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RESEARCH ARTICLE

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Geomorphology of the fluvial–estuarine transition zone, lower Neuse River, North Carolina

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Abstract

The fluvial–estuarine transition zone (FETZ) of the Neuse River, North Carolina features a river corridor that conveys flow in a complex of active, backflooded, and high-flow channels, floodplain depressions, and wetlands. Hydrological connectivity among these occurs at median discharges and stages, with some connectivity at even lower stages. Water exchange can occur in any direction, and at high stages the complex effectively stores water within the valley bottom and eventually conveys it to the estuary along both slow and more rapid paths. The geomorphology of the FETZ is unique compared to the estuary, or to the fluvial reaches upstream. It has been shaped by Holocene and contemporary sea-level rise, as shown by signatures of the leading edge of encroaching backwater effects. The FETZ can accommodate extreme flows from upstream, and extraordinary storm surges from downstream (as illustrated by Hurricane Florence). In the lower Neuse—and in fluvial-to-estuary transitions of other coastal plain rivers—options for geomorphological adaptation are limited. Landscape slopes and relief are low, channels are close to base level, sediment inputs are low, and banks have high resistance relative to hydraulic forces. Limited potential exists for changes in channel depth, width, or lateral migration. Adaptations are dominated by the formation of multiple channels, water storage in wetlands and floodplain depressions, increased frequency of overbank flow (compared to upstream), and adjustments of roughness via vegetation, woody debris, multiple channels, and flow through wetlands.

KEYWORDS
channel–wetland complex, coastal plain rivers, fluvial–estuarine transition zone, multiple channels, Neuse River, sea-level rise

1 | INTRODUCTION

The lower reaches of low-gradient coastal plain rivers are subject to water inputs from both upstream fluvial flows and downstream, from coastal backwater effects. Backwater effects include storm surges and other wind-driven water-level changes, as well as astronomical tides. With these mixed fluvial and coastal influences, and evolution in the Holocene under rising sea levels, I propose that these systems have distinctive morphologies reflecting these influences. This study addresses this question for the lower Neuse River, North Carolina. Rising sea levels are impacting fluvial systems globally, particularly low-gradient coastal plain rivers. The main geomorphic impacts are related to upstream movement of backwater effects and a rising base level, which potentially affects hydrological fluxes and storage, sedimentation, fluvial and alluvial morphology, and ecological habitats. This study arose from fieldwork examining the geomorphic impacts of Hurricane Florence (2018) on the estuary and fluvial–estuarine transition zone (FETZ) of the Neuse. Results suggested that the complex of active, semi-active, high-flow, and backwater flooded channels; floodplain depressions; and wetlands was well adapted to handling the unprecedented combination of river floods and storm surge from Hurricane Florence with limited geomorphic change (Phillips, 2022). This stimulated a closer examination of the geomorphic and hydrological nature of the Neuse River FETZ, to address hypotheses that it:

1. Is characterized by a complex of active channels and anabranches, high-flow channels, floodplain depressions, and frequently flooded wetlands that occupy the entire valley bottom.

2. Experiences channel–floodplain hydrological connectivity at most flow levels; specifically at discharges below the median and mean flows.
3. Shows evidence of longitudinal transitions along the valley bottom of landforms, hydrology, soils, and ecology characteristic of the leading edge of sea-level rise.
4. Encompasses a suite of forms and processes distinctly different from fully fluvial environments upstream and the estuary downstream.

Studies of low-gradient rivers often ignore or explicitly exclude tidally influenced systems (Lewin & Ashworth, 2014). Many studies of the geomorphology, sedimentology, geologic history, and hydrology of deltas exist, but there are otherwise few studies of non-deltaic fluvial-to-estuarine transitions. The FETZ is the zone of the river from the upstream area fully dominated by fluvial processes to the estuary dominated by tidal and coastal processes. The FETZ is larger than the tidal freshwater zone, which Jones et al. (2020) define on the basis of salinity, bidirectional velocities, and tidal stage fluctuations. The FETZ extends at least from where the channel bed is at or below the base level of the receiving estuary (on average, mean sea level) to the open-water estuary. Coastal backwater effects may extend further upstream. The FETZ thus includes areas that are frequently brackish in salinity, and (especially in microtidal or wind-dominated estuaries) the upstream portion may have barely or undetectable astronomical tides. These zones may be extensive. For example, in the Aransas River, Texas, Jones et al. (2020) found that the tidal freshwater zone varied in length by more than 12 km (median 59.9 km) over a year. In the Trinity River, Texas, the channel bed is below sea level at least 110 km upstream of Trinity Bay, and geomorphological evidence of the effects of rising sea level extend to 130 km upstream (Phillips & Slattery, 2006). Backwater effects are detectable at a gauging station on the Tar River, North Carolina, 50 km upstream of the estuary (Phillips & Slattery, 2006). The FETZ of the Santee River, South Carolina is 50–60 km long (Torres, 2017), and tidal effects in the Altamaha River, Georgia extend 76 km inland of the estuary (Sulaiman et al., 2021).

The boundaries of the FETZ are dynamic in response to changes in river flows and coastal storms, but where lunar tides are sufficiently strong, a distinct sequence of hydrological and sedimentological environments is present. In the Raritan River, New Jersey, for example, Renwick and Ashley (1984) found a well-defined sequence of zones through the FETZ, distinguished by the relative influence of fluvial discharge and tides, and by the sediment transport/deposition regime. Sulaiman et al. (2021) found abrupt changes in channel slope, cross-sectional morphology, planform, and bed grain size at the point where the incident energy of an upstream-propagating tidal wave declines to negligible levels in the Altamaha River.

However, some lagoonal estuaries, particularly those with limited oceanic exchange and/or situated on microtidal coastlines, are wind-dominated. Where wind rather than lunar tides or fluvial inputs dominates short-term water-level changes, hydrological and morphological changes in the FETZ of the rivers discharging to the estuaries may be more subtle than in tide-dominated estuaries. In either case, however, the FETZ represents the leading edge of impacts of rising sea level on fluvial systems. Changes in salinity and hydroperiod in wetlands, in addition to the hydrodynamic effects on channels, result in ecological changes which may have geomorphic impacts. Coastal freshwater wetlands are among the environments most likely to be impacted by climate change, but there has been scant research on those impacts (Grieger et al., 2020). Tidal freshwater forests are ‘sentinels for climate change’ according to Stahl et al. (2018), with sea-level rise likely to lead to forest death due to saltwater intrusion and submergence. Indeed, areas of ‘ghost forests’ featuring dead trees killed by salinity and transitioning to marsh are evident along the North Carolina coast, including some tributaries of the Neuse River estuary (Ury et al., 2021). These transitions, and those along a gradient from terrestrial forest to swamp forest to marsh to mud flat to open water, have mainly been studied along estuarine margins, rather than in lower reaches of rivers (North Carolina examples include Brinson et al., 1995; Hackney et al., 1996; Moorhead & Brinson, 1995; Peterson & Li, 2015; Phillips, 2018a,b).

Erosion, submergence, and transition of swamp forest to brackish or salt marshes occurs at the downstream end of FETZs, while extension of tides into previously non-tidal areas is occurring at the upstream end. The latter can increase the area of tidal freshwater wetlands and offset loss of ecosystem functions downstream (Ensign & Noe, 2018). Most of these affected habitats occur on coastal plain rivers, with the US east coast a major global hotspot (Ensign & Noe, 2018). Craft (2012), who studied three coastal plain rivers in Georgia and one in North Carolina, found that tidal freshwater forest accretion does not keep pace with sea-level rise. As forests convert to marshes, some ecosystem services are enhanced (e.g. sediment trapping and carbon sequestration), but others are reduced (e.g. denitrification, migratory bird habitat). A key is the extent to which these systems can migrate upstream, which is in the first instance a geomorphic problem, and lower reaches of coastal plain rivers are also likely to be geomorphic hotspots for change (Sulaiman et al., 2021). While this study focuses on geomorphic rather than ecological characteristics, ecological, hydrological, and geomorphological systems coevolve and respond to changes together.

Studies in the FETZ are complicated by the varying combination of fluvial and coastal effects, and by the scarcity of gauging stations in lower reaches of coastal plain rivers (Phillips & Slattery, 2006; Rodriguez et al., 2020). Further, the typical fluvial conditions of constant net downstream flow and a relationship between channel size and bank height on the one hand, and typical or channel-forming flows on the other hand, may not exist. For example, in many humid-region perennial streams, the bankfull or banktop discharge corresponds at least approximately to an annual peak flow with a 1–2 year recurrence interval. However, in the lower reaches of several rivers of the Gulf coastal plain of Texas, the recurrence interval of overbank flow is 0.5 years or less (Phillips & Slattery, 2007). This is difficult to establish in eastern North Carolina due to an absence of gauging stations in downstream areas, but the lower river valleys are often dominated by wetland types associated with seasonal and perennial inundation, indicating frequent overbank discharge.

1.1 | Study area

Though it has its unique characteristics (as do all geomorphic systems), the lower Neuse is at least somewhat typical of many rivers draining to the Atlantic and Gulf of Mexico across wide coastal plains, and likely coastal plain rivers elsewhere as well. These rivers flow across extensive areas of low regional slope through unconsolidated marine, coastal, and alluvial sedimentary deposits. Due to the low gradients, tidal or coastal backwater effects may extend well upstream of the estuary. While some such rivers flow to their own drowned river valleys connected directly to the ocean or a marine delta (e.g. Cape Fear, Savannah, and Brazos rivers), many others, like the Neuse, debouch into a large estuary such as the Pamlico–Albemarle Sound system, Chesapeake Bay, Sabine Lake, or Galveston Bay.

This study focuses on identifying and explaining unique geomorphic characteristics of the FETZ relative to the downstream estuary or upstream fluvial system. Though Neuse results are applicable to many other rivers as described above, differences are likely due to variations in the drainage areas and flow regimes of the rivers, hydrography of their receiving waters, astronomical tidal influences, geologic, climate and biogeographic context, and the nature and degree of human modifications such as dams, urbanization, dredging, etc.

The Neuse River rises in the Piedmont physiographic province of North Carolina. It flows through an urbanized area including Raleigh, across the coastal plain, and joins the Neuse estuary at New Bern, North Carolina (Figure 1). The Neuse River estuary is a drowned river valley connected to the lagoonal Pamlico Sound estuary. The drainage area is about 16 150 km^2, including the estuary. The watershed area upstream of the FETZ is about 10 000 km^2. At the gauging station near Fort Barnwell, within the FETZ, the mean discharge for the 1997–2020 period was about 117 m^3 s^{-1}. Discharges >1400 m^3 s^{-1} have occurred in conjunction with tropical cyclones (Hurricanes Floyd, Matthew, and Florence, in 1999, 2016, and 2018). In most non-hurricane years, annual peak flows are in the range of 280–710 m^3 s^{-1}. Tropical cyclones can also cause significant storm surge in the lower river. During Hurricane Florence (2018), surges of nearly 4 m above ground level occurred in New Bern.

The Neuse estuary is buffered from the ocean and lunar tidal effects by Pamlico Sound, and astronomical tides are nearly undetectable. Water levels are most profoundly affected by wind (Giese et al., 1985) Northeasterly winds result in higher stages and push water upstream, and strong northeasterly winds can result in minor flooding and storm surges in the estuary and lowermost river. Southwesterly winds lead to lower water levels and push water out into Pamlico Sound towards the Outer Banks. Strong southwesterly wind events can lead to low water levels in the Neuse FETZ and estuary, with or without droughts and low flows. Wind roses for New Bern and a site on the Outer Banks (reflecting Pamlico Sound) are shown in Figure 2. The estuary is oligohaline, with salt water occasionally penetrating well upstream of New Bern. The typical residence time of water in the estuary, estimated as total volume divided by median inflow, is about 30 days (Bales, 2003; Giese et al., 1985).

Previous geomorphological studies have documented very low sediment delivery to the FETZ and estuary due to sediment sequestration as alluvial storage upstream (Benninger & Wells, 1993; Kim, 1990; Nelson, 1973; Phillips, 1992b, 1993; Wells & Kim, 1989).

The riparian zone and floodplain along the study reach are comprised of bottomland hardwood swamp forests. These are dominated by water tupelo or tupelo gum (*Nyssa aquatica*) and bald cypress (*Taxodium distichum*), along with red maple (*Acer rubrum*), black gum (*Nyssa sylvatica*), willow oak (*Quercus phellos*), swamp bay (*Persia palustris*), and other species. Within the generally wet valley bottom, characterized by fine-grained and organic hydric alluvial soils, there occur ‘islands’ of sandier fluvial terrace soils where non-hydrophytic vegetation also occurs. Near the lower end of the FETZ, areas dominated by brackish marsh occur. These communities often have high plant diversity, but dominant species include sawgrass, *Cladium jamaicense*, and big cordgrass, *Spartina cynosuroides*.

1.2 | Sea-level effects

Quaternary sea-level history in coastal North Carolina has been studied extensively. Kopp et al. (2015) outlined recent and historic trends in sea-level rise along the North Carolina coast. The Albemarle–Pamlico estuarine system, including the Neuse River estuary, is a combination of lagoonal and drowned river valley estuaries, and Holocene and contemporary sea-level rise has long been recognized as a key driver in processes such as shoreline erosion,

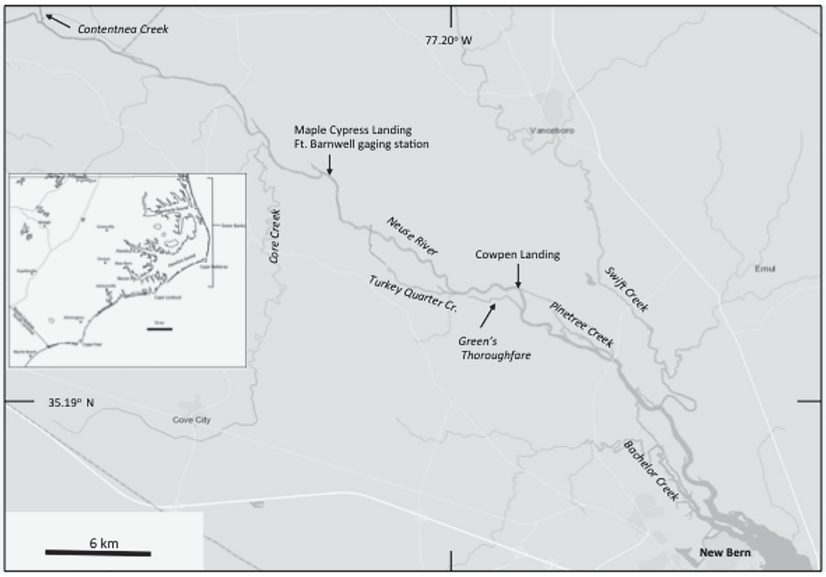

FIGURE 1 Lower Neuse River study area. Inset shows Neuse estuary in regional context

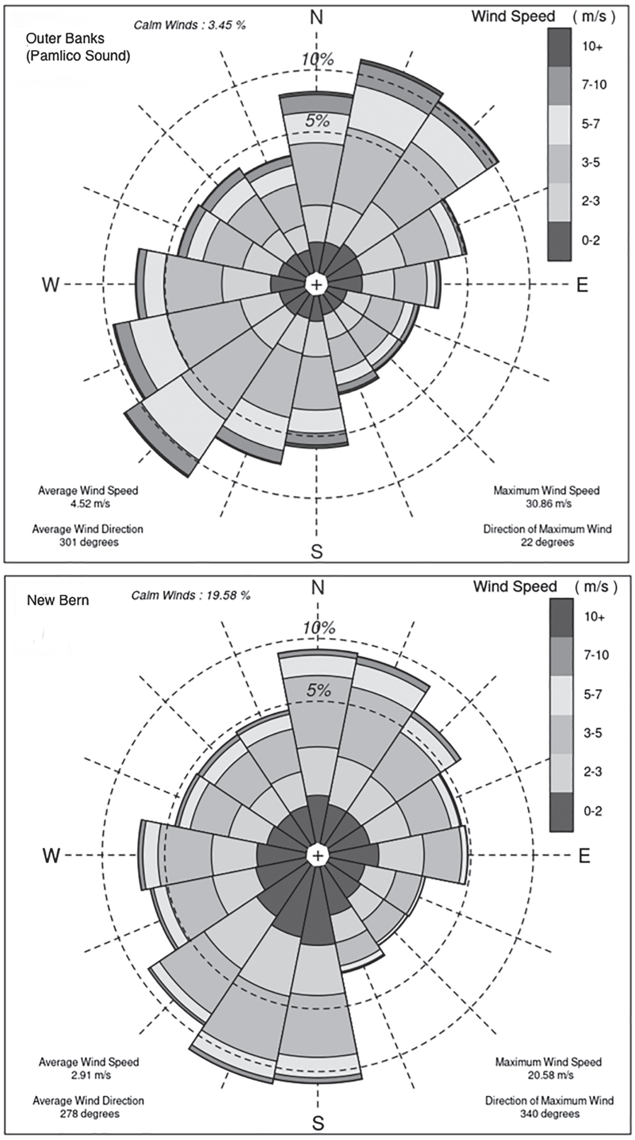

FIGURE 2 Wind roses for airports on the outer banks (near Frisco, North Carolina, top) and coastal regional airport in New Bern, from 1 March 1957 to 1 November, 2021. Generated from a tool provided by the North Carolina Climate Office (https://climate.ncsu.edu)

estuarine sedimentation, geomorphic transitions, and ecological change in the region (Bellis et al., 1975; Grand Pre et al., 2011; Mallinson et al., 2018; Mixon & Pilkey, 1976; Nelson, 1973; Riggs & Ames, 2003; Wells & Kim, 1989).

Geomorphic and ecological change linked to recent and contemporary sea-level rise in the study region has been documented by Brinson et al. (1995), Moorhead and Brinson (1995), and Peterson and Li (2015) with respect to freshwater and brackish wetlands; Phillips (1997) for alluvial floodplain sedimentation; and Phillips (2018a,b) with respect to geomorphic transitions. Shay et al. (2010) modelled effects of sea level on storm surges and tidal inundation based on both a case study (Hurricane Isabel, 2003) and projected sea-level rise of up to 2 m. Their results show, among other things, an intensification of the coastal backwater effects that already exist in the Neuse River upstream of the estuary.

A seismic profile and series of cores across the Neuse just downstream of the Trent River confluence in New Bern were included in Mattheus's (2009) study of morphology and sedimentation of North Carolina drowned river valley estuaries. The seismic line shows a reflector is 5–10 m below sea level in mid-channel, thinning towards the shorelines. This corresponds with a lithological contact between very loose clay, silt, fine sand, and organics overlying denser fine to coarse sand, interpreted as alluvial fills overlying earlier estuarine deposits. Mattheus and Rodriguez (2014) examined 20 lower coastal plan valleys and their sedimentary fills in North Carolina, focusing on small drainages contained within the coastal plain rather than larger rivers such as the Neuse, but including several Neuse estuary tributaries and nearby systems. Similar to the larger rivers, these show evidence of incision (and in the case of the smaller valleys on the outer coastal plain, formation) during lower sea-level stands, followed by drowning and sedimentary infill during sea-level rise.

The Neuse River FETZ has thus evolved under the influence of Holocene sea-level rise influencing both coastal backwater effects at the downstream end and freshwater inflows upstream.

2 | METHODS

Data collection and analysis was designed to investigate the hypotheses listed above. Specifically, the goals were to:

1. Identify active channels and anabranches, high-flow channels, floodplain depressions, and frequently flooded wetlands. This included determining the hydrological status of features visible on maps and images, and identifying features unclear or invisible on images.
2. Assess hydrological connectivity at a range of flow levels, including discharges below the median and mean flows.
3. Identify longitudinal transitions of landforms, hydrology, soils, and ecology along the valley bottom characteristic of the leading edge of sea-level rise.
4. Compare the forms and processes of the FETZ to fluvial environments upstream and the estuary downstream.

Data includes information from topography, soils, and wetland maps and databases; Google Earth™ images; U.S. Geological Survey (USGS) stream gauging station field measurements; and field observations.

Topographic data was in the form of digital elevation model (DEM) data. This included a 3 m horizontal DEM derived from LiDAR data, as well as a 10 m-resolution DEM, both obtained from the USGS via the National Map (https://apps.nationalmap.gov/viewer/). This was used to produce contour and shaded relief maps of the lower Neuse area, and to extract selected elevation profiles in the study area. More detailed quantitative terrain and hydrological analyses of the DEMs were attempted, but these produced results that contradicted field observations. This was likely because many features observed in the field that are important in determining flow and inundation patterns have length scales <3 m and are thus not well represented in the 3 m and 10 m horizontal resolution of the DEMs. Thus, the DEMs were relied on mainly for identifying larger landforms, visualization of the topographic setting, and general topographic characterization.

Soil maps and map data were obtained from the U.S. Department of Agriculture (USDA), Natural Resources Conservation Service, via the Web Soil Survey (https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm) and SoilWeb (https://casoilresource.lawr.ucdavis.edu/gmap/) tools. Map data is based on field mapping by USDA personnel at 1:24 000 scale using the U.S. Soil Taxonomy. Map units are linked in the web tools to descriptions, data, and interpretations of the soil map units. The map units are associated with particular combinations of landform settings, sedimentary parent material, soil hydrology and drainage, and vegetation communities.

The U.S. Fish and Wildlife Service's National Wetlands Inventory (NWI) was the source of wetlands maps, using the Wetlands Mapper tool (https://www.fws.gov/wetlands/data/Mapper.html), also at 1:24 000 scale. The classification system and criteria are described by the Federal Geographic Data Committee (2013). The wetland classes reflect the general hydrologic setting, frequency of flooding, inundation, and soil saturation, and dominant vegetation.

Aerial photographs were obtained from Google Earth™. These are mainly high-resolution, true-colour photographic aerial and satellite images, though resolution and image quality varies, and some older images are in black and white. In most parts of the study area the earliest available on Google Earth™ date to 1985, and the most recent were taken in 2019. These were used to identify key geomorphic and ecological features, for change detection, and to indicate the inundation status of various features. Earlier black and white aerial photography dating from 1957 to 1977 was obtained from the USGS EarthExplorer repository (https://earthexplorer.usgs.gov).

The only gauging station within the study area is USGS station 02001814, designated as Neuse River near Fort Barnwell, North Carolina. The station is adjacent to a bridge at a site locally known as Maple Cypress Landing. Data from this station was used to determine the characteristic discharge regimes. Field measurements were obtained from https://waterdata.usgs.gov/nc/nwis/measurements/?site_no=02091814&agency_cd=USGS. The field measurements are used to establish and maintain stage–discharge rating curves, and include measurements of channel width and cross-sectional area, water stage, velocity, and discharge. These data were used to identify thresholds at which multiple channels are activated.

I conducted field observations and photography, mainly via kayak, in 2018 and 2019 for reconnaissance and planning purposes (dates and associated discharges are shown in Table 2 in the Results section). Field observation in 2020 and 2021 was undertaken to resolve questions raised by the GIS and image-based analyses, and to ground-truth imagery and map data. Observations during high flows in February and March 2021 took advantage of the ability to relatively easily navigate the swamp forests to reach poorly accessible locations and to visually observe flow patterns. Locations of fieldwork are shown in Figure 1.

The field and aerial imagery observations are in essence a reconnaissance study, as more observations across a wider range of flows and stages, and perhaps monitoring programmes and tracer studies, are necessary to resolve some of the details.

3 | RESULTS

3.1 | Channel and valley geomorphology

In the upper estuary at New Bern, North Carolina, the Neuse River channel is slightly more than 1500 m wide. About 6 km upstream of the confluence with the Trent River at New Bern, the channel narrows to about 1000 m, with low-lying islands. These are dominated by brackish marsh vegetation, with some bald cypress trees present. Less than 2 km further upstream, the Neuse becomes a multichannel system, with two to four perennially flowing channels, and the main river channel narrowing to 150 m or less. This general form persists up to the upstream confluence of the river with Turkey Quarter Creek (Figure 1). Subchannels occur further upstream, but are partly or wholly vegetated. The open-channel portions appear on imagery to be connected to the Neuse only at the downstream end, while the upstream connections are vegetated channels and difficult to see on imagery and mostly not portrayed on maps. Some of these investigated in the field, however, are hydraulically connected to the river at normal flows. The vegetated channels, which also occur within floodplain areas not associated with open-water channels, are characterized by permanently inundated tupelo and cypress within the channel and often have nearly complete tree-canopy coverage. Four kinds of channel are evident. Active channels always convey flow and include the main river channel and anabranches such as Turkey Quarter Creek, Green's Thorofare, Pinetree Creek, and others. Backwater channels are continuously inundated, sometimes conveying flow downstream and sometimes ponded. Non-flowing conditions or upstream water movement occurs during northeasterly winds and at lower river stages. Downstream flow was observed at higher river stages. High-flow channels are activated at higher river stages. Some of these are apparently Neuse River paleochannels, while others are smaller channels within the floodplain. Sloughs—floodplain lakes that are abandoned channel segments—also occur. These are usually ponded, but at higher stages become connected to each other and active channels by high-flow channels or floodplain flow. The floodplain swamps—almost entirely from Core Creek downstream and to some extent between Contentnea and Core creeks, are inundated and convey visible flow at river discharges below the designated flood stage for the gauging station at Maple Cypress Landing.

Downstream of Maple Cypress Landing, the riverbanks are low and indistinct—there is often no sharp demarcation between the edge of the river and other open channels and the swamp forest, with no clearly discernible bank top or natural levee. Rather, at typical and high stages there is a transition over a few metres from channel to swamp forest. At low stages wet banks less than 1 m above river stages are visible. This is also the case in some locations upstream of Maple Cypress, but levees and banks are more common there.

From Contentnea Creek to Maple Cypress Landing, the DEM-derived relief map shows a relatively distinct main channel, but tributary and secondary channels are less distinct (Figure 3). Scroll bars roughly parallel to the river are apparent, some of which contain active or high-flow secondary channels. A Neuse River paleochannel is also present, with the lower reaches occupied by Grinnell Creek. Some remnant Pleistocene terrace islands are present, but these are mainly about 2–2.5 m in elevation, while the floodplain is <1.5 m.

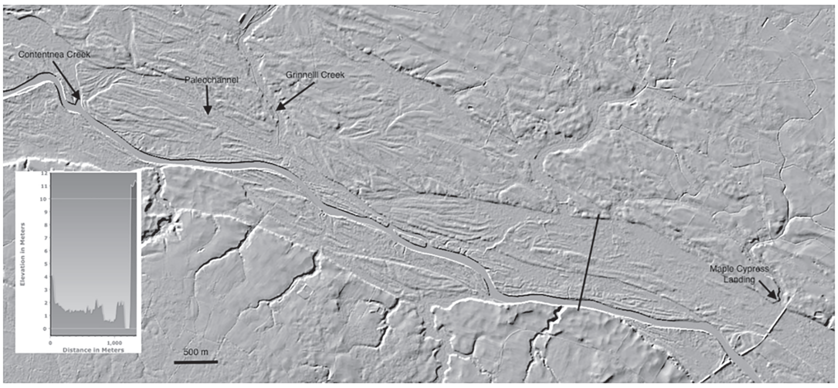

FIGURE 3 Shaded relief map of the Neuse River valley bottom from Contentnea Creek to Maple Cypress Landing. The elevation profile is along the line shown, from the left (north) side of the valley to right

Downstream of Maple Cypress Landing, part of the Grinnell Creek paleochannel continues along the left valley wall, with a backwater flooded portion connecting to the Neuse at Pitchkettle Landing (Figure 4). Some Pleistocene terrace remnants are present in mid-valley bottom, disturbed by sand mining. These terraces continue as linear parallel ridges downstream of Harris and Pitchkettle landings, and encompass a possible paleochannel connected to Turkey Quarter Creek.

The latter is an active channel further downstream (Figure 5), with an artificially constructed connection to the river (see 'Avulsions and anabranches' section below). The creek channel is not obvious on the relief map, so the general trend of the Turkey Quarter Creek corridor is shown. The island between the Neuse River and Turkey Quarter Creek contains numerous backwater-flooded subchannels, small active anabranch channels, high-flow channels, and isolated sloughs. Note that the complex of channels and floodplain is entirely below 1 m in elevation. No terrace remnants exist along Turkey Quarter Creek.

From the downstream confluence of the Neuse and Turkey Quarter Creek (Figure 6) another active anabranch occurs, Green's Thoroughfare. Though the place name 'thoroughfare' for a channel is often applied to an artificial channel, Green's Thoroughfare is natural, and apparently named for an early 18th-century plantation that abutted the channel near its upstream end (Saunders, 1886–1890). The linear channel visible in Figure 6 is a canal originally constructed to serve a lumber mill downstream at Street's Ferry (now the site of International Paper Co.'s pulp mill). Roughly paralleling the canal, which is ponded and has barriers at both ends and does not convey flow except during floods, is Pinetree Creek, which is not obvious on the DEM. This is an active anabranch, which does not appear connected to the river on its upstream end on maps. However, fieldwork and detailed examination of aerial imagery show that it is connected to the river as a forested channel just downstream of Cowpen Landing. The scallop-shaped area north of the canal is a high-flow channel occupying a Neuse paleochannel.

The river confluence with Swift Creek is downstream of Street's Ferry (there is no longer a ferry at the site, but the place name persists). The Gut (an active anabrach) and lower Bachelor Creek (Figure 7) occupy a Neuse River paleochannel. While patches of freshwater marsh occur further upstream, the island between Bachelor Creek and the unnamed subchannel (a backwater-flooded channel) is the upstream-most area of extensive marsh. Islands downstream of Hog Island are all marsh, with a few bald cypress trees.

3.2 | Wetlands and hydrologic status

With the exception of some alluvial terrace remnants upstream of Turkey Quarter Creek, the entire valley bottom is wetlands or open water. The aquatic zones are channels and abandoned channel water bodies. The latter include sloughs and linear lakes, but no oxbow lakes. The wetland types according to the NWI are shown in Table 1. The FETZ is dominated by type PFO6F, which in the study area is a persistently flooded hardwood swamp. Areas near channel edges are dominated by *T. distichum* and *N. aquatica*, while interior swamp areas are more strongly dominated by the latter. Other tree species are also present, as mentioned in the study area description. The marsh wetland types occur only downstream of the confluence with Swift Creek, and indicate sites exposed to higher salinity.

The flow and inundation status of floodplain wetlands, depressions, and subchannels was also assessed via fieldwork and imagery. Three of six field observations (previously reported in Phillips, 2022) occurred during flows greater than both the day-of-the-year mean and the overall mean discharge at the Fort Barnwell gauging station at Maple Cypress Landing (though there is only a 24-year record for this station). Three other field days were associated with discharges less than both the overall and day-of-year means; in one case in the lower quartile of flows (Table 2). During the three higher flow observations, 95 to >99% of the vegetated surfaces (floodplains, bars, and channel margins) were inundated, with visually evident flow. In addition to downstream and downvalley flows, the observed fluxes included both channel-to-swamp and swamp-to-channel exchanges.

On two of the lower-flow field days I observed flow through the vegetated areas, and inundation was >90% by visual estimation. Less than half the vegetated areas were inundated on the observation day with the lowest discharge, but even on this day, some flow through the vegetated areas was evident, and water levels in channels were only 0.2–0.4 m below the floodplain surface at non-inundated sites. Upstream movement was observed due to backwater effects near the main river channel, and during a wind-driven water-level rise on the lowest-flow day.

Ten images covering the 2007–2019 period were found with sufficient clarity and resolution to observe ponded or flowing water in vegetated areas (Table 2). Four images were from days with mean flows at Fort Barnwell less than day-of-year or period-of-record means, and two during lowest-quartile flows. However, the presence or absence of water could in most cases only be observed in canopy gaps, as even in winter images it was difficult to distinguish between

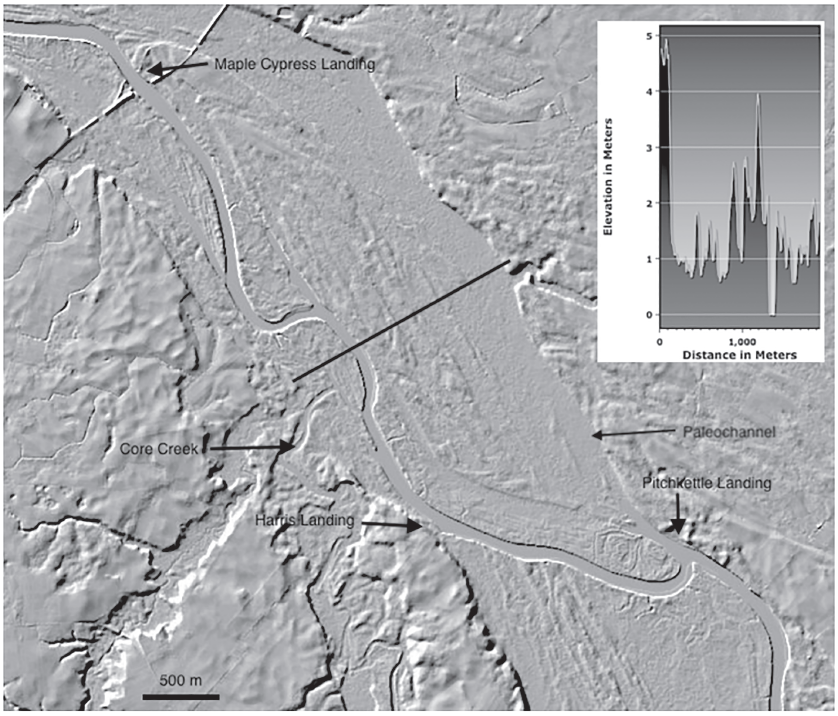

FIGURE 4 Shaded relief map of the Neuse River valley bottom downstream of Maple Cypress Landing. The elevation profile is along the line shown, from the left (north) side of the valley to right

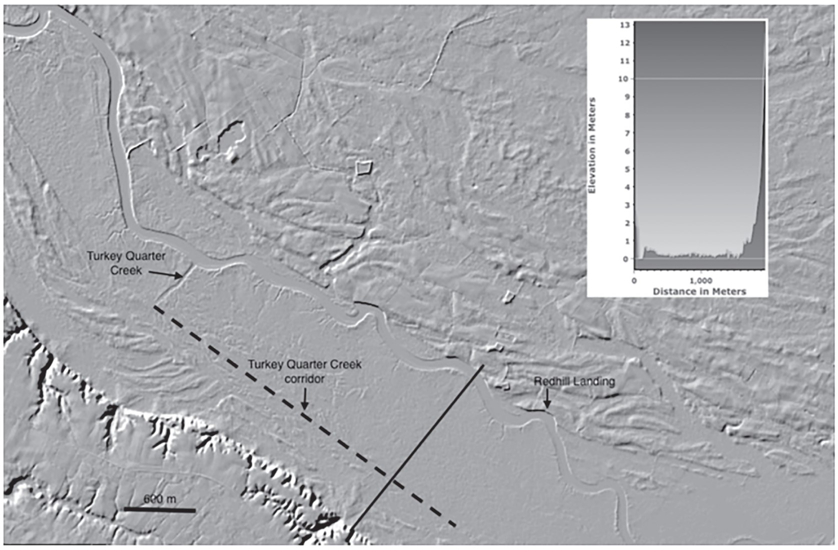

FIGURE 5 Shaded relief map of the Neuse River valley bottom downstream of Pitchkettle Landing. The elevation profile is along the line shown, from the left (north) side of the valley to right

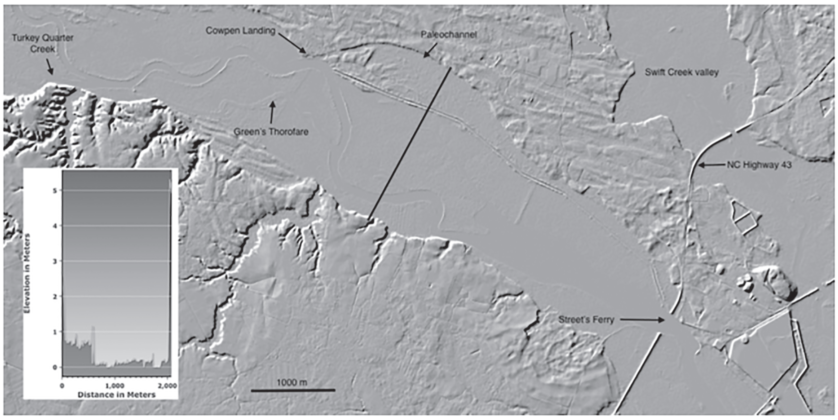

FIGURE 6 Shaded relief map of the Neuse River valley bottom in the vicinity of Green's Thoroughfare and Street's Ferry. The elevation profile is along the line shown, from the left (north) side of the valley to right

FIGURE 7 Aerial photograph of the lowermost fluvial and uppermost estuarine section of the Neuse River (2018 image, USGS National Aerial Imagery Program) [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 NWI wetland types in the study area (hydrologic regime is based specifically on conditions in the lower Neuse River)

Code	Description	Hydrologic regime	Comments
PF06F	Palustrine, forested, deciduous, semi-permanently flooded	Persistently flooded; water table near surface and isolated standing water present even during dry periods	By far the most common wetland type in the study area; found throughout
PFO6C	Palustrine, forested, deciduous, seasonally flooded	Frequently flooded, water table near surface and isolated standing water present even during dry periods. Commonly flowing	Mainly in upper portion of study area; not present downstream of Turkey Quarter Creek
PEM1T	Palustrine, emergent, persistent, semi-permanently flooded tidal	Persistently flooded, strongly affected by wind tides, subaerially exposed only during strong southwesterly wind	Marsh with a few cypress trees; present only in lower portion of study area
PF01C	Palustrine, forested, broadleaved deciduous, seasonally flooded	Frequently flooded, water table near surface and isolated standing water present even during dry periods	Present only near Contentnea Creek in upper portion of study area
PSS7C	Palustrine, scrub–shrub, evergreen, seasonally flooded	Frequently flooded	Found only near edge of valley bottom in lower portion of study area

water and wet mucky soil in densely forested areas. In all images, standing or flowing water was observed in all canopy gaps.

Images generally did not reveal major changes, with two exceptions. One is human modifications, mainly near New Bern in the lower end of the study area. This includes some shoreline residential development and a large quarry (for marl and aggregates) opened in 1958. The quarry was closed in 1996, but protective dikes that truncated tributaries and side channels still exist. The 1957 photographs indicate that most of the site was upland forest rather than floodplain. The other major change evident from comparing photography in 1957, 1964, and 1974 to later images is the erosion and drowning of marsh islands in the lowermost study area, resulting in a reduction in size of larger islands and disappearance of two smaller ones.

3.3 | Soils

Phillips (1992b) found that mica flakes in alluvial soils of the Neuse and other North Carolina coastal plain rivers are a good indicator of a dominantly Piedmont sediment source, with absence of mica flakes indicating dominantly coastal plain sources. Mica flakes are rare to absent downstream of the confluence with Contentnea Creek, and

TABLE 2 Dates of field observations and of aerial images (from Google Earth™) where water can be observed throughout floodplains, with mean daily discharge for the date at the Fort Barnwell gauging station, and average daily mean discharges for the date for the 1997–2020 water years. Overall average discharge is 146 $m^3 s^{-1}$

Fieldwork date	Discharge ($m^3 s^{-1}$)	Daily mean discharge	Observation area
11 May 2019	74	123	Right anabranch near New Bern; Bachelor Creek; The Gut
1 Jun 2020	245	88	Left anabranch near Bridgeton and subchannels
25 Feb 2021	668	168	Upstream of Maple Cypress Landing
9 Mar 2021	311	178	Cowpen Landing area; Green's Thoroughfare
16 Apr 2021	127	149	Turkey Quarter Creek
26 Apr 2021	58	131	Spring Garden; Pinetree Creek

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 Jul 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	~6 months post-Hurricane Florence; images during Florence flooding obscured by clouds

are not present in any of the soils mapped in the area (Table 3). Contentnea Creek is a major tributary whose watershed is entirely within the coastal plain, typically accounting for more than 25% of the discharge at the Fort Barnwell gauging station. The lack of Piedmont-derived sediment downstream is attributed to alluvial storage further upstream, and to being overwhelmed by non-mica-bearing coastal plain sediment sources (Phillips, 1992b).

Floodplain soils downstream of Contentnea Creek are of the Masontown/Muckalee map unit. The Masontown series is a Cumulic Humaquept, very poorly drained, with mucky loam A horizons overlying sandy loam, loamy sand, and sand C horizons. The cumulic subgroup indicates actively but relatively slowly accreting soils. This is consistent with field observations of recently exposed floodplain surfaces during falling stages after extended inundation. These had a muddy fine sediment film, but no deposition sufficient to cover the most recent leaf litter layer. The Muckalee series is a poorly drained Typic Fluvaquent, with a loam surface layer over loamy sand and sandy loam C horizons. Both the Masontown and Muckalee are found only on stream and river floodplains.

In the general vicinity of Green's Thoroughfare the soil maps show a transition (consistent with field observations) from the mineral Masontown/Muckalee complex to very poorly drained Histosols. These are mapped as the Dorovan series, a Typic Haplosaprist. These consist of thick (>2 m) layers of black muck over sand. The Longshoal series appears in the lower reaches of the study area, associated with brackish marshes. The Dorovan series in eastern North Carolina has been interpreted as representing portions of river valleys being actively drowned by rising sea level and consistently influenced by coastal backwater effects (Daniels et al., 1984; Phillips, 1992a). In the study area it is mapped only downstream of Cowpen Landing.

Along the margins of the floodplains and existing as islands within the floodplains are sandy soils associated with alluvial terraces. It may appear that the terraces supporting the Conetoe soils might be older, as this series has an argillic Bt horizon and is classified in the Ultisol order, while the other terrace soils lack Bt horizons and are classified as Entisols. However, beyond the fact that morphology and profile maturity alone are not always a reliable indicator of relative age, the Bt horizons of the Conetoe are sandy loam in texture and considered to be argillic because of some coating and bridging of sand grains with clay. Given the humid climate and moderately rapid to rapid permeability of all the terrace soils, this could be simply due to a greater availability of fine material in the parent deposits of the Conetoe rather than to age differences.

The DEM and soil maps show that sandy alluvial terrace remnants occur as 'islands' within the mucky loam and loam floodplain soils. These are generally <1 to 2.5 m in elevation above the floodplain, and about 1.5 to 4.0 m below the elevation of the nearest valley-side upland. These remnants indicate past avulsions.

3.4 | Discharge and multiple channels

The Fort Barnwell gauging station site has from one to four actively flowing channels or floodplain segments. Before 2014, the USGS field measurements reported only the overall or average values. From 2014, when multiple channels were measured, they were reported separately. From January 2014 through 1 October 2021, 49 measurements occurred. Of these, 25 reported multiple channels (two to four), 14 with four channels. The largest discharges for single-channel measurements from 2014 onwards range from about 66 to 74 $m^3\ s^{-1}$, with associated cross-sectional areas of about 173–198 m^2. The smallest cross-sectional area for the main channel in a multichannel measurement was 205 m^2, associated with a discharge in the main channel of nearly 91 $m^3\ s^{-1}$.

Median discharge at the station is 67 $m^3\ s^{-1}$. The flood stage designated by the National Weather Service at this site is 13 ft (4 m) and is associated with a discharge of about 617 $m^3\ s^{-1}$. The highest recorded stage during the period of record occurred during Hurricane Floyd in 1999, and is associated with an estimated discharge of 1620 $m^3\ s^{-1}$. This might have been exceeded during Hurricane Florence in 2018, as the gauge failed before the peak was reached.

A graph of discharge vs. cross-sectional area (total for all channels measured) shows the cross-sectional area increasing relatively slowly with discharge up to a 60–70 $m^3\ s^{-1}$ threshold, and more rapidly thereafter (Figure 8). This reflects the rapid increase in flow area as subchannels are occupied. At discharges above about 50 $m^3\ s^{-1}$, mean flow velocities begin approaching the maximum observed here (about 1 $m\ s^{-1}$) (Figure 9). Velocities > 1 $m\ s^{-1}$ were measured only in concrete culverts conveying flow under the roadway; maximum velocity measured in the main channel was 0.85 $m\ s^{-1}$. Together with Figure 8, this shows that up to the multiple channel threshold increased discharge can be partly accommodated by higher velocities within the main channel, but at higher flows multiple channels result in adjustment mainly by increased cross-sectional area. The mean daily flow with a 50% exceedence probability (median discharge) is indicated in Figures 8 and 9. This indicates that multichannel flow is initiated near this value and well below mean discharge.

Note that measurements are not always taken at exactly the same location, owing to issues of access, ease/difficulty of measurement, and safety. Some occurred at the gauge site, but others were up to 180 m upstream. Also, some measurements were rated by the field crews as ‘fair’ or ‘poor’ rather than ‘good’. Further, the site is

TABLE 3 Soil series mapped in the Neuse River FETZ

Series	Taxonomy	Texture	Hydrology	Setting
Masontown	Cumulic Humaquept	Mucky loam over sand	Very poorly drained, frequently flooded	Floodplain swamps
Muckalee	Typic Fluvaquent	Loam over loamy sand	Poorly drained, frequently flooded	Floodplain swamps
Dorovan	Typic Haplosaprist	Mucky peat over sand	Very poorly drained, very frequently flooded	Floodplain swamps
Bibb	Typic Fluvaquent	Sandy loam over silt loam	Poorly drained, frequently flooded	Floodplain swamps near Contentnea Creek[a]
Johnston	Cumulic Humaquept	Mucky loam over sandy loam	Very poorly drained, frequently flooded	Floodplain swamps near Contentnea Creek[a]
Longshoal	Typic Haplosaprist	Mucky peat over muck	Very poorly drained, very frequently flooded	Brackish water marshes
Conetoe	Arenic Hapludult	Loamy sand over sand	Well drained, rarely flooded	Pleistocene alluvial terrace remnants
Seabrook	Aquic Udipsamment	Loamy sand over sand	Moderately well drained, rarely flooded	Pleistocene alluvial terrace remnants
Tarboro	Typic Udipsamment	Sand	Somewhat excessively drained, rarely flooded	Pleistocene alluvial terrace remnants

[a] Soils in this area were mapped in an older survey. The Bibb/Johnston complex soils would likely be mapped as Masontown/Muckalee now.

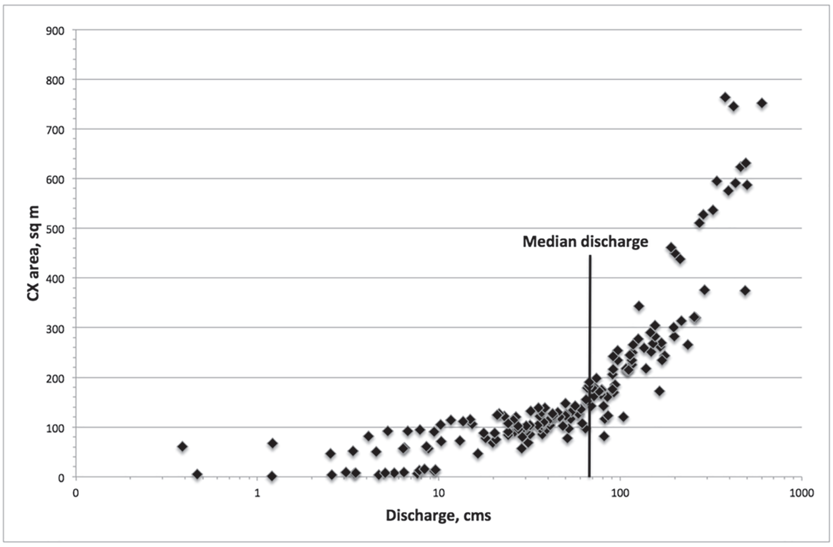

FIGURE 8 Discharge vs. channel cross-sectional area plot for field measurements at the gauging station at Maple Cypress Landing, identified as Neuse River near Fort Barnwell, station 02001814. Note the logarithmic scale on the horizontal axis

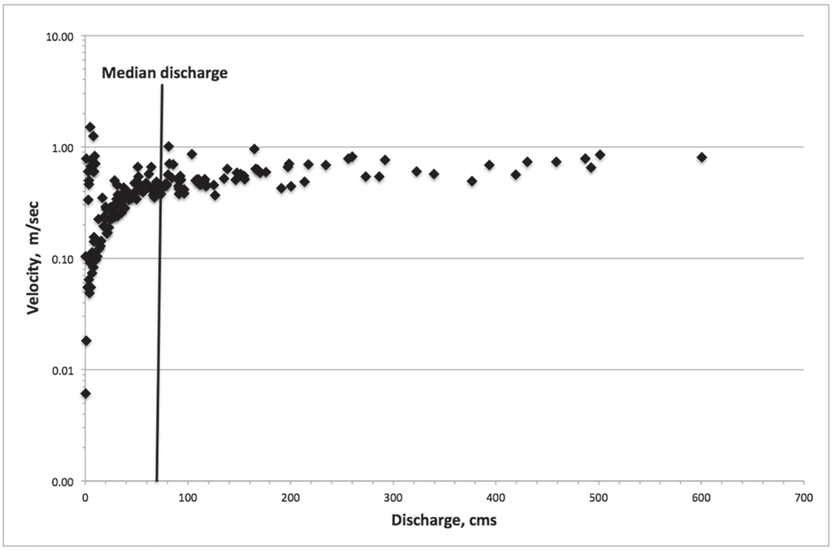

FIGURE 9 Discharge vs. mean velocity plot for field measurements at the gauging station at Maple Cypress Landing, identified as Neuse River near Fort Barnwell, station 02001814. Note the logarithmic scale on the vertical axis

characterized by a road crossing, partially via bridge and partially via causeway. These caveats notwithstanding, results suggest that at discharges greater than the median, flow is accommodated by multiple channels.

High-flow channels of various kinds are common on low-gradient coastal plain rivers and multiple-channel measurements at higher flows are common at USGS gauging sites. However, at the Neuse River gauging station at Kinston, the next station upstream, multiple channels show up in field measurements only at flows above banktop stages, the National Weather Service-designated flood stage at the site. By contrast, at the Fort Barnwell/Maple Cypress site, multiple channels are recorded at flows of only about 13% of those associated with banktop stage.

The USGS site information indicates that flow is affected by both astronomical and wind tides. The astronomical tides occur at primary harmonic periods of 12.42 and 24.84 h. However, stages and discharges here are weakly affected by backwater effects, and mainly influenced by discharges from the river and from Contentnea Creek. Rapid stage changes in the 10–20 cm range associated with wind tides appear as a sawtooth pattern superimposed on the hydrograph.

3.5 | Avulsions and anabranches

Subchannels whose size and orientation indicate that they are likely major Neuse anabranches or former river channels are listed in Table 4. Those labelled 'paleochannel' are believed to be former main channel locations abandoned by avulsions (this is revisited in the Discussion section). The subchannels upstream of Street's Ferry are shown in Figure 10, while The Gut and Bachelor Creek are readily visible in Figure 7. Many of these channels, or sections thereof, are not visible on maps or photographs; their locations were determined via field investigations. Note that numerous smaller subchannels and sloughs occur within the valley bottom wetland/channel complex.

Six channel segments in Table 4 are active, and three others may be active, backflooded, or high-flow and require observations during lower stages to confirm. Three are tributary occupied, supporting their interpretation as Neuse paleochannels. Two segments are completely or partially backflooded, and two others may be backflooded or active. Six channel reaches were assessed as high-flow or possibly high-flow channels; all were observed conveying flow during field observations at high stages or in images acquired during relatively high flows. One of these, upper Taylor Creek, may be active at all flows.

Turkey Quarter Creek has an artificially constructed connection to the Neuse main channel. No historical record of this could be found, but a levee-like feature of apparent dredge spoil is present where no other similar features exist. The connecting channel is also unusually straight, and Turkey Quarter Creek passes near to plantations and farms that were present by 1740, as per the *Colonial Records of North Carolina* (Saunders, 1886–1890). There are also several locations where the right bank of the creek abuts upland rather than floodplain, making these suitable sites for landings. The channel downstream of the connection is fed by several small tributaries, and springs from marl outcrops, and was an open-water tributary before the connecting channel was cut.

Green's Thoroughfare (Figure 7) is an anabranch just downstream of Turkey Quarter Creek. Unlike areas further upstream, the island between this channel and the Neuse includes no Pleistocene terrace remnants. Rather, it is entirely comprised of frequently flooded mucky soils. This also applies to all anabranches and sloughs downstream of Turkey Quarter Creek.

3.6 | Leading edges

The Neuse River thalweg elevation is below sea level at the Contentnea Creek confluence, and relative sea-level rise has greatly affected the FETZ. Accordingly, we would expect to find signatures of the leading edge of encroaching backwater effects within it.

Vegetation responds to changes in hydroperiod and salinity. Plant geography in the FETZ and vegetation change have not been examined in enough detail to make definitive statements, but field observations are at least broadly consistent with vegetation changes expected from sea-level rise and documented in other FETZs in the Carolinas (cf. Brinson et al., 1995; Ensign et al., 2014; Moorhead & Brinson, 1995; Stahl et al., 2018; Taillie et al., 2019; Ury et al., 2021). 'Ghost trees' are standing dead trees killed by increased wetness for non-hydrophytes or by increased salinity for hydrophytes. Especially

TABLE 4 Subchannels in the Neuse River FETZ

Feature	Status	Comments
Grinnell Creek paleochannel	Upper: HFC Mid: TO Lower: HFC, BF	Terrace islands present between paleochannel and river. Upper channel elevation significantly above river level
Maple Cypress paleochannel	HFC; BF near confluence with Neuse	Possibly a continuation of the Grinnell paleochannel; elevation above river level except at confluence. Terrace islands present between paleochannel and river
Village Creek	AC	Forested channel near upper end; most of channel well above river level
Upper Turkey Quarter paleochannel	HFC	Terrace islands present between paleochannel and valley side. Above river elevation
Rainbow Lake	AC or BF	Upstream portion forested channel. Active or backflooded status uncertain. Terrace island present between channel and river. No terrace islands downstream of this point
Turkey Quarter Creek	AC	Upstream connection to river artificially constructed. Same elevation as river
Turkey Quarter Island channels	AC or BF	Upstream portions forested channel. Active or backflooded status uncertain
Taylor Creek	Upper: AC or HFC Lower: TO	Upstream portion forested channel. Probably active, but not observed at lower discharges
Green's Thoroughfare	AC	Same elevation as river
Cowpen paleochannel	HFC	Elevation above river. Lower reaches obscured by canal construction
Pinetree Creek	AC	Upper reaches forested channel. Same elevation as river. Several connector channels typically flow to river, but may be backflooded
The Gut	AC	Bachelor Creek occupies lower portion of this channel
Bachelor Creek	TO, AC	Lower reaches frequently backflooded. Unnamed channel parallel to creek is backflooded or ponded except during high flows

AC = active channel; BF = backflooded; TO = tributary occupied; HFC = high-flow channel.

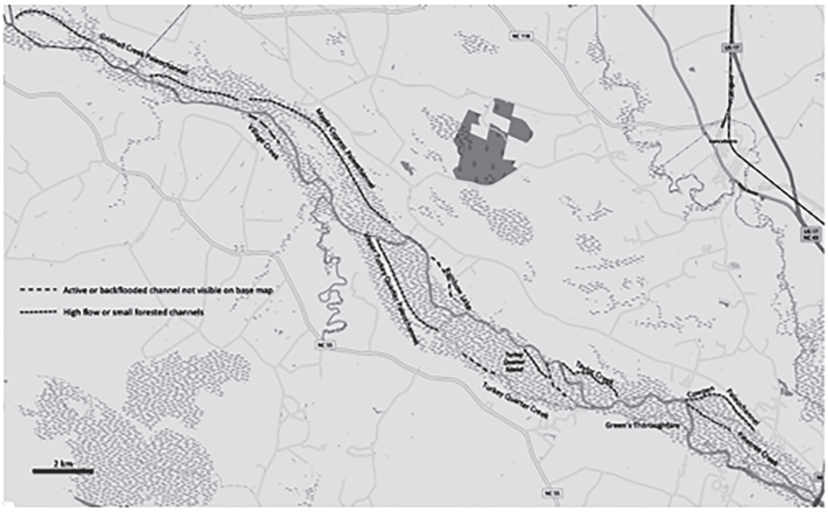

FIGURE 10 Subchannels in the Neuse River FETZ upstream of Street's Ferry. Features not visible on the base map added by author (base map from OpenStreetMap via USGS National Map)

indicative is *T. distichum*, which survives constant inundation but can be killed by higher salinity (*N. aquatica* is similar in these respects, but decomposes more rapidly and is less visually evident). Dead cypress are common (along with other ghost trees) in the upper estuary and lower FETZ of the Neuse and are being replaced by more salt-tolerant marsh grasses. These include *S. cynosuroides*, *C. jamaicense*, and *Phragmites australis* (common reed), though the latter may be more influenced by escape from disturbed sites than by hydrological changes.

As mentioned earlier, the Dorovan soil series is diagnostic of fluvial valleys subject to long-term increasing backwater effects of sea-level rise. Near the upstream end of Turkey Quarter Creek, soil maps show a clear transition on the floodplain, with Dorovan soils absent upstream and strongly dominant downstream (except on the marsh islands, where the Longshoal series occurs). At approximately the same location, terrace islands disappear in the downstream direction. Because some terrace remnants are still present along the valley sides, it is likely that from Turkey Quarter Island downstream the terraces are buried under Holocene deposits dominated by the organic Dorovan soils. Further upstream, a short distance above Maple Cypress Landing, the NWI maps show a transition from mainly very frequently flooded types downstream to seasonally flooded upstream.

Phillips (1992b) noted the approximate correlation between the upstream limit of Dorovan soils and the Walterboro scarp. The latter is a paleoshoreline separating the lower, younger Talbot marine terrace to the east from the Wicomico terrace inland (terrace and scarp nomenclature follows Daniels et al., 1972). DEM data allow better identification of the Walterboro scarp than was possible at map scales in the 1990s. The scarp is relatively distinct south of the Neuse, where it forms a local drainage divide (Figure 11). Mill Run Creek flows towards the Neuse along the base of the scarp, and the headwaters of the creek have breached the scarp feature. The scarp's contact with the Neuse on the south side of the valley is just upstream of the lower end of Turkey Quarter Creek. Typical upland elevations in the vicinity of the scarp are around 9 m on Talbot Terrace and 15 m a.s.l. on the Wicomico. Two tributaries that cross the Walterboro Scarp—Swift and Bachelor creeks—show similar trends, in that the transition from mineral to organic soils corresponds to the scarp.

4 | DISCUSSION

4.1 | Hydrology and morphology of the FETZ

I hypothesized that the Neuse River FETZ consists of a complex of active channels and anabranches, high-flow channels, floodplain depressions, and frequently flooded wetlands that occupy the entire valley bottom. This is indeed the case in the lowermost FETZ, while upstream of Turkey Quarter Creek some islands of slightly higher terrace remnants persist. Additionally, the study identified channels that are predominantly backflooded and former main river channels that are now occupied by tributaries.

I also proposed that channel–floodplain hydrological connectivity exists at most flow levels. Field observations, analysis of gauging station data, and imagery confirmed that connectivity exists at discharges well below median and mean flows.

Results also confirmed the hypothesized (and previously suggested) transitions along the river corridor reflecting, or characteristic of, the leading edge of sea-level rise. This includes a transition from dominantly organic (downstream) to mainly mineral alluvial soils, corresponding with the Walterboro Scarp paleoshoreline, increasing prevalence at the lower end of the FETZ of salt-tolerant marsh vegetation rather than bottomland hardwood swamps, and 'ghost trees' killed by increasing salinity and hydroperiods. Downstream reductions in bank height and the disappearance of terrace remnants are also consistent with recent encroachment by rising water levels.

I also hypothesized that the FETZ encompasses forms and processes distinctly different from fluvial environments upstream and the estuary downstream. This is indeed the case, as summarized in Table 5. The fluvial properties listed reflect the Neuse River from

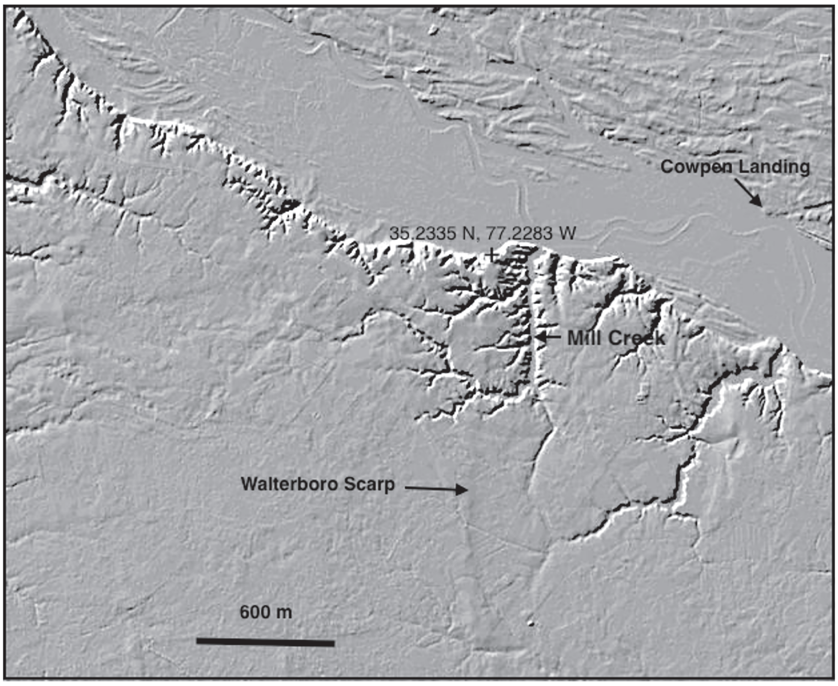

FIGURE 11 The Walterboro scarp paleoshoreline

TABLE 5 Comparison of fluvial, estuarine, and transition zone features of the lower Neuse River

Landform or feature	Fluvial	FETZ	Estuary
Channels	Single	Multiple	Single, embayed
Dominant channel width (m)	50–65	60–150[a] 150–1000[b]	>1000
Types of channel present	Single active, high flow, sloughs	Multiple active and backflooded, high flow, tributary occupied, sloughs	Active, backflooded, or embayed
Banks	Distinct	Low, indistinct	Distinct[c] Low, indistinct[d]
Floodplain inundation	Occasional to seasonal	Semi-permanent	Rare[c] Semi-permanent[d]
Minimum channel–floodplain connectivity stage	Overbank or near overbank	Low (<median discharge)	Storm surge[c] Low (<mean low water)[d]
Dominant wetland types	Bottomland hardwood forest	Bottomland hardwood forest; freshwater and brackish marsh	Brackish marsh
Floodplain sediment	Mineral	Organic	Mineral[c] Organic[d]

[a] Contentnea Creek to Street's Ferry.
[b] Downstream of Street's Ferry.
[c] Low and high bank shorelines.
[d] Marsh fringe shorelines.

Kinston to the FETZ. Some estuary properties in Table 5 distinguish between low and high bank shorelines that are rarely flooded except in large storms, and marsh fringe shorelines.

The Neuse River FETZ is a complex mosaic of channels (active, backflooded, high flow), wetlands that often convey surface flow, and floodplain depressions. Apart from the terrace islands, the entire complex can store and convey water (at varying velocities) in response to both upstream fluvial inputs and downstream storm surges and backwater effects at flows well below median discharges or stages. The distinction between channels and wetlands is often unclear and gradual, and the floodplain (as opposed to the terrace) islands contain forested perennial subchannels as well as depressions.

We inevitably ask how this relates to existing classifications. No classification of the infinitely variable natural environment can easily and unambiguously incorporate every observation, and it seems more reasonable to view such categorizations as identifying key discriminating factors and benchmark conditions rather than as analogues to biological taxonomies that seek to catalogue all significant varieties. Nonetheless, we are compelled to at least consider labels and descriptive terms to facilitate communication.

The channel–wetland complex of the lowermost Neuse River is somewhat similar to bayhead deltas with respect to its landscape setting and multichannel morphology. However, 'delta' implies a locus of deposition, and a bayhead delta is defined as a sedimentary system forming where sediment-laden freshwater enters brackish water, neither of which are applicable to the Neuse FETZ. However, the free exchange of water between channels and islands may be typical of deltas. Analysis of the hydrological exchange between channels and islands in Wax Lake delta in the Louisiana Gulf of Mexico showed that the deltaic islands are zones of significant water flux, with about a quarter to half (23–54%) of incoming distributary flow entering the islands (Hiatt & Passalacqua, 2015). Flow travel times through channels were at least threefold faster than through the islands. The study also found the islands to be more sensitive to tidal flow reversals. They concluded that the islands are an important part—along with channels—of the distributary hydrological network of the delta. Tracer studies found that flow between channels and islands could be reversibly bidirectional via secondary channels, varying according to differential water levels associated with river influx, winds, and tides; and that flow within islands could also be bidirectional. Dominantly unidirectional (channel to island) secondary channels also exist. Hiatt and Passalacqua (2015) characterized that the channel–island network shows a mixed divergent and convergent network behaviour. The Neuse FETZ is at least broadly similar in these regards.

The multichannel system of the lower Neuse could be described as anastomosing, a common planform in low-gradient, fine-grained systems. However, in anastomosing rivers the islands are not inundated at sub-banktop flows (Carling et al., 2014), while in the study area wetland islands are inundated and often conveying flow even at median discharges. Another terminology option for the planform morphology of the lowermost Neuse is 'island-braided' (Carling et al., 2014), though it hardly fits neatly into the traditional conception of that term. Braiding is generally associated with high-sediment-load, gravel-bed rivers, and some of the Neuse's vegetated and frequently inundated areas are contiguous to the valley side and not true islands. However, a key trait of braided rivers, as opposed to other multichannel planforms, is that the islands or bars are frequently flooded and all are inundated at banktop flow. In the classic braided river, these banks are those at the outer margins of the valley bottom river corridor, encompassing all the lower-flow subchannels. In the study area, like the channel margins within the river corridor, the outer margin banks are often indistinct, with a gradually sloping transition to higher, terrestrial environments, as opposed to a relatively abrupt break in slope. At stages and discharges that occur frequently throughout the year, and well below the elevation of a clearly terrestrial setting at the margins, the islands and floodplains are inundated and usually conveying flow.

Though they specifically restricted their discussion to valley corridors unaffected by coastal processes, Lewin and Ashworth's (2014) review of negative relief in alluvial floodplains of large rivers (channel widths roughly 100 m or greater, which applies to much of the Neuse FETZ) indicates that complex mosaics of channel, ponded, wetland, and riparian landforms and ecosystems are common. They also identified rheic, transitional, and perirheic components. Rheic forms convey flow and include main channels and anabranches. Transitional features comprise slackwaters and backwaters of various kinds, channel remnants still connected to active rheic channels, and internal drainage channel networks. Perirheic features include sloughs and oxbows, and floodplain depressions of various kinds. All three classes of feature are present in the Neuse study area.

4.2 | Applicability to other coastal plain rivers

The channel/wetland complex of the lower Neuse, as well as some of the 'leading edge' transitions found there, also occur to varying extents in nearby rivers such as the Tar-Pamlico (another tributary to the Pamlico Sound), the Newport and Cape Fear rivers, North Carolina, and the Waccamaw River, South Carolina (Ensign et al., 2013, 2014; Eulie et al., 2018; Noe et al., 2016; Phillips, 1992a), though none of the other rivers has been examined in detail for all of the identified features. Examination of maps and images, and field experience in several Gulf of Mexico coastal plain rivers (e.g. Phillips, 2013, 2014, 2017; Phillips & Slattery, 2006, 2007) suggests that the phenomena found in the Neuse are widespread in similar coastal plain settings.

Some differences would be expected. In FETZs with significant astronomical tides, clearer transitions can be observed in channel morphology, sedimentology, and hydrodynamics (Renwick & Ashley, 1984; Sulaiman et al., 2021; Torres, 2017). In a wind-dominated system the spatial transitions are less abrupt. Thus, transitions over time in response to coastal submergence may be more difficult to detect in rivers draining to wind-dominated estuaries than in tidal rivers. One aspect worthy of further study in wind-dominated systems is the synoptic climatology and hydrology associated with the interaction of high discharges from upstream and wind effects downstream. During Hurricane Florence in September 2018, for instance, high stages in the lower FETZ were dominated by wind-driven storm surge effects (up to 4 m in New Bern), despite upstream Neuse discharges in the top three of all recorded flows. Minimal geomorphic impacts of the storm occurred in the FETZ, as river flood and storm surge waters spread over the channel/wetland complex.

4.3 | Response to sea-level and climate change

The geomorphology of the Neuse River FETZ indicates the ongoing, and suggests the future, upstream extension of coastal backwater effects. This is associated with upstream migration of the locus of sediment deposition and a transition from mineral to organic soils. The backwater zone corresponds to a zone of indistinct or very low banks, and lack of discernible natural levees. As backwater effects migrate upstream, permanently, semi-permanently, and frequently flooded wetlands extend on the upstream leading edge at the expense of occasionally or seasonally flooded swamps. At the downstream end of the FETZ, oligohaline and brackish marshes replace bottomland hardwood swamps. Both trends will continue, or accelerate, along with the burial of Pleistocene terrace remnants by modern alluvial sediments.

The avulsion regime may also be transformed from a typical one associated with valley aggradation and overbank flow, to a regime associated with backwater-induced spillover.

Just downstream of the Contentnea confluence is also where the first evidence of Pleistocene or later avulsions occurs, a characteristic typical of deltas and FETZs. Avulsions typically occur in aggrading systems where sediment loads regularly exceed transport capacity. This is not the case in the study area, though it may have been earlier in the Pleistocene when sea levels were lower. The likely mechanism is backwater setup in the main river that reduces its slope gradient advantage, forcing some of the discharge from upstream into secondary channels—a phenomenon identified by Sassi et al. (2011) in the Mahakam Delta.

Incision of channels below sea level is possible, but limited due to low slopes and lack of debris flows or turbidity currents in the transition zone. The buildup of channel banks by deposition is also limited due to low sediment supply, and bank erosion is inhibited by high resistance associated with dense vegetation and fine sediment, along with low shear stresses. Channel gradient adjustments are likewise limited by low landscape slopes, and proximity to base level. In such circumstances the development of multiple channels is the primary mechanism for fluvial adjustments (Huang & Nanson, 2007).

Coastal submergence may not be geographically uniform, even within a single estuary system. Foraminifera in salt marsh cores from two different locations within the Pamlico–Albemarle estuarine system show differential rates. Relative sea level rose by about 2.4 m in the past ~3 ka at Cedar Island in southern Pamlico Sound near the mouth of the Neuse estuary, and ~3.3 m over the same period at Roanoke Island, where northern Pamlico Sound connects to Albemarle Sound (Kemp et al., 2017). Tidal hydrodynamics, compaction, or local sediment dynamics cannot explain the differences, which Kemp and co-workers attribute to the effects of ocean and/or atmospheric circulation. This suggests that while all coastal plain rivers in the region have been and are being subjected to coastal submergence, local and regional differences may exist in the sea-level forcing as well as in the environments of the rivers.

In a study of 67 alluvial rivers in the United States, Slater et al. (2019) found that river channel conveyance capacity adjusts to modes of climate variability by expanding or contracting. Generally, they found that bankfull channel capacity increases via channel enlargement by bed and bank erosion, and by decreasing roughness during wetter periods with increased runoff. During dryer phases of climate oscillations, channels aggraded and increased in roughness, leading to reduced conveyance capacity. They concluded that 'river networks may be viewed as dynamic, breathing systems that expand and contract over interannual to multidecadal timescales in synchrony with regional climate'.

The Neuse River FETZ is, and has been, subject to the climate oscillations considered by Slater et al. (2019), plus Holocene and contemporary sea-level rise. The rising base level provides an additional constraint on flow conveyance. The lowermost Neuse is also constrained in terms of the ability to enlarge or infill its channels or to adjust its slope, as described above. Bank erosion is limited due to low unit stream power and resistant banks. The main degrees of freedom for adjustment of channel conveyance capacity are this roughness, which can change via vegetation and organic debris, the number of channels, and frequency of overbank flow. In these environments, traditional concepts of geomorphic adjustments to flow changes (cf. Phillips, 2013) may not be applicable. Instead, changes in the mosaic of open channels, vegetated channels, ponded storage, and flowing swamps, along with terrace islands, are likely, though the dynamics and mechanisms of such changes are little known.

This study did not focus on the biogeomorphology of the FETZ, but vegetation is critical to resistance, and to the roughness of the river corridor in slowing high flows. Growing-season water use by plants is also a significant factor. Bald cypress typically germinates in specific geomorphic environments, particularly stream banks or margins, and infilling sloughs or oxbows (e.g. Keim et al., 2006; Shankman & Kortright, 1994; Stahl et al., 2018) Because of the unique aspects of FETZs subjected to coastal submergence, a better understanding of the coevolution of hydrological, ecological, and geomorphological aspects of the FETZ is needed. None of the trees common in the study area can germinate in standing water, but those that can tolerate constant inundation when mature (e.g. cypress and tupelo; Dicke & Toliver, 1990; DuBarry, 1963; Kozlowski, 1984; Sun, 1995) currently exist in permanently flooded channels and ponded areas. The role of geomorphic and hydrologic change, and of disturbances, in the establishment and maintenance of these basally submerged trees is unclear.

4.4 | Implications for management and adaptation

The transition zones from rivers to estuaries, with their complex of channels and wetlands, provide important ecosystem services, including fish, wildlife, bird, and vegetation habitat; sequestration of carbon, sediment, nitrogen, and various pollutants; and storage of floodwaters from both river flows and storm surges. These functions and values, coupled with their status as hotspots for geomorphological and ecological responses to climate change, make FETZs priorities for adapting to environmental change.

In some FETZs, topographic constraints and rapid urbanization limit the ability of wetlands and aquatic systems to expand upstream. In the lower Neuse, topographic constraints are not significant with respect to the longitudinal axis of the river. Channel slopes are low well upstream of the FETZ, and geomorphic responses to sea-level rise are already transgressing the Walterboro scarp. Laterally, however, there may be some constraints to wetland expansion at the valley walls of the river corridor. Urbanization has indeed been extensive in recent decades around the Neuse estuary and in the New Bern area. However, further up the river corridor the inherent constraints of the waterlogged, inundation-prone landscape have largely prevented development except at some isolated locations where channels abut the valley sides. US wetlands protection programmes have also helped protect much of the area, as has inclusion of the lowermost islands of the FETZ, Turkey Quarter Island, and some additional swamplands in the state's Neuse River Gamelands preserve.

In the southeastern United States, logging of bottomland tupelo/cypress hardwood forests often results in the replacement of these species by non-native trees that are inferior with respect to ecosystem services. In the study area, logged areas often appear as relatively sparsely vegetated ponds for years or decades after harvesting. While this may be due in part to soil compaction and dewatering during forestry operations, it is also attributable to the fact that many of these areas were consistently inundated before logging.

Establishment of these forests apparently depends on extended periods of low water, which in the lower Neuse would require a period of consistently southerly or southwesterly winds as well as low river flows. Such synoptic events might be viewed as opportunities for reforestation if resources are available, though this would be logistically difficult. Natural regeneration could also occur during storm-driven deposition events, and at the patch scale by uprooting and tree breakage disturbances, which provide locally elevated points and nurse logs. *Nyssa* sprouts readily from stumps, and stump-sprouting and coppice trunks are common in the study area. Cypress in general does not as readily produce stump sprouts, and these are rare in the lower Neuse. Cypress stumps do serve as nurse sites for other species. In general, however, too little is known of the hydrological, geomorphological, or ecological aspects of the establishment and maintenance of swamp forests in the FETZ to provide much guidance. In general, management should recognize the importance of low-water periods, localized deposition, and disturbances, and minimize any removal of toppled or broken trees.

The Neuse FETZ readily absorbed the impacts of Hurricane Matthew in 2016 and Florence in 2018 (Phillips, 2022). The former produced little downstream storm surge but was the flood of record at Kinston and the second highest on record at the Fort Barnwell station. While flood damage occurred upstream of the FETZ, little occurred within or downstream. Similarly, the FETZ weathered upstream flood discharges and record high storm surges of Florence. This underscores the ability of the channel/wetland complex to store and delay floodwaters and release them downstream relatively gradually. Flood protection programmes should therefore include maintenance of the FETZ in its semi-natural state and direction of any engineered solutions to other areas.

5 | CONCLUSIONS

The fluvial–estuarine transition zone of the Neuse River features a river corridor that conveys flow along the entire valley, in a complex of active, backflooded, and high-flow channels, sloughs and other floodplain depressions, and wetlands. Hydrological connectivity among these features exists at median discharges and stages, and at least partial connectivity at even lower stages. Water exchange among the various elements can occur in any direction, but at high stages the complex operates to effectively store water within the valley bottom and eventually convey it to the estuary along both slow and more rapid paths.

The general hydromorphology of the FETZ, along with specific features such as very low or indistinct channel banks and histosols formed under swamp forest, are unique to the FETZ compared to the estuary downstream and fluvial reaches upstream. The geomorphology of the FETZ has been shaped in an environment of Holocene and contemporary relative sea-level rise and contains several signatures of the leading edge of encroaching coastal backwater effects. This legacy accounts for the ability of the lowermost river to accommodate extreme flood flows from upstream, and extraordinary storm surges from downstream (as illustrated by Hurricane Florence).

Some aspects of the lower Neuse River are not necessarily typical of coastal plain rivers in general (e.g. the wind-dominated nature of the Neuse estuary), but many characteristics are, at least in general, common. In the lower Neuse—and in fluvial-to-estuary transitions of many other coastal plain rivers—the options for geomorphological adaptation and adjustment to climate change, sea level, and upstream flows are limited. Landscape slopes and relief are low, channels are close to base level, sediment inputs are low, and banks have high erosion resistance relative to hydraulic forces. Potential is therefore limited for channel deepening (by incision or by vertical floodplain accretion), shallowing, widening, or narrowing, and lateral migration. Adaptations are therefore dominated by the formation of multiple channels, water storage in wetlands and floodplain depressions, increased frequency of overbank flow (compared to upstream), and adjustments of roughness via vegetation, woody debris, multiple channels, and flow through wetlands.

DATA AVAILABILITY STATEMENT

Data for this study are available from the author upon reasonable request.

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