26–41 knots; kt), and maximum gusts from 30.4 to 39.1 m s^{-1} (59–76 kt), though Matthew's winds were stronger farther south and along the Outer Banks. Rainfall amounts were high, however. Stations near Elizabethtown in the Cape Fear River valley recorded 330 and 479 mm of rain, and a station near Kinston (Neuse River) 419 mm. Also in the Neuse River basin, two stations near Goldsboro recorded 338 and 415 mm. Single-day precipitation records were set at six sites in the Carolinas, all with estimated recurrence intervals of >200 yr (Weaver et al., 2016; Musser et al., 2017).

Florence made landfall as a 41.2 m s^{-1} (80 kt) category 1 hurricane on the Saffir-Simpson scale on 13 September 2018 at Wrightsville Beach, NC. The storm had weakened considerably at sea. Again, along the NC coast from Jacksonville to Pamlico Sound, minimum sea-level pressures (984.1 to 1003.7 mb), maximum sustained wind (18.0 to 25.2 m s^{-1}; 35–49 kt), and maximum gusts (24.7–38.6 m s^{-1}; 48–75 kt) were not remarkable by tropical cyclone standards (Stewart and Berg, 2019). But the rain and runoff amounts were remarkable. Record peak flows were recorded at 33 gaging stations in the Carolinas. Precipitation totals >250 mm were common, and exceeded 500 mm at NC rain gages at or near Emerald Isle, Jacksonville, Morehead City, Maysville, and Newport. A station in Jacksonville and one in Swansboro recorded 779 and 867 mm of rain.

While precipitation was extensive, Florence and Matthew were not particularly powerful storms in terms of maximum sustained winds, minimum central pressures, or the Saffir-Simpson scale (in many

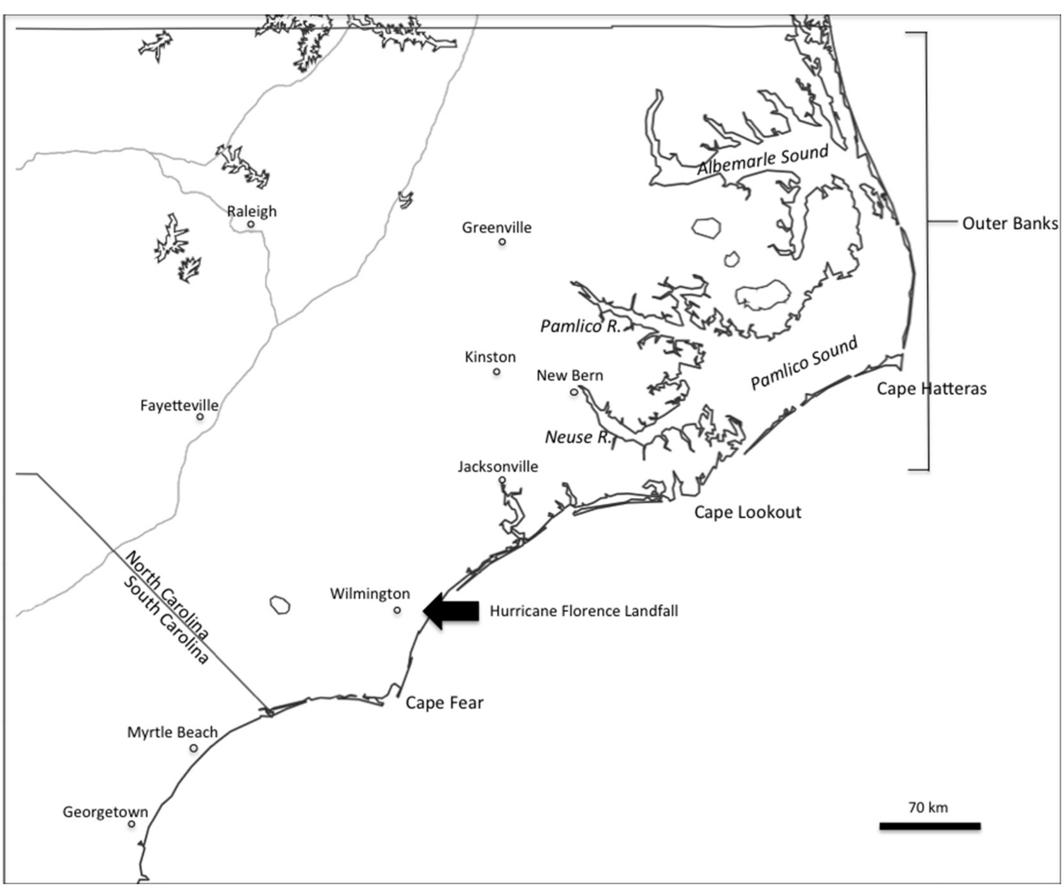

Fig. 1. General area influenced by Hurricane Florence.

cases they had been downgraded to tropical storm status when much of the damage was done).

In the case of Matthew, interaction of the tropical cyclone with a midlatitude pressure ridge caused the storm's cloud and rainfall pattern to shift from the southeastern to the northwestern side of the circulation, resulting in deep moisture and heavy rainfall to spread well inland (Stewart, 2017). The storm's track, essentially parallel to the coast from landfall to where it turned east out to the Atlantic north of Cape Hatteras, was also a factor, maintaining rain along the coastal plain region for long periods. Runoff and flooding from Matthew was exacerbated by wet antecedent conditions—the NC State Climate Office reported that monthly rainfall totals for September 2016 in the coastal plain ranged from 1.5 to more than 3 times normal.

Florence's abundant precipitation was largely associated with its slow movement and large areal extent, which ensured that rain fell over a large area of the eastern Carolinas for a long time. Once it made landfall, the forward motion of the storm slowed to a crawl; 1.5 to <5 km h^{-1}. Storm rainfall and gale or near gale-force winds remained over some areas for several days.

Both storms combined river flooding from inland precipitation with storm surge from the coast. Storm surges of about 2 m were experienced at Charleston, SC and Hatteras, NC during Matthew. Between the Carolina border and Cape Hatteras, inundation levels reached 0.6 to 1.3 m above ground level, including an historical record at the tide gauge along the Cape Fear River in Wilmington. Soundside flooding on the Outer Banks was estimated at 1.3 to 2 m (Stewart, 2017).

The Neuse River estuary was hardest hit by storm surge from Florence, even though the area never directly experienced hurricane conditions in terms of maximum sustained wind. Maximum storm surge inundation heights were estimated at 2.4 to 3.4 m above the ground surface (Stewart and Berg, 2019). At a site examined in the field shortly after the storm, I measured wrack lines indicating water levels up to 4 m above mean high water (which would include wave effects in addition to storm surge). Inundation levels were generally 0.6 to 1.3 m above ground level along the remainder of the western shore of Pamlico Sound and southern shore of Albemarle Sound, but 0.6 m or less above ground along the sound side of the Outer Banks, according to the NHC analysis (Stewart and Berg, 2019).

2.2. Other storms

Between Hurricanes Matthew and Florence was Hurricane Harvey in 2017 on the Gulf Coast, the largest rainfall event in US history, largely because of its slow post-landfall movement and meandering path over the Texas coastal plain.

In 2019 Hurricane Dorian influenced the Carolinas, particularly along the Outer Banks. The storm's track and rate of forward movement (much faster than Florence) did not produce prodigious inland rainfall in the Carolinas. However, the storm did dump 386 mm on Pawley's Island, SC, and 580 mm on Hopetown (Bahamas) when the storm slowed to a crawl (Avila et al., 2019). Thus Dorian seems consistent with Matthew, Harvey, and Florence in delivering massive amounts of precipitation.

In October 2015, there was major flooding in South Carolina. Strictly speaking, this was not a tropical cyclone event, but was strongly influenced by a hurricane. An upper atmospheric low pressure system funneled tropical moisture from Hurricane Joaquin, which primarily affected the Caribbean area, and did not make landfall in the US. Heavy rainfall occurred across South Carolina 1–5 October, causing major flooding in the central and coastal parts of the state. Nearly 700 mm of rain fell near Mount Pleasant in Charleston County during this period. USGS stream gages recorded peaks of record at 17 locations, and 15 other locations had peaks that ranked in the top 5 for the period of record (some of these topped in 2016 and/or 2018). An analysis by the Carolinas Integrated Sciences and Assessments unit characterized the event as a "fire hose of deep tropical moisture" across SC, and calculated that precipitation exceeded estimated 500-yr recurrence intervals at six locations and the 1000-yr event at one (Brennan et al., 2015).

2.3. A new normal?

More frequent and powerful tropical cyclones are likely as the climate warms. Attribution of specific events is an emerging science, but evidence suggests that recent tropical cyclone flooding in the Carolinas represents a hydroclimatological regime shift—a new normal, at least with respect to extreme precipitation and storm surge.

Warmer sea surface temperatures (>26 °C) facilitate formation and strengthening of tropical cyclones and enhance their ability to store and transport moisture. Easterling et al. (2017), in a pre-Matthew and Florence analysis, projected average Atlantic tropical cyclone rainfall within 500 km of the storm center to increase by 8 to 17%, mainly from enhanced water vapor content in the warmer atmosphere, and predicted that extreme precipitation events caused by hurricanes are likely to be even heavier in the future. Hurricanes Matthew, Harvey, Florence and other storms soon proved them right—especially Harvey, which struck the Texas coast in 2017.

Kunkel and Champion (2019) examined the 100 largest area-averaged, multiple day precipitation events in the US record from 1949 to 2018. Hurricane Harvey was the single largest event, with Hurricane Florence ranked seventh. Hurricane Matthew (2016) resulted in 24-h rainfall records at six locations in the Carolinas (Weaver et al., 2016). Hurricane Florence produced new peak streamflow records at 28 gaging stations in the region (Feaster et al., 2018).

Paerl et al. (2019) used standard calculation methods to suggest that there was only a 1.6% chance of the NC region having three precipitation events the size of Floyd, Matthew, and Florence in 20 yr. This deviation from the historic record, and the standard reasoning about tropical cyclones, warming, and precipitation, led them to suggest that we have undergone a regime shift toward more extreme tropical cyclonic precipitation. They used conservative estimates of the probability (recurrence interval) of the storms. Setting aside Floyd, which differed from the other storms in that two other tropical cyclones had been through the region earlier in 1999, leaving wet soils and high flows before Floyd even got there, peak streamflows for Matthew and Floyd at multiple locations with 30 or more years of records were estimated to have a >500-yr recurrence interval (0.2% probability in any given year; Weaver et al., 2016; Feaster et al., 2018). Using the same calculation methods as Paerl et al. (2019), the odds of having two 500-yr events in three years are 0.0000358, or about 0.0036%. These estimates are based on bracketing time periods in which large storms occur, and an assumption that the long-term record is stationary. Nonetheless, evidence suggests that we may have indeed reached a new normal.

The 2015–2019 period had the warmest overnight low temperatures on record in NC, with 2019 setting the record for the warmest lows in the recorded past, and 2019 was overall the state's warmest year in the 125-yr record (Dello et al., 2020). Sea surface temperatures in the tropical Atlantic, Caribbean, and offshore of the Carolinas were much warmer than average for September and October 2016 (relative to a 1981–2010 baseline), according to the monthly global climate reports produced by the National Oceanic and Atmospheric Administration's National Centers for Environmental Information (https://www.ncdc.noaa.gov/sotc/global/). The same is true for August and September 2018.

Hurricane Harvey in 2017 meandered slowly along the Texas coast, dumping vast amounts of rainfall. Florence infamously slowed to a crawl (1.6 to 3.2 km h^{-1}) after it made landfall in southeastern NC. This slow movement, keeping the storms over a given area for long periods, coupled with the extra moisture-carrying capacity of the storms, created perfect conditions for extraordinary precipitation quantities.

Kossin (2019) showed that hurricanes have slowed their rate of movement by 10% in recent decades in a study that included data through 2016 (thus not including Harvey and Florence). The slowdown is linked to weakening in atmospheric circulation in the tropics as a result of global warming, though the specific mechanisms are unclear (Kossin, 2019). Landfalling hurricanes also maintain their strength longer after landfall, exacerbating their inland impacts (Li and Chakraborty, 2020). This is attributable to warmer sea surface temperatures, which induce a slower decay by increasing the stock of moisture that a hurricane carries. Li and Chakraborty (2020) also showed that climate-modulated changes in hurricane tracks contribute to the increasingly slow decay: As Earth warms, the power of hurricanes will extend farther inland. Additionally, conservation of angular momentum means that when a storm is reducing its winds without also reducing its total energy, the storm will increase in area. This is exactly what happened with Hurricane Florence. The storm was about 800 km wide as it approached landfall, covering a surface area of about 4000 km^2 (Fig. 2).

3. Study area

3.1. Lower Neuse River

The Neuse River, with a drainage area of 14,790 km^2, rises in the Piedmont physiographic province of North Carolina, and flows generally southeast through or near the cities of Raleigh, Goldsboro, and Kinston, across the coastal plain. At New Bern the Trent River joins the Neuse near the head of the Neuse River estuary. This study is concerned with the Neuse downstream of the confluence with Contentnea Creek, a major tributary in the coastal plain, between Kinston and New Bern. From this point downstream there is a transition from fluvially dominated, through a fluvial-estuarine transition zone upstream of New Bern, to the coastal-dominated estuary (Figs. 3 and 4).

The Neuse and neighboring Pamlico River are drowned river valleys that are part of the Pamlico Sound estuary, which in turn is part of a larger Pamlico-Albemarle estuarine system (Fig. 1). The Neuse is oligohaline, and lunar tidal influences are small (<0.1 m tidal range). Because the volume is large—equal to about 30 days mean discharge of the Neuse River, fluvial inflows have limited influence on water levels in the estuary. Wind is the major factor determining short-term water level changes, with strong southwesterly winds pushing water out into Pamlico Sound and lowering water levels, and strong northeasterly winds have the opposite effect. The estuary ranges from about 1 km wide at New Bern to 10 km at the estuary mouth.

Field work was focused on the stretch of shoreline from Dam Creek to Otter Creek (Fig. 3), which features bluffs that stand about 10 m above mean water levels. These represent the valley side slopes of the drowned (by Holocene sea-level rise) Neuse and were fluvially dissected during lower sea-level stands. Thus, the bluffs are interspersed with steep-sided valleys containing hardwood swamps, typically perched atop clay- and organic-rich swamp soils approximately a meter above mean low water. These ravine swamps, as I refer to them, are dominated by mature tupelo gum (*Nyssa aquatica*) and bald cypress trees (*Taxodium distichum*).

3.2. Geomorphic impacts of hurricanes

Studies of geomorphological changes associated with tropical cyclones in North Carolina have largely focused on barrier islands (e.g., Dolan and Godfrey, 1973; Mallinson et al., 2011; Moran et al., 2015). One exception is studies of Hurricane Floyd in 1999, where (like Matthew and Florence) the greatest impacts were associated with inland flooding. All major rivers draining to Pamlico Sound experienced floods at the 500-yr recurrence interval owing to Floyd (Bales, 2003). Flows were sufficient to displace most of the water in the estuary, and N and P loads over a 36-day period amounted to 50 to 90% of average annual loads.

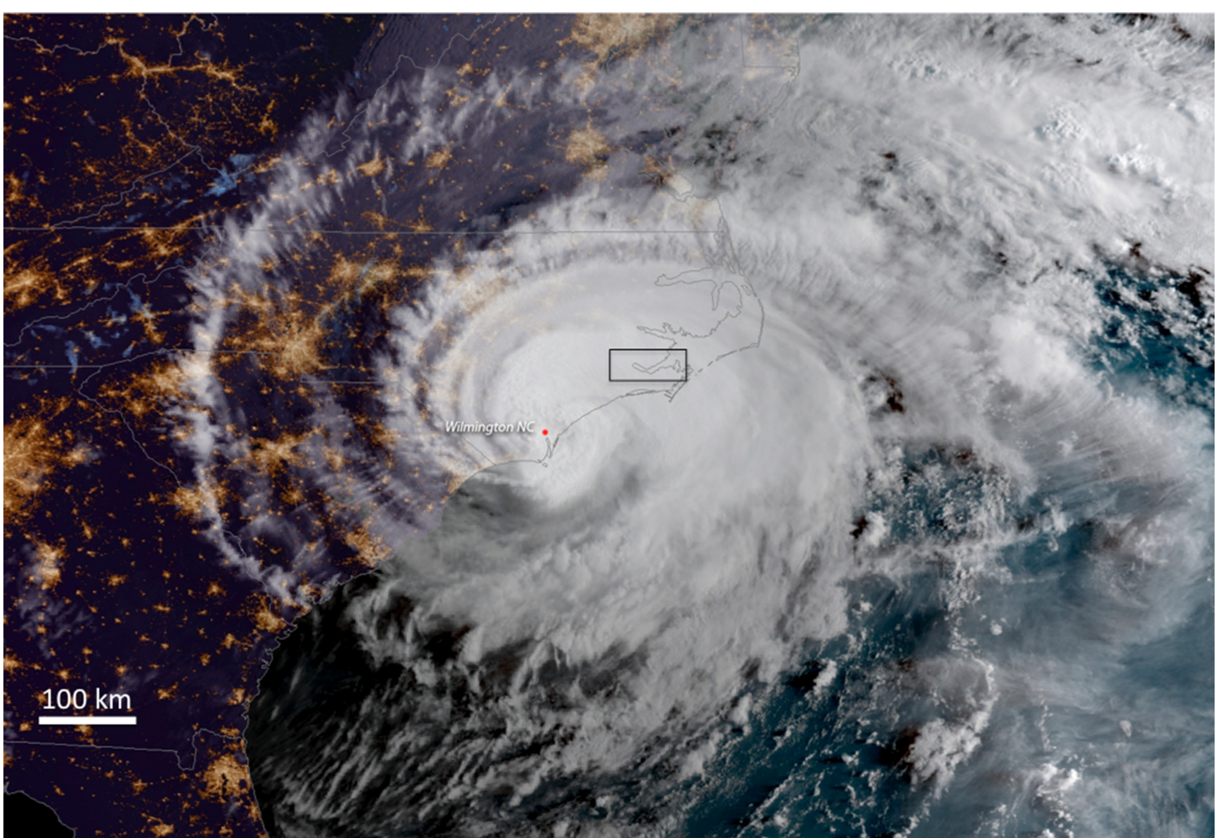

Fig. 2. National Oceanic and Atmospheric Administration Satellite image of Hurricane Florence shortly after landfall. Study area shown in the box.

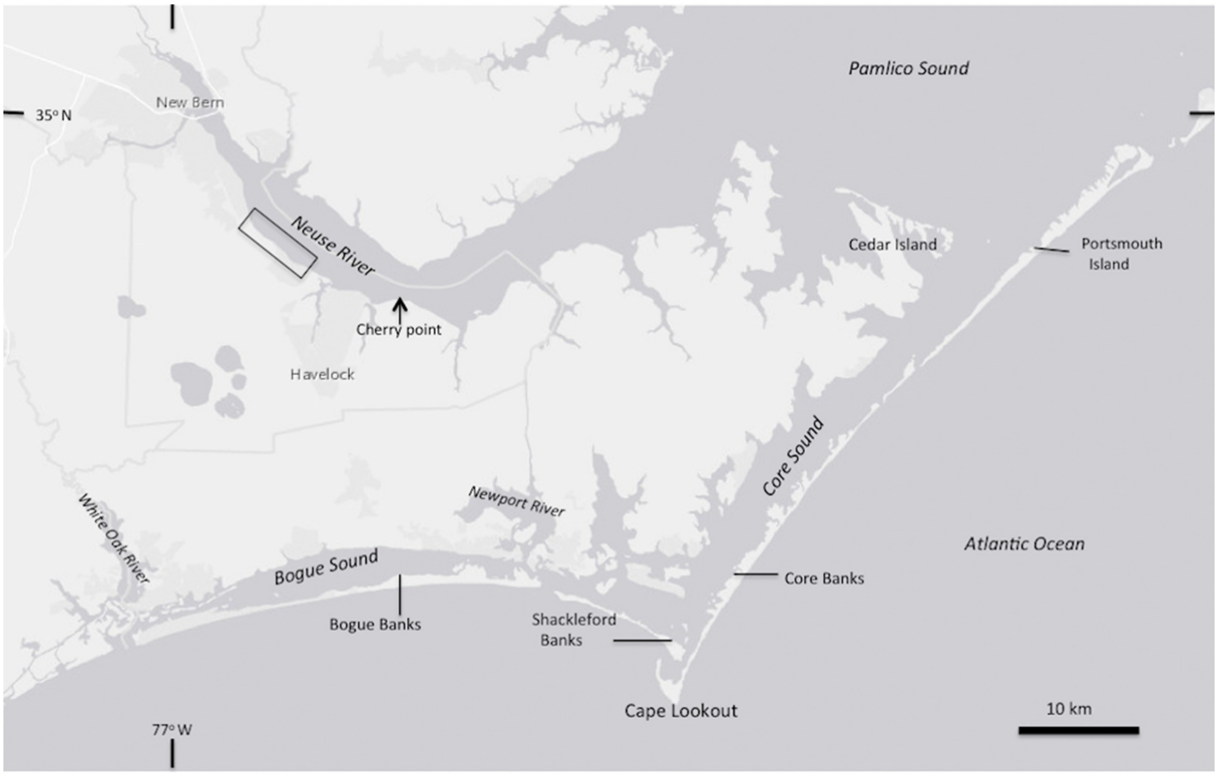

Fig. 3. Neuse River estuary. The box indicates the area where shoreline erosion and ravine swamps were examined. Field measurements of high water indicators in the Stately Pines subdivision are in the southeast end of the box.

Lecce et al. (2004) examined floodplain sedimentation from Floyd on the Tar River, finding surprisingly little. A field survey of the lower 350 km of the river showed that this >500-yr flood deposited very little overbank sediment (<1 mm) on most of the floodplain. They attributed this to the sequence of events—Floyd made landfall just 10 days after Hurricane Dennis, during which high but not extreme river flows

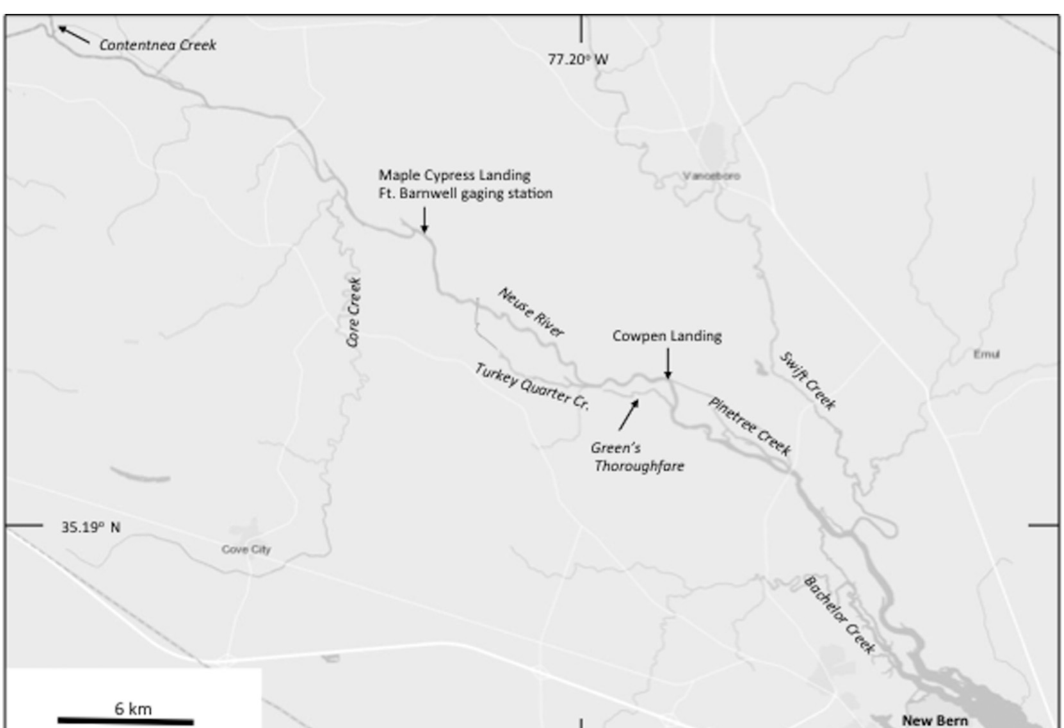

Fig. 4. Lowermost Neuse River, fluvial-estuarine transition zone, and upper estuary.

flushed out most of the readily-available sediment. The late summer timing also meant that the region had a full vegetation cover, and crops that were mature but mainly not yet harvested, limiting upland erosion. Flood timing and sequence was also found to be more important than flow magnitudes in determining environmental impacts along the Tar River with respect to heavy metal concentrations in sediments (Pease et al., 2007).

Hurricanes Fran and Bertha passed over the Neuse River estuary area in 1996, and Phillips (1999) examined their impacts on erosion of bluff shorelines along the Neuse. The emphasis in that study was also on the importance of event sequencing. While the two storms were quite similar meteorologically as they affected the Neuse estuary area, their geomorphic impacts were quite different. Hurricane Bertha in July 1996 resulted in very little shoreline erosion and bluff retreat but did remove toppled trees and toeslope debris from the blufflines. This left the shoreline vulnerable to wave attack and undercutting of the bluffs when Fran arrived in September, leading to 3 to 12 m of retreat of the ~10 m high bluffs (Phillips, 1999).

Shoreline erosion on the Neuse River estuary over a 40-yr period was found to be correlated chiefly with shoreline composition, rather than wave energy (Cowart et al., 2011). This is consistent with Phillips (1999) to the extent that the state of the bluff shorelines at the time of wave attack was of primary importance, rather than wave size. Cowart et al. (2011) found that the vast majority of the shoreline length was eroding over the 40-yr period studied, as is the case with the Pamlico-Albemarle estuarine system in general (Eulie et al., 2017). Similar results were obtained on Cedar Island in southern Pamlico Sound (Cowart et al., 2010). Eulie et al. (2017) compared short- and long-term (decadal vs. 50-yr) erosion rates for the entire Pamlico-Albemarle system and found that variables related to wave height and exposure were important for the short term, but less important for long-term erosion rates.

Like the Neuse estuary (and the Pamlico-Albemarle estuary as a whole), the adjacent Pamlico River estuary is wind-dominated with respect to water level changes. Inundation of marshes there is dominated by storms and seasonal wind patterns, with similar sedimentation regimes in shoreline and interior marshes (Lagomasino et al., 2013). Interior marshes experience order-of-magnitude increases in accretion when water levels exceeded storm berms and inundated the entire area.

Coastal wetland response to sea-level rise during the 1990–2015 period was investigated at two sites in the Neuse estuary system by Phillips (2018a), using a model based on interactions among relative sea level, wetland surface elevation, hydroperiod, vegetation, and sedimentation The system is typically (but not always) dynamically unstable and non-resilient. Because of patchy distributions of microtopography and vegetation, and spatial gradients of environmental factors, extensive local variations in stability/resilience and in the key relationships that trigger instabilities occur. Both of the two field sites exhibited dynamically unstable fragmentation, and neither is keeping pace with relative sea-level rise. Storm history (hurricanes being the most important) was found to be a key factor, including the magnitude, frequency and timing of tropical and extratropical cyclones; event sequencing; and time between storms.

A study of environmental gradients and complexity at the landscape scale by Phillips (2018b) was conducted in a broader region of the central NC coast, including the Neuse estuary. This study focused on state transitions among geomorphic and ecological systems and environments in response to coastal submergence. Empirically derived spatial adjacency graphs reflecting observed patterns of contiguity were developed, and five environmental gradients related to relative sea level were assessed (elevation, hydroperiod, salinity, vegetation, and process regime). Results indicate a complex system that on the landscape level cannot be described or modeled based on linear gradients or successional relationships, though the system complexity can be fully explained, in the aggregate, by the five identified gradients. That study, however, did not directly address hurricane or other storm impacts.

4. Methods

4.1. Storm surge

Within the shoreline and ravine swamp study area, field high water indicators were measured, which indicate the rise in water level caused by storm surge, plus wave effects. These included wrack lines, and deposits of shoreline materials such as ferricrete fragments, formed only at the base of shoreline bluffs in this area (Phillips et al., 1997). The elevation of the upper limit of the indicators was determined relative to the local mean high water level.

For the study area as a whole, storm surges were determined using data accessed via the USGS's Flood Event Viewer (https://stn.wim.usgs.gov/FEV/#FlorenceSep2018). This includes post-event high water marks surveyed by USGS personnel, rapid deployment gages (temporary gages emplaced before the storm), and water level and barometric pressure sensors. Only high water marks where accuracy was rated as “good” (±0.1 ft. or 3 cm) were used, and indicators noted as likely or possibly associated with local rainfall ponding were excluded.

4.2. Shoreline erosion

Shoreline erosion in the field study area was based on pre- and post-storm observations and ground-level photography, and comparisons of before and after aerial photographic images from GoogleEarth™.

Bluff retreat was measured by comparing the distance from the base of the bluffs to fixed points in a post storm image taken a few days after the hurricane (21 September 2018) with pre-storm images—the most recent from 18 June 2018, and a better quality image from 19 February 2017. Horizontal distances were measured normal to the local shoreline orientation and restricted to points where both fixed points and the bluff base could be confidently identified. The bluffs are fronted by dominantly sandy beaches, but these vary in width on a day-to-day basis because of wind-driven water level changes, and the beach was temporarily widened by storm deposits. Therefore, measurements based on the waterline or wet sand line in a given image are not necessarily reliable indicators of shoreline position.

4.3. Ravine swamps

Changes—mainly sand deposition—in ravine swamps were assessed by comparing pre- and post-storm images, as described above, by pre- and post-storm field observations and photography, and by augering. Pre-storm, the affected areas were characterized by mucky clay swamp soils, with permanently high water tables and occasional to permanent inundation. The storm deposits, which ranged in texture from sandy loam to sand, are easily distinguishable from the pre-storm surface. Depth of the deposits was measured by augering through the sandy sediment to the buried mucky clay surface.

4.4. Fluvial impacts

The Neuse River from Contentnea Creek to the estuary (Fig. 4) was evaluated for evidence of geomorphic change based on comparison of pre- and post-storm GoogleEarth™ images, and field observation via kayak in May 2019, April 2020, and February–April 2021.

5. Results

5.1. Storm surge

High water marks surveyed by the USGS are features such as mud, stain, and seed lines that represent suspended materials deposited from suspension as maximum water levels begin falling. In the study area, where normal river stages are at sea level (elevation 0) marks are relatively consistent, indicating an elevation, and thus a surge, of about 3 m. In one location where a seed line was found at a sensor site, the sensor and seed line gave identical results. The water marks ranged from 2.60 to 3.89 m (Table 1).

Sediment deposits on sloping shorelines (as opposed to bluff faces or vertical structures such as bulkheads and seawalls) may be somewhat higher, representing the upper limit of wave swash in addition to storm surge. Sites for reliable measurement of maxima were rare because of the nature of the study area shorelines, as high-water deposits are not preserved on the bluff faces. However, at several sites in the Stately Pines subdivision (Fig. 3) where residential lawns slope to the river, such deposits (including ferricrete fragments) ranged from 3.55 to 3.71 m above the local mean high-water level (Fig. 5). In some cases erosional features occurred at higher elevations, but these appeared to have been formed or enlarged by groundwater sapping and runoff rather than (or in addition to) waves.

The storm surge peaks coincided with minimum atmospheric pressure at sensor sites, but water levels ≥0.6 m above mean high water persisted for several days. According to contemporary news reports, New Bern water levels persisted for >24 h at or above ~2 m above ground level.

An 800 km wide storm moving at 5 km h^{-1} would affect an area over which the eye passes for 160 h, or nearly a week. In the Neuse River estuary, a tide gage at New Bern near the confluence of the Trent and Neuse rivers showed storm-driven water level rise between 06:30 (local time) on 13 September and falling to normal levels by about 03:00 on 17 September—a total of nearly four days. A water level sensor on the Neuse River in New Bern showed the stage rise beginning and ending a bit later, with a total storm-elevated water level rise existing for 5.25 d. Sensors at Cherry Point show the barometric pressure beginning a steep decline at about 18:00 on 12 September, and returning to normal levels (1000 mb) at about 10:00 on 16 September (about 3.7 d). The water level rise at the same site (from beginning a steep, steady rise to return to within the range of non-storm stages) lasted from about 10:00 on 12 September to about 02:00 on 18 September (~4.7 d). Maximum sustained winds at Cherry Point (33.5 m s^{-1} or 65 kt), never reached hurricane intensity, though gusts up to 39.3 m s^{-1} (76.5 kt) were recorded. However, winds of ≥11 m s^{-1} (21.4 kt or 25 mph) persisted for more than three days.

5.2. Shoreline erosion

At 14 locations where image quality, ground cover, and fixed points allowed confident measurements, bluff retreat from Hurricane Florence averaged about 11 m (Table 2). At some sites at the US Forest Service Flanner Beach Recreation area, boulder riprap was present at the bluff base, and at one other site an approximately 2 m high wood bulkhead was present at the bluff base. These protective features did not prevent bluff retreat, but did appear to result in less erosion than at unprotected sites. However, the number of data points is not sufficient to draw conclusions, and the means are influenced by an anomalously low-retreat protected site (3.33 m retreat) and an anomalously high retreat (22.56 m) unprotected site. While relatively few fixed points with readily identifiable pre- and post-storm bluff line locations were found, pre- and post-storm images (Fig. 6) are entirely consistent with the data in Table 2.

The bluff shorelines expose transgressive sedimentary deposits, at the base of which is a clayey swamp paleosol. This layer has a much greater erosion resistance than the overlying material (Fig. 7). Thus at unprotected sites this basal layer retreated less than the overlying material, leaving an erosional platform at the top of the resistant layer. Subsequently, erosion of the bluff face by runoff and groundwater sapping, and earthflow and slump failures deposited a layer of sediment on top of the platform.

This storm terrace is scarped by waves at the lower end and has been retreating since Florence. In some cases logs or downed trees buried by the post-storm deposits retain evidence of the former extent of the scarp (Fig. 8). Measurement of seven such features in April 2021 showed *minimum* post-Florence terrace scarp retreat of 0.90 to 2.36 m (mean = 1.45 m).

The combination of bluff retreat and onshore sand transport created a wide post-storm beach. The presence of clay balls and ferricrete shows that at least some of the post-storm beach was reworked bluff material, but ripple marks on the beach and nearshore also showed onshore transport. Because the offshore water depths are shallow and the slope gentle, the short-term water level changes driven by wind create apparent changes in beach width even in the absence of any erosion or accretion. Thus, confident quantitative measurement of beach width changes were not possible. Visual assessments show a pronounced increase in beach width after the storm, and a return to approximately pre-Florence widths in less than two years (Fig. 9).

5.3. Ravine swamps

Figs. 10–12 show before/after aerial images of three ravine swamps indicating the sand deposition. Augering the storm deposits indicated mean sand deposition depths of 71 cm (range 62 to 95). Augering occurred in the three ravine swamps shown in Figs. 10–12, with five excavations at each site.

At Dam Creek, which has a more extensive drainage area and higher discharge than the other sites, most in-channel sand was flushed out by high flows during the extensive runoff, and the channel and outfall positions were not changed. At the Tadpole Creek site, pre-storm a short

Table 1
High water marks from USGS measurements. The darker shaded entries are in the upper estuary, upstream of New Bern; unshaded are in the Neuse River fluvial/estuarine transition zone; lighter shaded are along the estuary near the field study zone.

Site no.	Type	Elevation (ft)	Elevation (m)	Lat, long
NCCRA27827	Seed line	10.25	3.12	35.1250, −77.0500
NCCRA27046	Stain line	10.48	3.19	35.1247, −77.0520
NCCRA27022	Stain line	10.05	3.06	35.1365, −77.0281
NCCRA26991	Seed line	10.35	3.15	35.1516, −77.0514
NCCRA26906	Seed line	10.84	3.30	35.1044, −77.0181
NCCRA27002	Seed line	9.77	2.98	35.1585, −77.0701
NCCRA27110	Seed line	8.53	2.60	35.2187, −77.1486
NCCRA26999	Seed line	8.92	2.72	35.2327, −77.1419
NCCRA27193	Seed line	12.75	3.89	35.2764, −77.2327
NCPAM26918	Mud	9.91	3.02	35.0051, −76.8641
NCCRA26916	Seed line	9.60	2.93	35.0570, −76.9551
NCCRA12509	Sensor & seed line	10.05	3.06	35.0658, −76.9673

Fig. 5. Examples of storm high water indicators. Upper left: wave breaching of upper end of shoreline bulkhead tie-in. Lower left: Flood scars on swamp trees caused by abrasion from floating logs. Right: Shoreline bulkhead where cap board was removed by waves, with nearby wrack line and storm wave deposits.

incised channel comprised the fluvial outfall and connected the swamp to the estuary. This channel was completely infilled, with no visible evidence of its previous existence. The outfall was displaced 35 m west, and is now a wide, unincised spillover or drip line (depending on flow) zone at the swamp end, with a highly variable braided channel crossing the sand beach.

The Flanner Beach swamp experienced a more-or-less opposite transition in its discharge point. Pre-storm the outfall was a spillover zone or drip line perched on the mucky clay swamp sediments. Sand deposition displaced the outfall about 25 m west. It is now a channel incised into the sand deposits. Some standing water swamp still exists at both the Tadpole Creek and Flanner Beach sites, with a veneer of sand on the bottom. Observations within a week of the storm indicate that flows either inhibited deposition during the storm or flushed out most sand rapidly as water levels declined.

All three sites have been regularly if informally observed since the early 1990s. While occasional sand encroachment on the shoreline end of the swamps occurred during storms, no extensive sand deposition comparable to Florence was ever observed. This is despite the fact that pre-Florence flood scars on trees (created by floating logs abrading tree bark) show inundation of at least 2 m on previous occasions.

5.4. Fluvial impacts

Geomorphic impacts upstream of the estuary were minimal. No major erosion, deposition, or channel change was noted in the field or via imagery that could be confidently attributed to the storm or that was not consistent with typical changes in an active alluvial river. Some anthropic storm debris was deposited, especially in brackish marshes just upstream of the estuary, and some local deposits of rafted organic debris—probably, but not definitively, from Florence–were observed.

Extensive areas of a non-native aquatic plant considered an invasive weed in North Carolina were noted (alligator weed, *Alternanthera philoxeroides*). This plant had not previously been reported in the lower Neuse and may have been spread by flood flows or storm surges—alligator weed was present before the storm in some Neuse estuary tributaries. Geomorphic impacts of *Alternanthera philoxeroides* have not been studied, but given its high rate of biomass production, dense concentrations, and ability to grow and reproduce as a rooted or floating aquatic plant or in wetlands, some impacts are inevitable.

Water levels in the upper estuary and lowermost river were the highest ever recorded. At the only gaging station within the study reach, at Maple Cypress landing near Fort Barnwell, the highest stage recorded during the Florence event was the third highest ever recorded (Hurricanes Floyd and Matthew were the top two). However, both stage and discharge were at least somewhat higher, as values at the peak were not recorded because of equipment failure. Discharge at the site reached at least 1130 m s^{-1}.

The minimal geomorphic change despite the high flows is attributable to the morphology of the fluvial-estuarine transition zone. Well-defined banks are generally absent in this area, with a gradual transition over a few meters from open water in the channel to a channel fringe with trees, to swamp (Fig. 13). The swamps near the river and on islands between anabranches usually maintain flow.

Three of six field observations occurred during flows greater than both the day-of-the-year mean and overall mean discharge at the Fort Barnwell gaging station (though note that the record for this station is only 24 yr). Three others were on days with discharges less than both the overall and day-of-year means; in one case in the lower quartile of

Table 2
Bluff retreat (m). Protected sites had boulder riprap or a bulkhead at the base of the bluffs.

	Minimum	Maximum	Mean	N
Protected	3.33	13.30	7.89	6
Unprotected	9.99	22.56	13.31	8
Total	3.33	22.56	10.99	14

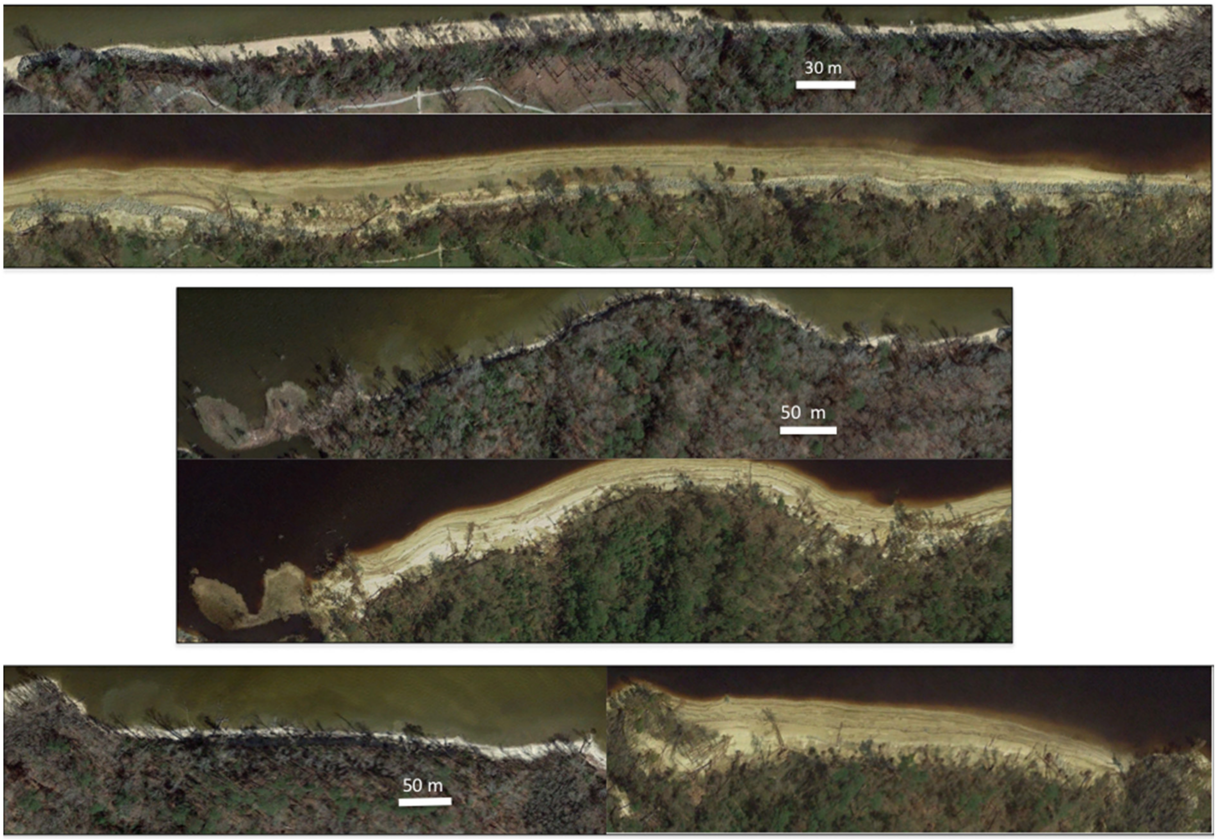

Fig. 6. Images from February 2017 and post-Florence (September 21, 2018). The upper pair shows a shoreline protected by granite boulder rip-rap at the Flanner Beach Recreation Area, and the middle pair an unprotected shoreline between Flanner Beach and Otter Creek. The bottom pair (left/right) shows unprotected shorelines just west of the Stately Pines subdivision.

flows (Table 3). In the three higher flow observations, 95 to >99% of the vegetated surfaces (floodplains, bars, and channel margins) were inundated, with clearly discernible flow. On two of the lower-flow observation days, flow through the vegetated areas was observed, and inundation was >90% by visual estimation. On the lowest-flow observation day, <50% of the vegetated areas were inundated, and some of

Fig. 7. Pre- and post-storm photographs of Neuse River shoreline just southeast of Flanners Beach.

Fig. 8. Storm terrace retreat: remnant soil (1) on log buried in earthflow and slump deposits on storm terrace showing how minimum post-storm retreat was measured; bluff failure material deposited on eroded storm terrace strath (2); resistant clay-rich swamp soil at base of Flanner Beach formation (3); ferricretes commonly formed by precipitation of iron in groundwater discharge along the bluffs (4).

these areas appeared ponded. Even on this day, however, some flow through the vegetated areas was evident, and water levels in channels were only 0.2 to 0.4 m below the floodplain surface at non-inundated sites.

Observed flow in the vegetated areas occurred in all directions (up- and downstream, and from the main river channel to anabranches or vice-versa). However, upstream movement occurred only because of backwater effects near the main river channel, and during a wind-driven water-level rise on the lowest flow day.

Ten images over the 2007–2019 period were found with sufficient quality to observe ponded or flowing water in vegetated areas. Four of these were taken on days where daily mean flows at Fort Barnwell were less than day-of-year or period-of-record means, and two during lowest-quartile flows (Table 3). However, the presence or absence of water could in most cases only be observed in canopy gaps—even in leaf-off images, on ground surfaces in non-gap areas it was difficult to distinguish between water and wet mucky soil. In all images standing or flowing water was observed in all canopy gaps.

Overall, evidence indicates that nearly the entire valley-bottom area of the fluvial estuarine transition, which essentially encompasses everything from valley wall to valley wall except for higher terrace remnants and some human-made features, conveys flow at all but the lowest discharge levels. The implications of this are explored in the Discussion section.

5.5. Other impacts

Other geomorphic impacts were observed that were not studied in detail, but worth noting.

Despite maximum sustained wind velocities that are not uncommon the lower Neuse area in tropical cyclones, extratropical cyclones (nor'easters), and intense frontal thunderstorms, wind damage from Florence was extensive. The major geomorphic impact was tree uprooting, which has extensive impacts on bioturbation, erosion, mass wasting, microtopography, and soil development. This evidently occurred because of the long duration of higher winds, which eventually pried off roofing shingles (for instance) and toppled trees that would have withstood shorter durations of wind stress.

The combination of exceptionally high storm surge and high winds resulted in aeolian transport of sand and silt inland. In the Stately Pines subdivision windblown sand and silt was deposited on and in structures (e.g., window frames) >30 horizontal meters from the

Fig. 9. Shoreline about 3 months and 34 months post-storm. Note ferricretes and storm terrace with only thin veneer of slope deposits (top), and thicker layer of slope deposits on eroded platform at bottom.

Fig. 10. Flanners Beach swamp before and just after Florence (left); ground-level view taken just after the storm.

mean high water line and >20 m from maximum storm surge levels. These occurred >12 m in elevation above the normal shoreline, and >8 m above maximum surge levels. The only plausible source of this material during the storm conditions is wind transport of wave spray with suspended sediment.

Also noted were several cases of bluff erosion by groundwater sapping. Bluff failures could not always be confidently assessed with respect the importance of undercutting by waves or other processes. However, in some instances the bases of the failures were above the highest surge levels, and in a few instances protected by bulkheads that remained intact. There was no evidence of incision by surface runoff, and post-storm groundwater seepage at the base of the failures was observed.

6. Discussion

6.1. Geomorphic impacts

6.1.1. Storm surge

The storm surge associated with Florence was the highest in living memory in the lower Neuse area, though long-term records are lacking. At a National Weather Service (NWS) water level recorder in Oriental on the north shore of the Neuse, the peak on 14 September 2018 was 0.67 m higher than the "major flood" level designated by NWS, and 1.45 m higher than the previous record high.

The ~3 m storm surge in the Neuse River and the extended period of storm-related high water levels are attributable to the large size and slow movement of the storm, the storm track, and the wind-dominated nature of the Neuse-Pamlico Sound estuary. The extended duration of storm effects kept stages high via consistent wind stress on the estuary. The storm track was such that winds from the northerly directions that raise water levels were maintained throughout the event. This is in contrast to storms such as Hurricanes Bertha and Fran, where the Neuse was exposed to winds on both sides of the cyclonic circulation, resulting in a high water storm surge followed by very low water levels as southerly winds forced water out toward the Outer Banks.

The issue of compound flooding from tropical cyclones caused by the combined effects of storm surge, local rainfall and runoff, and high river flows has received increasing attention in the last decade. Gori et al. (2020), who noted that coastal flood risk models have traditionally only taken into account surge flooding, examined compound flooding from tropical cyclones, focusing on the Cape Fear River, NC, using case studies from two landfalling storms coupled with physical modeling. Results showed that intense outer rain bands falling over inland portions of the Cape Fear area can drive river flow plus surge compound flooding, (increasing water levels by up to 0.36 m). Intense eyewall precipitation along the coast can result in localized compound impacts to coastal streams and tributaries, particularly if peak rainfall coincides with peak storm tide. These localized compound impacts can result in defined interaction zones, where neither storm tide alone nor rainfall-runoff alone can fully explain the observed maximum water levels.

The case of Neuse River flooding around New Bern in 2018 has not been examined in this kind of detail, but given near-record floods coming down the river combined with a 3 m storm surge in the Neuse estuary, compound flooding can certainly be suspected.

However, the general consistency of high water mark elevations in the middle Neuse estuary, upper estuary, and fluvial-estuarine transition zone suggest that in this area of the river flooding was primarily attributable to storm surge, as the estuarine sites are minimally affected by fluvial inflows. The highest water mark (elevation 3.89 m) did occur at the upstream-most fluvial-estuarine transition zone site, suggesting that backwater effects from storm surge may have "dammed" high river flows, creating locally higher compound flooding well upstream of the coastal zone.

Standard predictive models of hurricane storm surge are based on forecasts of peak surge heights driven by maximum wind velocity, pressure drop, and the radius of maximum winds. Thus storm size (area) is

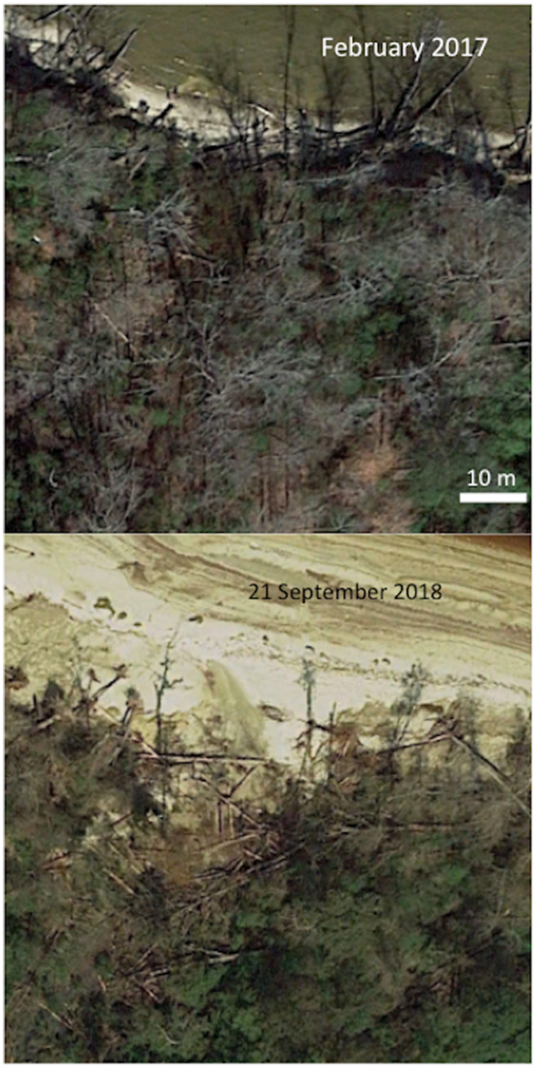

Fig. 11. Ravine swamp between Flanners Beach and Otter Creek before and just after Florence. Note the extensive bluff retreat and wide post-storm beach.

incorporated via the radius of high winds, and the rate of forward movement is also included–but the duration of elevated water levels is not forecast (Meteorological Development Laboratory, 2021). The surge models also do not include wave set-up or runup.

6.1.2. Shoreline erosion

Unprotected shoreline bluffs along the Neuse estuary are chronically eroding, and accelerated retreat from storms is expected. Mean bluff retreat from Florence was at the upper end of short-term erosion rates, the largest of which resulted in shoreline retreat of 3 to 12 m from Hurricanes Fran and Bertha (Phillips, 1999; Cowart et al., 2011; Eulie et al., 2017), but the largest localized bluff retreat (>20 m) was unprecedented.

In the field study area, the Florence event differed substantially from the Bertha/Fran erosion in 1996. In the earlier episode, Bertha caused minimal bluff retreat, but removed toppled trees, large woody debris, and sedimentary aprons at the slope base. The second storm then resulted in wave attack on the unprotected bluffs, erosion by slope undercutting, and emplacement of a new woody debris accumulation (Phillips, 1999). During Florence, the extended period of high water and wave attack allowed this entire sequence to occur during a single event.

While wind velocities in Florence are within the range of those typically experienced during storms, the durations may have been particularly important with respect to wave energy and its effects on shoreline erosion and damage or destruction to shore structures. Wave power in joules per meter of wave front is:

$$P = 17\, H^2 T^2 \tag{1}$$

where H is wave height (m) and T is wave period (s). Significant wave height and period (H_c, T_c) are approximated for duration-limited or fetch-limited cases (subscripts d, f) by:

$$H_{c,d} \approx (u^2/g) h_t (gt/u) \tag{2b}$$

$$H_{c,f} \approx (u^2/g) h_x (gX/u^2) \tag{2a}$$

$$T_{c,d} \approx (u/g) p_t (gt/u) \tag{3a}$$

$$T_{c,f} \approx (u/g) p_x (gX/u^2) \tag{3b}$$

where u is wind velocity, X is fetch, g is the gravity constant, and h, p are dimensionless parameters.

For a given wind velocity under duration-limited conditions, wave height and period vary as a linear function of wind duration, and power as the square of duration. For the shoreline study area, fetches would have varied from about 7.5 to 22 km during the event.

Additionally, during Florence the higher storm surge allowed wave attack on a larger portion of the bluff face. This resulted in differential erosion of the less resistant sand and interlayered sand/clay overlying the resistant clay-rich swamp facies. The resulting storm terrace—wave cut surface atop the swamp deposits covered by slope failure deposits—was essentially a new morphology at the reach scale. Pre-Florence there were scattered local platform-type features along the bluff line, but not the continuous storm terrace formed by the storm and persisting at least into 2021.

6.1.3. Ravine swamps

Ravine swamps examined in detail underwent a fundamental geomorphic (as well as hydrological and ecological) transition from constantly wet conditions with mucky clay soil to a 0.6 to 1 m thick sandy substrate where the water table is usually at least 0.4 m beneath the surface, or to swamp with a sandy veneer overlying mucky clay. This is unprecedented in recent decades. Attempts at deeper augering to search for older sand layers were not successful because of hole collapse; coring would be necessary to resolve this.

The standing-water portions of the ravine swamps are dominated by mature *Nyssa aquatica* (tupelo gum) and *Taxodium distichum* (bald cypress). Both trees grow in standing water environments, but both also require non-inundated conditions for germination. This suggests several different possibilities for the initial establishment of these stands. One is that they developed under a slightly drier hydrologic regime, where the ravines dried out seasonally. This is at least plausible because of Holocene and contemporary sea-level rise elevating water tables. A second is that they developed during an unusual (at least by late twentieth and early twenty-first century standards) prolonged drought period. The third is that episodes of storm sand deposition such as occurred during Florence allowed their establishment. Recruitment of cypress is extensive at some of the 2018 deposition sites.

Recent and contemporary tree recruitment in the wet interiors of the swamps occurs primarily from stump sprouting of broken trees or establishment on local points above water levels created by the root wads of uprooted trees or fallen trunks (nurse logs). Most treefall by uprooting or breakage occurs during strong storms, especially tropical cyclones. Thus, tree uprooting in storms is clearly important in maintaining the ravine swamps and may have played a role in their

Fig. 12. Tadpole Creek before and after Florence: Base of cypress tree (1) at creek mouth before and after storm; post-storm diffuse/drip line discharge of creek (2); swamp covered by sand deposits. At right is ground level view of depositional area.

establishment. Both cypress and tupelo gum seeds are distributed primarily by water and storm surge deposition of seeds along with sediment.

Another important factor in the studied ravine swamps is the shallow nature of the nearshore zone. At normal water levels it is typically 300 to 400 m from the water line to the ~1 m depth. This shallow—or relatively shallow during Florence's storm surge—provides a ready source of sand transported as sandy bedload and in suspension.

6.1.4. Fluvial impacts

The minimal geomorphic impacts in the lowermost fluvially-dominated reaches of the Neuse River and in the fluvial-estuarine zone are attributable to the morphology of the lower valley. Channel bed elevations are below sea level, and typical water levels are close to sea level. Banks are low and often occur as a transition zone from river to swamp rather than as a clear demarcation, and levees are rare.

This portion of the river has the capacity to convey and to store large amounts of water. Dense vegetation cover and dominantly fine-grained soils provide for high resistance to erosion. Sediment trapping upstream of the fluvial estuarine transition zone, documented in earlier work (Simmons, 1988; Phillips, 1992, 1993) limits depositional impacts, as does the extensive accommodation space associated with valley wall to valley wall inundation.

The low, indistinct banks are attributable to river stage having a variable and loose relationship to fluvial discharge, owing to the ponding and backwater effects from the estuary, and the influence of wind tides. Further, as the channel bed is also below sea level, there is limited ability to incise. Deepening of the channel is thus dependent on bank accretion, which is minimal because of very low sediment loads. These characteristics are caused by the Holocene evolution of the lower river valley as it is drowned by rising sea level.

6.1.5. Other impacts

Tree uprooting as well as structural damage from wind was extensive relative to wind velocities because of the long duration of relatively higher winds. Wind force per unit of cross-sectional area A exposed to the wind varies as the square of wind velocity, and wind load F (in kg) is given by:

$$F = 0.613\, V^2 A\, C_D \tag{4}$$

where C_D is a drag coefficient. The wind load on trees (or other objects) is also affected by dynamic pressure, and the mass of air and its contents (throw weight). Wind loads on trees reflect the cumulative impacts of a constantly applied pressure, additional pulsing of shorter wind bursts, occasional rolling shock waves of high pressure, acceleration and deceleration around a mean value, and a variable weight windstream. Mean and peak wind velocity values cannot fully represent the full dynamic nature of storm winds on trees. The periodicity of tree swaying, coupled with the frequency of wind pressure peaks, can generate tremendous synergies of load and resistance (Coder, 2018). Failure by material fatigue is a function not only of stress amplitude, but also the number of cycles (e.g., by wind calm/gust sequences). Thus, long-lived wind events with variable velocities are effective in breaking and toppling trees.

The occurrence of groundwater sapping on shoreline bluffs and high-relief areas along the dissected valley side slopes where ravine swamps occurred is not surprising. However, this is not typically considered in assessments of geomorphic impacts of tropical cyclones and perhaps deserves further investigation in the context of more frequent high-precipitation events. Groundwater sapping has been found to be important in development of stream networks in coastal plain landscapes in Florida (Schumm et al., 1995; Devauchelle et al., 2012). The amphitheater-like valley heads of the ravine swamp drainages in the

Fig. 13. River banks in the Neuse River fluvial-estuarine transition zone. All photos taken on 16 April 2021, a day of below mean discharge. Top: View looking upstream at the confluence of Turkey Quarter Creek and the Neuse River. Banks are low (lower left), or essentially absent (lower right) with a gradual transition from river to floodplain swamp.

lower Neuse and observed groundwater seepage suggest the possibility of similar processes. Thus more extreme storm precipitation events could drive expansion of these networks. While some examples of this were observed post-Florence, these have not been investigated in detail and are only anecdotal examples at this point.

Sediment transport via wind-blown sediment-laden spray, as observed in this study, does not seem to have been previously addressed in the literature. This phenomenon needs additional research to determine how frequently it occurs and the quantities of sediment involved.

Table 3
Dates of aerial images where water can be observed throughout floodplains, and of field observations, along with mean daily discharge for that date at the Fort Barnwell gaging station, and average daily mean discharges for the date for the 1997–2020 water years. Overall average discharge is 146 $m^3 s^{-1}$. See Fig. 4 for locations.

Image date	Discharge ($m^3 s^{-1}$)	Daily mean discharge	Comments
18 Feb 2007	144	176	Earlier images have insufficient visibility or resolution
5 May 2009	35	89	
25 July 2012	150	71	
20 Feb 2013	130	171	
21 Nov 2014	28	101	
29 Jan 2016	294	176	
14 May 2016	241	108	
12 Oct 2016	1147	142	Hurricane Matthew
12 Jan 2017	199	141	
12 Mar 2019	388	169	
Fieldwork date	Discharge	Daily mean discharge	Observation area
11 May 2019	74	123	Right anabranch near New Bern; Bachelor Creek; The Gut
1 June 2020	245	88	Left anabranch near Bridgeton & subchannels
25 Feb 2021	668	168	Upstream of Maple Cypress landing
9 Mar 2021	311	178	Cowpen landing area; Green's Thoroughfare
16 April 2021	127	149	Turkey Quarter Creek
26 April 2021	58	131	Spring Garden; Pinetree Creek

6.2. Particulars and portents

Tropical cyclone activity has increased recently and will likely continue to do so, and areally extensive, slower-moving storms (such as Florence) are also likely. Therefore a key question is the extent to which impacts of a specific storm in a given region may be diagnostic of future trends, typical of hurricanes in general, or a function of the particular situation. As summarized in Table 4, the major drivers of hydrologic response and geomorphic change in the lower Neuse River and estuary were strongly affected by the areal size and rate of movement properties of Florence (and thus potential portents for the future) and the particular properties of the study area and storm synoptics.

The exceptionally high storm surge, prolonged wave attack of the estuarine shorelines, and high total wind loads were all related directly to the duration of storm conditions. The long duration is directly related to the slow forward movement of the storm and its large area and is thus a possible portent of a new tropical cyclone regime. However, local properties also played an important role, particularly the wind-dominated nature of the estuary. The track of the storm was also critical, in keeping the Neuse area on the northern side of the circulation and therefore continually exposed to water-level-raising winds from the northern and eastern quadrants.

The extreme precipitation and runoff was tied mainly to the emerging new tropical cyclone regime. The greater moisture storage and delivery capacity of storms in the warming climate, coupled with slow movement and large areas is a recipe for extreme precipitation, as Florence (and Hurricane Harvey) illustrate. High antecedent soil moisture and high stream flows pre-storm obviously play a role in runoff and flood impacts. However, with intense precipitation embedded within several days of rainy conditions, antecedent conditions are somewhat less important, as soils become saturated during the storm. The storm surge also likely played a role in urban flooding in New Bern and rainfall flooding in general, as runoff was prevented from reaching streams and estuaries.

Florence's impacts in the Neuse area underscore the importance of event duration in additional to magnitude in determining geomorphic impacts. Wave heights are strongly influenced by wind duration (in addition to velocity and fetch), as are the high wind loads—and the wind pulsing, which is inevitable in a long-duration event.

Particulars—geographical contingencies—were especially important with respect to sand deposition in regime swamps and the fluvial-estuarine transition zone. An abundant sediment supply instigated the burial of the ravine swamps with sand. One source was the sandy upper portions of the adjacent eroded bluffs; another was the wide, shallow area in the study area. With winds from north and easterly directions, the latter delivered abundant onshore transport, and the ravine swamps served as basins for retaining the sand fraction.

In the fluvial-estuarine transition zone, geomorphic evolution under Holocene coastal submergence has created a complex of active, backwater, and flood channels, sloughs, and wetlands that is well suited to absorb upstream propagation of storm surges and to convey river flood flows. Under conditions such as hurricane Florence, the entire valley bottom becomes a flowing complex of rapid and slow flows and water storage. This is possible because the wetlands in the lower Neuse have mainly been protected. Since 1972, Section 404 of the U.S. Clean Water Act has made it more difficult to fill or drain swamps and marshes. About 6 km^2 in the Turkey Quarter Creek vicinity are preserved as part of the Neuse River Game Lands, which also includes wetlands and riparian forests just upstream of New Bern. The cessation of commercial navigation on the Neuse in the early twentieth century, and the general difficulty of developing this low-elevation, frequently flooded terrain, coupled with the protections above has mainly restricted commercial activities in unprotected portions to timber harvesting and sand mining on Pleistocene terrace remnants. While the logged and mined areas lose some of their ecological values relative to less disturbed swamps, their water storage capabilities are enhanced.

Along the Neuse and other coastal plain rivers in the Carolinas, floods near or above previous records occurred, though storm surges were not as severe as in the Neuse. While impacts on humans and economic activities along developed portions of the river corridors were severe, geomorphic impacts, particularly along undeveloped reaches, were minimal (though these have not been examined in detail). Along the Waccamaw River, SC, for instance, which experienced its flood of record during Florence, there occurred no avulsions, cutoffs, sedimentary burials, large areas of bank erosion or other channels visible from aerial imagery or field observations. Where river corridors have extensive fluvial-estuarine transition zones that have developed under a regime of coastal submergence, and where the wetland-channel complexes have been protected, the ability to resist geomorphic change from large, slow, wet storms will be high.

7. Conclusions

Tropical cyclones are major drivers of geomorphological and ecological change in coastal areas influenced by them, and ongoing and future Anthropocene changes in cyclone frequency, intensity, moisture content, areal extent, and rates of forward movement will certainly foster changes in the geomorphic impacts of the storms. However, impacts of tropical cyclones (and other storms) depend not only on the magnitude (which itself has many dimensions) and frequency of the storms, but also on the geographical contingencies of the affected areas, and the historical contingencies and synoptic particulars of individual storm systems.

As this example from Hurricane Florence and the lower Neuse River, North Carolina shows, it is not straightforward to extrapolate from changes in tropical cyclone characteristics to specific geomorphological effects. Some aspects of Florence's impacts are indeed linked to the areal extent, slow movement, and high moisture content of the storm, and

Table 4
Drivers of geomorphic change in the lower Neuse River area associated with Hurricane Florence, relevant specific aspects of the study area and storm, and factors associated with the "new normal" of late Anthropocene tropical cyclones.

Storm driver	Place particulars	Storm particulars	New normal (slow movement, large area, high moisture content)
Exceptionally high storm surge	Wind-dominated estuary	Storm track relative to estuary geometry & orientation	Long duration of high winds
Shoreline wave attack	Shoreline orientation, exposure, & wave fetches	Storm track relative to estuary geometry & orientation	Long duration of high winds
Exceptionally high precipitation & runoff	Local hydrological response	Moisture content; rain bands; antecedent soil moisture	High rates & long duration of precipitation
Runoff (pluvial) floods	Local hydrological response	Blocking of drainage by high storm surge	High rates, long duration & extensive area of precipitation
Fluvial floods	Watershed hydrological response	Antecedent flows; runoff concentration in lower watershed	High rates, long duration & extensive area of precipitation
Long exposure to high winds	Local wind exposure	Wind field	Long duration of high winds due to slow movement & large area

are thus possible portents of the emerging late Anthropocene storm climatology of the Carolinas. However, impacts were also profoundly influenced by specific characteristics of the lower Neuse River region, and of the specific track of Florence relative to the NC coastal region and the Neuse estuary.

A broader lesson for geomorphology and for adaptation to impacts of climate change is that it is important to take into account geographical and historical contingencies in anticipating, mitigating, and managing climate-driven changes. As devastating as hurricanes have been in eastern North Carolina, their impacts are more severe, and ability to recover far less, in less affluent nations. Rather than tacitly assuming that impacts of a given climate-driven phenomenon will be comparable in a given region, it should be recognized that they can be quite variable, depending on local and regional geographical variations. In drawing lessons from impacts of tropical cyclones (or other floods, droughts, sea-level rise, wildfires, etc.) it is important to distinguish between those associated with the *particulars* of geography and event synoptics and *portents* of future impacts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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