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Landscape change and climate attribution, with a case study of estuarine marshes

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ABSTRACT

Determining effects of climate change on landscapes involves numerous uncertainties. This paper presents and illustrates a protocol for climate attribution of landscape responses. The major steps are ascertaining potential climate-related responses, establishing plausibility for a climatic influence, identifying alternative or additional causes, testing possible climate and non-climate causes, and interpreting the role of climate and climate change in the landscape response. The protocol is based on existing practice in the historical and interpretive branches of Earth and ecological sciences, and explicitly considers negative (non-confirmatory) results for climate and other factors. The protocol is applied to the conversion of brackish marsh to open water in the upper Neuse River estuary, North Carolina. Conversion since at least the mid twentieth century can be attributed to relative sea-level rise, driven primarily by general climate warming, with no supporting evidence for any additional or alternative drivers. The only other factor with supporting evidence is human modification in the form of ditches, around which conversion was concentrated, though marsh loss also occurred in unditched portions. Rapid recent marsh loss is attributable to Hurricane Florence (2018), particularly the storm surge. Weak positive inferential support exists for a role of climate change in the storm, but aspects of the storm's impact not linked to climate are more important for the marsh conversions. Overall, the landscape response can be linked to climate, exacerbated by direct human impacts of marsh ditching, and strongly influenced by local place factors and the specific storm track. Recent and ongoing climate change is a significant factor, but not paramount, in determining the landscape response. The Neuse River case study is not unusual—and is probably typical—in identifying a combination of climate and other factors strongly influencing landscape response.

1. Introduction

Recent and ongoing climate change is implicated in a variety of environmental changes and responses, including landforms and geomorphological processes (East et al., 2022; IPCC, 2022). However, as geomorphological phenomena are influenced by a variety of factors other than climate—and by climate independently of contemporary climate change—determining the role of meteorological events, climate, and climate change in landscape responses can be problematic. The purpose of this study is to present a protocol for assessing the role of climate in landscape responses and illustrate its application in a case study of conversion of estuarine marshes to open water in North Carolina.

Climate change and meteorological events have always driven changes in geomorphological, hydrological, and ecological processes and the associated landscape responses. As climate change accelerates, so do landscape responses. However, few (if any) such processes and responses are driven exclusively by weather and climate phenomena. Landscapes are influenced by atmospheric, biological, hydrological, geophysical, and geochemical processes, as well as by inherited topographical, geological, and pedological frameworks and ecological legacies. Further, apart from extraterrestrial inputs (e.g., solar radiation) and some geophysical processes (e.g., tectonics, volcanism, planetary rotation), human activity directly or indirectly affects all of these. Further still, there exist constant interactions and feedbacks among climate, hydrology, soils, landforms, biota, and human activities. Notwithstanding the increasingly serious and apparent impacts of recent and ongoing climate change on landscapes, in some cases direct anthropic environmental impacts (e.g., urbanization, mining, agriculture, air and water pollution) exceed those of climate and arguably take priority in terms of management, policy, mitigation, and remediation efforts. Landscape changes often have serious health and safety, food

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security, economic, and legal implications as well as environmental impacts. Accordingly, there exists a need to refine our ability to identify climate impacts on landscape changes and determine their importance relative to other triggers and drivers of change.

This paper presents and then illustrates a framework for accomplishing this. The framework is based on existing practices in Earth and environmental sciences, emphasizing on historical and interpretive approaches, as the extensive data sets often available for attribution studies of meteorological events are often not available. Additionally, the time scales of landscape change—even when restricting attention to contemporary and recent historical responses—are often longer than observational records.

In their commentary on attributing geomorphic and sedimentary responses to modern climate change, East et al. (2022) highlighted some of the common challenges, including limited data records (in terms of length and completeness) and data availability, factors such as land use and seismicity obscuring climate effects, and signal attenuation in sedimentary records. This study is relevant to both of East et al.'s (2022) key recommendations—selection of climate-sensitive study sites, and reporting of null results (i.e., cases where climate is not a major factor).

1.1. Event and response attribution

Qian et al. (2022) provide a recent review of event attribution research in atmospheric sciences, and a compendium of studies of climate attribution (i.e., assessment of the role of recent and contemporary anthropically-influenced climate change) is maintained by the Climate Attribution Database (https://climateattribution.org). While the latter includes many studies of indirect relevance to geomorphology (such as climate change impacts on hydrological responses, sea-level, and ecosystems), there is little direct attention to geomorphic processes and landforms.

An example of an event attribution approach is the World Weather Attribution (WWA) initiative. WWA is focused on determining the extent to which major meteorological events are attributable to our changing climate. Their attribution protocol is outlined in Philip et al. (2020) and summarized in van Oldenborgh et al. (2021). They outline an eight-step process, starting with determining which events to analyze and concluding with communicating the results. The second step, event definition, determines which aspect of the event to analyze. WWA sticks to meteorological and hydrological variables and does not include impacts. Step three is observational trend analysis, to determine how rare the event is in the current climate, and the extent to which this has changed over the period of observation. An appropriate climate model is then chosen, and step five is model analysis, using the models to estimate how much more intense or likely the event has become (if at all) because of anthropogenic emissions. One approach is to run two simulations—one for the current climate, and one for a hypothetical climate the same as the current one, but with human modifications removed. A second is to simulate the historical climate under various scenarios, up to the present and about two decades beyond. These simulations are then analyzed the same way as the observations. This assumes that the influences of natural forcings such as variations in solar input and volcanic eruptions is small compared to the anthropogenic ones. In step six, the WWA protocol combines information from the observations and models to produce an assessment of how the probability and intensity of the physical extreme event has changed. The final step before disseminating the results is to evaluate risk, considering the hydrometeorology event itself; exposure of people, property, or other resources; and vulnerability.

The protocol for extreme weather event attribution is not directly transferable to landscape response attribution for several reasons, chiefly associated with the fundamental differences between climatology and meteorology on one hand vs. geomorphology (or pedology or paleoecology) on the other. Even more fundamentally, weather and climate event attribution aims to determine the extent to which meteorological and climatological events can be attributed to climate change, whereas landscape response attribution (LRA) seeks to assess the extent to which climate drives or controls landscape responses. LRA may be associated with specific events or types of event and thus directly linked to weather event attribution or may be independent. The study of effects of climate on landscapes, of course, dates to the early days of the landscape sciences and predates climate and landscape simulation modeling.

This study is focused on attribution for specific responses in specific locations or regions. General statements about the role of climate in landscape responses are valid and figure prominently in the LRA protocol. This knowledge base is the key to establishing climate as a suspect in driving responses. Thus, for a simple example, the knowledge that droughts can trigger aeolian erosion and dust storms gives us strong reasons to suspect climate when accelerated wind erosion occurs during or following a drought. Similarly, certain landscape dynamics are symptomatic of climate variations, e.g., permafrost thawing or increased runoff, and thus point to climate change as a potential driver. All landscapes and Earth surface systems are individualistic, however, with important elements of singularity, idiosyncrasy, and historical and geographical contingency. Thus, for example, though it has been demonstrated that climate change and extreme weather events can trigger landslides, it is not feasible to apply that conclusion to specific landslides without local investigation, or to develop general principles, even within a given region (Dikau and Schrott, 1999; Jomelli et al., 2007). The same applies to (partially or potentially) climate-driven events in general (e.g., Knighton and Nanson, 2001; Cutter et al., 2008; Phillips and Van Dyke, 2016; Hughes and Croke, 2017).

A distinction exists between landscape responses that are directly linked to climate such as permafrost thawing, glacial retreat, and soil temperature increases; and those indirectly driven by climate, such as responses to changes in fire regimes or relative sea-level. However, the attribution principles are the same in either case.

2. LRA protocol

The methodology outlined here is a codification—something of a decision tree or checklist—based on traditional good scientific practice in the interpretive and historical branches of geosciences and ecology. It is thus entirely consistent with existing frameworks for interpretation and attribution of landscape change (recent examples include Fryirs and Brierley, 2012; Downs and Piégay, 2019). The LRA protocol is intended to facilitate the reporting of negative (non-confirmatory) results (as championed by East et al., 2022) for both climate and other factors.

The approach is also informed by and consistent with the dominant controls and dominant processes concepts. The dominant processes concept, first developed in hydrological modeling, recognizes that too many potentially relevant hydrological processes exist to feasibly include them all in a single model. But in any given watershed a handful of processes dominate hydrological responses, and effective models may be developed based on those dominant processes. The dominant processes concept argues for adapting models to local conditions and needs, rather than attempts at “one size fits all” models (Grayson and Bloschl, 2000; Sivakumar, 2004, 2008). Phillips (2011) generalized the dominant processes concept to a dominant controls concept in Earth and environmental sciences more broadly. The dominant controls concept holds that while many factors and processes can influence a given phenomenon (in this case landscape responses), in any given environmental system some will be irrelevant and others of comparatively negligible influence, leaving a few dominant controls to deal with. Other explicit applications of dominant controls/processes approaches in hydrology, geomorphology, and ecology include Collins et al. (2017); Seibert et al. (2017), Ran et al. (2020), and McMillan et al. (2022). The LRA protocol is designed to identify the dominant controls of landscape responses, with an emphasis on determining whether climate (and climate change) is among them.

Once a landscape response is identified for study with a potential climate driver, there are five steps in the protocol, summarized in Table 1: Plausibility, Timing, Other Plausible Causes, Tests, and Interpretation.

The plausibility step involves establishing whether it is reasonable to suspect climate or some climate-related phenomenon as a driver of or influence on the observed response. In some cases, this is straightforward, as in studies of geomorphic or ecological impacts of a storm, flood, or drought. In other cases, this is not clear-cut. For example, consider changes in river morphology, which may be driven by tectonics, human modifications, or internal interactions within fluvial systems in addition to climate and related factors such as vegetation cover and sea-level.

Plausibility can be established based on theory and basic principles, and/or empirical evidence. The latter may include observational and measurement data, or various kinds of historical evidence, including stratigraphic and paleoenvironmental records. Suppose, for instance, the observed response is a decline in forest soil organic matter. If basic principles and theory suggest that rising temperatures lead to a decline in soil organic matter in the type of setting under study, or if empirical evidence shows evidence of a process-response relationship, then a temperature increase is a plausible potential cause.

The second step involves establishing timing. If the landscape response occurred or began before the suspected climate change driver or event, then the potential climate cause can be ruled out. For instance, Šamonil et al. (2020) identified potential pedological, geomorphological, and hydrological responses to forest damage caused by outbreaks of spruce bark beetle. Bark beetle range expansion has been linked to climate warming, making climate a potential contributor to such responses. However, to link responses to climate, it would first have to be shown that an affected area was unaffected (or less affected) by bark beetles prior to recent climate change, and that the purported response did not precede the bark beetle outbreak.

Step three involves identifying all other plausible causes for the observed response. A decline in stream discharge, for instance, could certainly be driven by climate, but also by land use and land cover change, increased withdrawals, diversions, or flow capture by groundwater. The non-climate causes should be ruled out if possible or included as possible alternative or co-causal factors. Sometimes a clear yes/no answer may not be possible, in which case the possible cause should remain under consideration.

Tests are devised and carried out in step four. This involves identifying observations and outcomes that would be consistent or inconsistent with the purported cause, or ideally prove their relevance or rule them out. In the stream flow case, for instance, there may exist direct evidence proving that changes in withdrawals or diversions have or have not occurred. In other cases, inference might be weaker, such as changes in vegetation cover that would tend to increase evapotranspiration, but by an uncertain amount. It is difficult to generalize about tests, as this encompasses the entire range of processes and environments in geomorphology, hydrology, and ecology, but some general guidelines are provided by East et al. (2022).

The LRA protocol is summarized in flow chart form in Fig. 1. In the next section the LRA protocol is applied to the problem of conversion of coastal marshes to open water in the upper Neuse River estuary, North Carolina.

Table 1
Landscape response attribution steps.

1. *Plausibility*—must be established based on:
1.1. Theory, basic principles AND/OR:
1.2. Empirical evidence
1.2.1. Observation, measurement, data
1.2.2. Historical (including paleoenvironmental) evidence
2. *Timing*: Did response occur (or is it occurring) contemporaneously with climate change or divers, or relatively shortly afterwards?
2.1. Yes—potential climate driver
2.2. No—climate driver cannot be established
3. *Other plausible causes*: Do other potential causes or drivers for the observed response exist?
3.1. Identify plausible causes, using criteria in item 1.
3.2. Are identified causes potentially relevant?
3.2.1. No, can be ruled out
3.2.2. Strong yes—present or observed
3.2.3. Weak yes—not known to have occurred, but cannot be ruled out
4. *Tests*: For each possible cause, identify observations or outcomes that either support or refute the potential explanation.
4.1. Strong inference
4.1.1. Positive—proves or very strongly supports
4.1.2. Negative—disproves or very strongly refutes
4.2, Weaker inference
4.2.1. Positive—weighs for
4.2.2. Negative—weighs against
5. *Interpretation*
5.1. Based on item 4, evaluate weight of evidence for and against climatic cause and any other possible causes.
5.2. Develop conclusions on climate or climate-related driver

3. Case study: Neuse River marsh islands

The LRA protocol is applied here to the recent deterioration of marsh islands near the mouth of the Neuse River, North Carolina, at the upper end of the Neuse River estuary. The estuary is the drowned lower valley of the Neuse, which drains about 15,000 km^2 from the Piedmont physiographic province, across the coastal plain, to the Pamlico Sound estuary. In recent years several marsh islands in the upper estuary at the lower end of the fluvial-estuarine transition zone (FETZ) have experienced significant conversion of marsh to open water, mainly on the interior of the islands. What is the potential role of climate in this change?

Though some wetlands can persist or expand, net loss of coastal wetlands from erosion and conversion of marsh to open water caused by relative sea-level rise (SLR) is globally common (e.g., Fitzgerald and Hughes, 2019; Saintilan et al., 2019). It has been known for decades that the loss often occurs in the form of marsh fragmentation, whereby a continuous marsh is converted to a mosaic of marsh and open water (e.g., Phillips, 1986; Nyman et al., 1994). Recent studies confirm this common phenomenon (Phillips, 2018a, 2018b; Schoolmaster et al., 2018; Stagg et al., 2019; Wu, 2019; Schepers et al., 2020). Marsh loss is often caused or influenced by other factors, particularly human impacts, independently of or in conjunction with SLR.

The Neuse estuary is experiencing the effects of rising sea-level and coastal submergence, reflected in a net loss of wetlands, estuarine shoreline erosion, and creation of “ghost forests” (standing dead trees killed by waterlogging and/or higher salinity) (Bellis et al., 1975; Brinson et al., 1995; Moorhead and Brinson, 1995; Cowart et al., 2011; Kopp et al., 2015; Eulie et al., 2017; Phillips, 2018a, 2018b; Taillie et al., 2019; Gunderson et al., 2021). The FETZ exhibits several geomorphic signatures typical of the leading edge of coastal submergence, as described by Phillips (2022b).

Net marsh or wetland loss, however, is affected by factors other than climate-driven eustatic sea-level rise. Coastal submergence may also include subsidence caused by tectonics, isostatic processes, or factors such as autocompaction within sediments. Marsh loss is also sometimes attributable to reductions in sediment supply, so that wetlands are unable to accrete sufficiently to offset autocompaction or water level rises. Destruction or damage to vegetation by pests, disease, grazing, or human activities can also contribute to marsh loss by reducing organic matter inputs, limiting sediment trapping ability, and exposing sediment to waves and currents. Direct human agency such as ditching and drainage can also lead to wetland loss.

The marsh islands studied here are shown in Fig. 2. The conversion to open water is shown in Fig. 3. The contrast of the 2018 and 2019 images

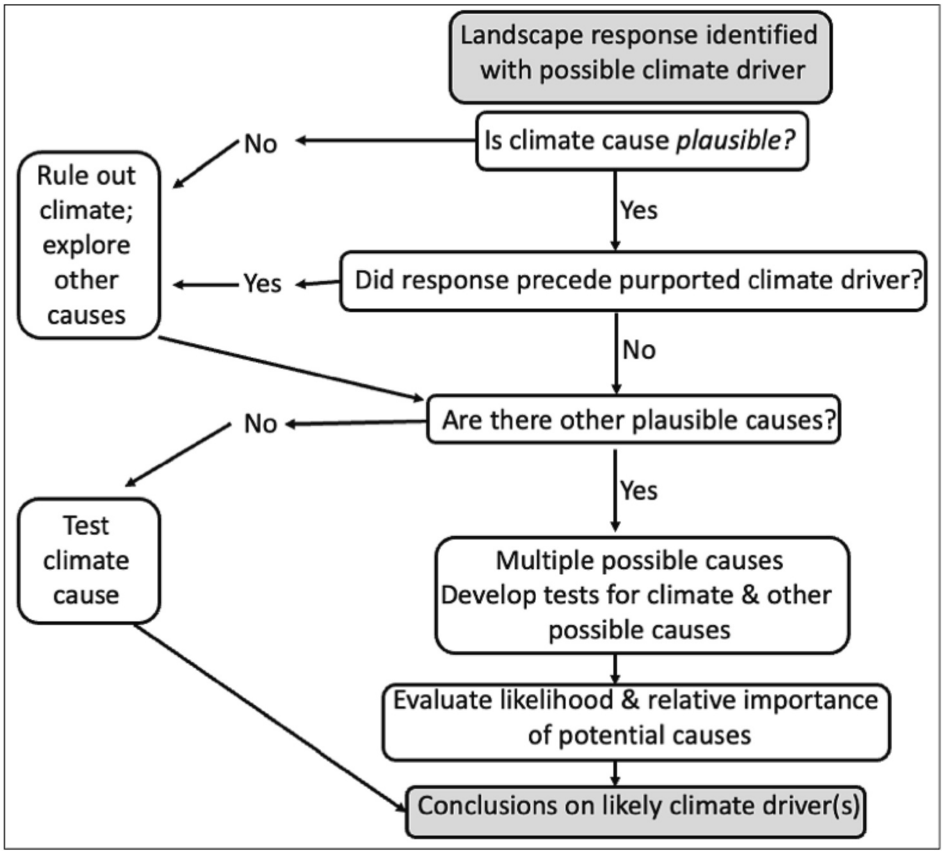

Fig. 1. LRA protocol.

to the 2017 is obvious. Note that the 2018 photo was taken a few days after Hurricane Florence, which affected the area from 12 to 18 September. The 2019 image shows that the marsh loss has persisted (also confirmed by field observation in 2022). Water level measurements for the island zone are not available, except for during Florence, as discussed below. Based on observed water lines on a nearby boat launch ramp (Glenburnie Park, New Bern, about 500 m from the southeast end of the larger study island), water levels were higher in the 2018 and 2019 images than in the 2017 image. However, the open water areas are not visible on any pre-Florence images, including an October 2015 image in which the water level is higher than the post-storm images shown in Fig. 3.

Key questions raised in this case are:

(1) Is the marsh loss linked to relative SLR?
(2) Marsh conversion to open water apparently occurred during Hurricane Florence. Did this occur independently of SLR (i.e., would it have occurred anyway, independently of sea-level effects)?
(3) To what extent was Florence related to climate change?

These questions are broadly relevant to coastal wetlands in general, and in the southeastern U.S. coastal plain, but climate attribution in this case is a decidedly local matter. This is because storm surge impacts of Florence were focused on the Neuse area, and comparable effects on upper-estuary wetlands were not experienced elsewhere, and because the evaluation of possible alternative, non-climate causes must be based on explicitly local factors.

Vegetation cover on the islands is dominated by salt-tolerant herbaceous vegetation typical of brackish marshes in North Carolina, including big cordgrass (*Sporobulus cynosuroides*, formerly *Spartina cynosuroides*) and sawgrass (*Cladium jamaicense*). Some woody shrubs such as bay (*Persea* spp.) also occur, and isolated clusters of bald cypress (*Taxodium distichum*), both living and dead, occur along the island fringes.

3.1. Plausibility

Potential climate related drivers for the marsh loss are well established in the form of eustatic sea-level rise. This has been occurring throughout the Holocene, though wetlands can sometimes keep pace or even expand if net vertical accretion exceeds coastal submergence. Historical air photos show a decline in area of the Neuse River marsh islands from the mid-twentieth century to present, consistent with chronic wetland loss caused by sea-level rise (Phillips, 2022b), though likely episodic (as are most geomorphic and ecological changes), in association with storm events. However, analysis of tidal gages by Houston (2021) shows recent acceleration of sea-level rise, with the long-term record closest to the study area (Wilmington, NC), showing an acceleration of nearly 0.05 mm yr^{-2}.

The pre- and post-Florence images (Fig. 3), along with the severe impacts of the storm in New Bern and the Neuse estuary (Phillips, 2022a), make the storm an obvious culprit. Storms are frequent occurrences, so it is not clear whether the marsh loss reflects normal storm impacts overlaid on sea-level rise or other causes. However, there is also reason to believe that Hurricane Florence and other recent tropical cyclones represent a "new normal" or a moving baseline caused by climate change (Kossin, 2019; Kunkel and Champion, 2019; Li and Chakraborty, 2020; Balaguru et al., 2022; Shearer et al., 2022). As the marsh loss occurred during or following both recent sea-level rise and the 2018 storm, the timing criterion of the LRA protocol is also met.

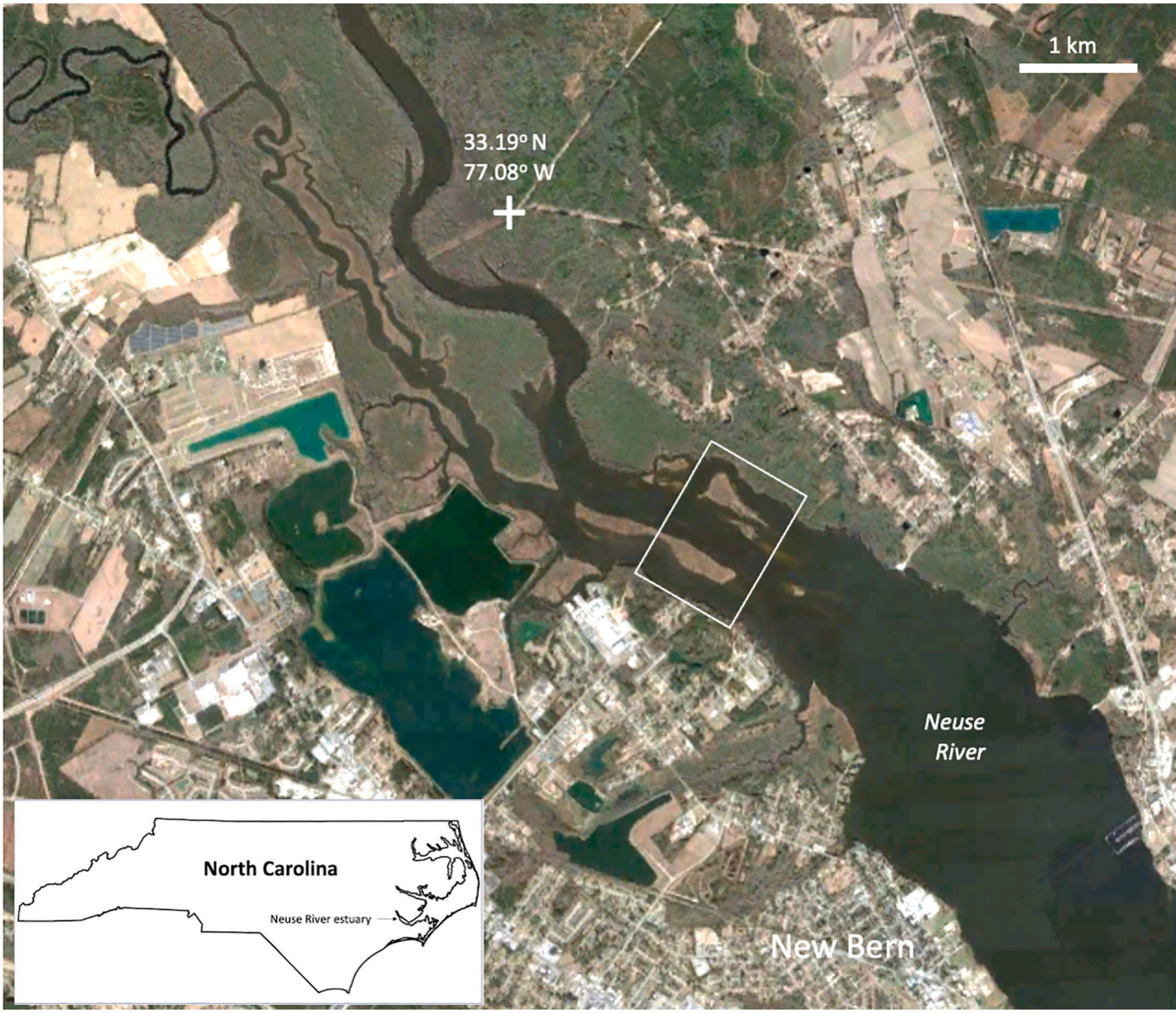

Fig. 2. Study islands near New Bern, North Carolina.

3.2. *Other possible causes*

Beyond sea-level and increased frequency and/or magnitude of storms, potential causes for the marsh loss include reductions in sediment supply, damage to or destruction of marsh plants, construction of ponds by beaver, direct human impacts (in this case, ditches), and erosion by boat wakes.

If a reduction in fluvial sediment supply is a significant factor, then there should be some evidence of reduced riverine sediment input, or a potential causal agent present (e.g., construction of dams or reservoirs upstream, extensive reforestation, soil conservation and sediment control measures). Resuspension of benthic sediments and shoreline erosion are other possible sediment sources.

If marsh plant mortality was a major factor, we would expect to observe some indications of the effects of any disease or pests in the surviving vegetation, or adjacent wetlands. Consumption of marsh plants and physical disturbance of wetlands by nutria (*Myocastor copyus*) and inundation by beaver (*Castor canadensis*) are also possible causes, and both semiaquatic rodents are present in the Neuse FETZ. If they are a cause of the recent marsh loss, then evidence of the animals (if not the creatures themselves) should be observed on the study islands. This includes distinctive nutria burrows, and dams or lodges (or remnants thereof) of beavers.

Direct human impacts on the islands in recent decades are minimal, but some ditches are evident on the larger island (right side of Fig. 3, local place name Marsh Island) and in other wetlands in the vicinity. No historical record of these could be found, and their purpose is unknown. They are visible on aerial photographs from the mid-1950s, and most likely represent attempted mosquito control. Such features are known to contribute to marsh deterioration beyond their construction by facilitating intrusion of storm tides and salt water. If these are a significant driver of the loss, a focus of loss on these features should be present, and a significantly greater proportional conversion on Marsh Island vs. the other study islands.

Boat traffic is common in the vicinity, and boat wakes are a potential source of erosion. If this is the case fringe erosion would be dominant, as opposed to interior deterioration.

3.3. *Evaluating alternative causes*

Reduced terrestrial sediment supply is not responsible for the marsh loss. Input of fluvial sediment from upstream to the Neuse River estuary

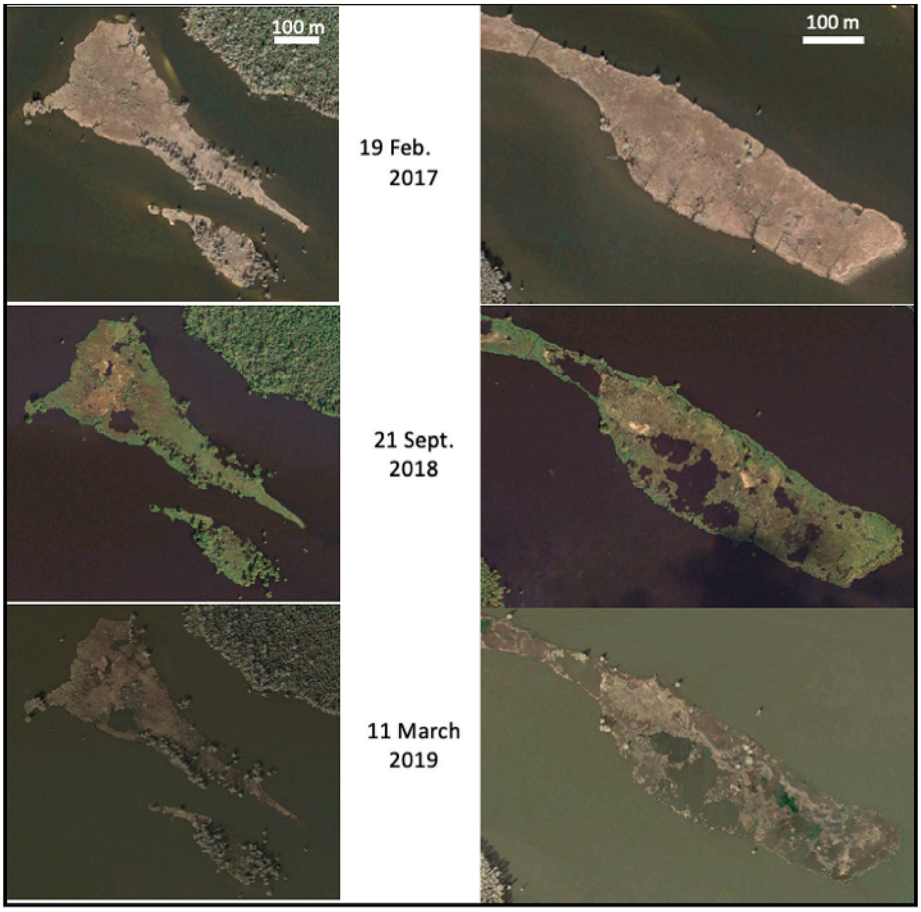

Fig. 3. Google Earth™ images showing conversion of marsh to open water.

is very limited, with most sediment sequestered within or upstream of the FETZ (Kim, 1990; Phillips, 1992, 1997; Benninger and Wells, 1993). Marsh island soils are muck and peat Histosols; mapped as the Longshoal series, characterized by organic layers at least 1.3 m thick over mineral sediments (https://soilseries.sc.egov.usda.gov/OSD_Docs/L/LONGSHOAL.html). Sediments supplied to the lower FETZ and estuary are dominantly from local, coastal plain sources, and there has been no widespread net reforestation or new erosion and sediment control programs. Dams on the Neuse are well upstream, in the Piedmont, and have been in place for several decades, and have no discernible impact on sediment delivery to the lower river (Phillips, 1992). Reduction in the other potential sediment sources (resuspension of bottom sediments, shoreline erosion) fails the plausibility test, as there exists no theoretical reason to suspect reductions in these sources, and no empirical evidence thereof.

There is also no evidence of unusual mortality or plant die-off on the study islands or in nearby wetlands, in aerial imagery or in field observations between 2019 and 2022. Nutria, and particularly beaver, activity, has been observed in the FETZ, including other marsh-dominated islands. However, no evidence (burrows, lodges, dams, chewed wood) was observed in the field, and the paucity of woody vegetation makes the area unattractive for beaver. Further, a marshy area about 3 km upstream of marsh island where extensive nutria activity was noted did not experience marsh loss evident on aerial imagery.

Boat wakes do not appear to be a significant driver of conversion. Marsh loss occurred primarily on the marsh interior rather than edges. A possible exception is the south side of the largest island, but this is also a ditched area, as described below. Further, the marsh vegetation is highly resistant to small waves, such as those produced by boat wakes. In such settings erosion by the wakes associated with small recreational boats is negligible (Bauer et al., 2002). In the study area unvegetated banks are exposed only during very low water events.

Fig. 4 shows the sections of Marsh Island that had been ditched. The 2017–2018 comparison shows a clear concentration of conversion to open water along the lower margin of the island compared to the northern edge. However, large areas of conversion occurred in unditched areas, and one ditch appeared unaffected immediately after Hurricane Florence. Eighteen months after Florence, continued deterioration is evident in the ditched areas, including the one ditch in the northwest corner of the area shown in Fig. 4 that did not experience visible conversion during Florence. However, enlargement of all the open water areas created during Florence can be observed. The ditched study area of marsh island does show greater proportional conversion than the other two, unditched islands, as shown in Table 2.

4. Climate attribution

Potential causes of the loss of marsh in the island zone of the upper Neuse River estuary and the supporting and refuting evidence are shown in Table 3. Relative SLR and ditching of the marsh are supported by observational evidence, while the storm surge explanation is equivocal (with respect to climate change impacts), as discussed further below. There is no supporting evidence, and some refuting evidence, for reduced sediment supply, marsh plant dieback, faunal effects of nutria and beaver, and boat wake erosion as causes.

4.1. Sea-level rise

The ability of coastal marshes to maintain themselves under relative

Fig. 4. Marsh conversion to open water in ditched areas of Marsh Island.

Table 2
Marsh conversion to open water, 2017–2019.

Study area	Total area (m^2)	Area converted (m^2)	Percent converted
Smaller upper (north) island	10,905	1810	16.6
Larger upper (north) island	55,500	4501	8.1
Marsh Island (studied portion)	82,840	25,043	30.2

SLR depends on their net vertical accretion vs. the rate of submergence. The Neuse River FETZ and estuary are characterized by very low fluvial sediment inputs (Kim, 1990; Phillips, 1992, 1997), so that marsh accretion is dependent on organic matter production and retention and other sediment sources such as resuspension of bottom sediments and shoreline erosion. These are apparently inadequate to maintain the Neuse marsh islands—reductions in island size and the disappearance of at least one small island are evident by comparing contemporary imagery with aerial photographs from the 1950s (Phillips, 2022b). The presence of isolated bald cypress trees around the islands also attests to the erosion and drowning of the islands. While mature *Taxodium distichum* can survive in permanently inundated sites and is commonly found in deepwater swamps and along river margins, the species requires subaerial exposure for germination, and cannot be submerged for long periods. Thus, bald cypress in open water in sites that are permanently inundated indicates erosion, subsidence and/or water level rise, or geomorphic change such as channel migration sometime within the lifetime of the tree (Mattoon, 1915; Demaree, 1932; Shankman and Kortright, 1994). In the study area, they indicate sites that were once part of the islands but are now submerged (Fig. 5). Standing dead cypress ("ghost trees") in the same area may also indicate sea-level rise effects via salinity intrusion (Penfound and Hathaway, 1938; Bellis et al., 1975; Taillie et al., 2019).

4.2. Hurricane Florence and climate change

Hurricane Florence impacted the lower Neuse River and estuary from 12 to 18 September 2018. Analyses of the storm and its effects are provided by Feaster et al. (2018) and Stewart and Berg (2019). Some geomorphic impacts of Florence on the Neuse (not including the effects on the marsh islands) were analyzed by Phillips (2022a).

Though maximum sustained winds in the Neuse area never reached hurricane strength (75 mi h^{-1} or 34 m s^{-1}), winds $\geq$20 mi h^{-1} (9 m s^{-1}) persisted for more than four consecutive days. Precipitation was intense, and recorded Neuse River peak flows at the two downstream-most gaging stations (78 and 38 km upstream of New Bern) were the third highest ever recorded (Feaster et al., 2018), but were likely the highest ever experienced, as the gaging stations failed to record the storm's peak flows (Phillips, 2022a). Maximum storm surge inundation heights in the Neuse estuary area were estimated at 2.4 to 3.4 m above the ground surface (Stewart and Berg, 2019; Phillips, 2022a). At a site examined in the field shortly after the storm, wrack lines indicated water levels up to 4 m above

Table 3
Summary of positive and negative evidence relevant to the potential causes of the marsh island conversion to open water. Shaded evidence is present; unshaded indicators are not present.

Potential cause	Supporting evidence	Refuting evidence
Relative sea-level rise (SLR)	•Indications of increased salinity •Ongoing, chronic deterioration •Regional evidence of SLR	•No indications of increased salinity •Loss confined to single event(s)
Increased hydrodynamic stress due to storm surge	•Pronounced post-surge loss •Increased surges due to climate change	•Increased surge not attributable to climate change
Reduced sediment supply	•Reduced fluvial input •Identifiable interruptions or limits on sediment supply (e.g., dams) •Reduction in benthic sediment redistribution •Reduction in non-fluvial sediment sources (e.g., shore erosion)	•Increased fluvial input •No identifiable interruptions or limits on sediment supply •Increased benthic sediment mobilization •Increase in non-fluvial sediment sources
Marsh plant mortality (by factors other than inundation or salinity)	•Evidence in surviving vegetation & nearby wetlands •Effects confined to or concentrated in specific species	•Lack of evidence in surviving vegetation & nearby wetlands
Plant consumption & disturbance by nutria	•Observed nutria •Burrows, evidence of nutria feeding, etc.	•No nutria observed •No evidence of burrows, feeding, etc.
Inundation by beaver dams	•Observed beaver •Dams, lodges, chewed wood	•No observed beaver •No dams, lodges, chewed wood
Direct human impacts	•Presence of ditches, canals, or other modifications •Strong association of marsh loss with anthropic features	•Absence of ditches, canals, or other modifications •Weak or no association of marsh loss with anthropic features
Erosion by boat wakes	•Erosion concentrated on island edges	•Deterioration concentrated in island interior

Fig. 5. *Taxodium distichum* (bald cypress) adjacent to marsh island, indicating conversion to open water.

mean high water (which would include wave effects in addition to storm surge). Multiple news media reports indicated flood water depths in the streets of New Bern at about 11 ft (3.35 m). Phillips (2022a) estimated a modal storm surge of about 3 m in the Neuse estuary overall.

Maximum storm surges near the marsh islands 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. Only high water marks where accuracy was rated as "good" (±0.1 ft or 3 cm) or "excellent" (±1.5 cm) were used, and indicators noted as likely or possibly associated with local rainfall ponding were excluded (Fig. 6). Results are shown in Table 4.

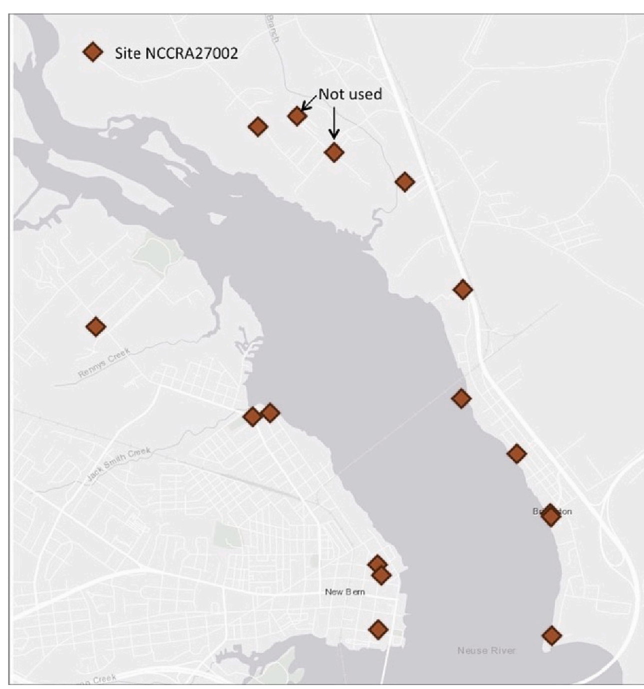

Fig. 6. Location of high water marks from Hurricane Florence measured by the U.S. Geological Survey near New Bern used in this study. Data are listed in Table 4, starting at site NCCRA27002 at upper left and moving clockwise to site NCCRA27044.

Table 4
High water marks from Hurricane Florence measured by the U.S. Geological Survey. Sites start at the top of Fig. 6 and are listed in clockwise order. Data from USGS Flood Event Viewer (https://stn.wim.usgs.gov/FEV/#FlorenceSep2018). Distance indicates shortest straight-line distance from measurement site to Neuse River.

Site number	Type	Elevation (m)	Latitude, longitude	Distance (m)
NCCRA27002	Seed line	2.98	35.1585, −77.0701	358
NCCRA26991	Seed line	3.15	35.1516, −77.0514	600
NCRRA27705	Stain line	2.75[a]	35.1465, −77.0348	749
NCCRA27022	Stain line	3.06[b]	35.1365, −77.0281	325
NCCRA27017	Rub marks from floating dock rollers	3.45[c]	35.1264, −77.0283	0
NCCRA27009	Stain line	3.12[b]	35.1212, −77.0220	73
NCCRA12508	Stain line	3.37[b]	35.1154, −77.0182	47
NCCRA26906	Seed line	3.30	35.1044, −77.0181	42
NCCRA12508	Peak measurement, rapid deployment gage	3.17	35.1022, −77.0359	0
NCCRA26910	Seed line	3.12	35.1050, −77.0378	267
NCCRA26912	Seed line	3.05	35.1100, −77.0374	195
NCCRA27827	Seed line	3.12	35.1250, −77.0500	55
NCCRA27826	Seed line	3.12	35.1110, −77.0379	284
NCCRA27046	Stain line	3.19[b]	35.1247, −77.0520	170
NCCRA27044	Stain line	2.88	35.1330, −77.0698	1194

[a] Height about ground surface measured at 1.20 m; elevation estimated by author.
[b] Measurement known to be tranquil, stillwater indicator.
[c] Rub marks may overestimate high water mark.

Table 4 indicates that water levels were sufficient to cover the marsh islands and submerge most of the herbaceous vegetation. Data from a water level sensor (site shown in Fig. 6) shows that by 00:00 on 13 September water levels were about 0.6 m (above sea level, NAV88 vertical datum). About 8 h later water levels began rising rapidly, peaking at 3.17 m just before midnight. On 14 September water levels fell rapidly to about 2 m, then declined to about 1.2 m by midnight (Fig. 7). By midday on 17 September water levels were back below 0.6 m. The National Weather Service Advanced Hydrologic Prediction Service information for New Bern (https://water.weather.gov/ahps2/hydrograph.php?wfo=mhx&gage=bern7) indicates that water levels of 1.0 to 1.2 m are relatively common, and these apparently do not result in observable changes in the marsh islands. Detailed survey data for the marsh islands are not available, but the ground surface elevation is entirely <1 m, so water levels of at least 1.2 m could potentially trigger erosion of the marsh islands. The USGS water level sensor shows that this putative threshold was reached shortly after noon on 13 September and returned to 1.2 m on the falling limb just before 01:00 on 15 September, for a total period of slightly <37 h.

Storm damage assessment imagery (Fig. 8) taken midday on 15 September 2018 shows the marsh islands not submerged, with the open water conversions having already occurred (compare to Fig. 3).

While the link between the storm, high water, and marsh loss is clear, the specific processes are less so, and impossible to observe directly. Salt marsh fragmentation in a Spanish estuary was found to be linked to increased hydrodynamic stress (Aranda et al., 2022). Given the storm surge experienced on the marsh islands, bottom shear stresses necessary to cause erosion were likely exceeded. Bottom shear stress (τ) is a function of the specific gravity of water (9850), depth in m (d) and hydrodynamic slope (S):

$$\tau = \gamma \, d \, S \tag{1}$$

With marshes inundated by 2 m of water, achieving the necessary shear stress to entrain exposed silty sediment (approximately 0.05 N m^{-2}; Fischenich, 2001) could be achieved with slopes of as little as 2.5 $\times$ 10^{-6}. Such erosion of bare areas could uproot vegetation, though higher stresses would be necessary to erode plant-covered sections. The higher-resolution imagery used in Fig. 3 shows obvious variations in ground cover associated with different vegetation types, which may be associated with variable resistance. No sufficiently detailed topographic data is available, but field observations in extant marshes indicate variable microrelief, and some depressions and small ponds are evident in imagery. Most likely low-lying and low resistance areas (including the artificial ditches) were the focus of erosion from hydrodynamic forces during the surge.

This pattern of marsh loss, which includes interior conversion to open water as well as fringe erosion, has been observed in other Neuse River estuarine marshes (Phillips, 2018a, 2018b). Once interior conversion (fragmentation or disaggregation) is initiated, the open water areas are often expanded. For example, studies in coastal Louisiana suggest that variations in tidal amplitude and variations in resistance are major predictors of short-term marsh loss, along with marsh fragmentation (Schoolmaster et al., 2018). This suggests that once fragmentation is initiated, it may be accentuated, and that variations in erosion resistance could lead to variations in erosion. Peat collapse (often associated with stresses of saltwater intrusion) can initiate pond formation, with surface depressions or small ponds enlarged by erosion (Delaune et al., 1994). Stagg et al. (2019) found that disaggregation of wetlands promotes accelerated conversion to open water, and identified a key elevation threshold whereby degrading fragmented wetlands have elevations ≤0.09 m (North American Vertical Datum 1988) or 0.27 masl (the Neuse marshes are mainly <0.20 masl). In a Maryland marsh, Schepers et al. (2020) found that degradation into ponds was irreversible, because of enlargement and erosion associated with tidal exchange in a microtidal system.

Thus, while definitive statements on the erosion or marsh loss mechanisms during the storm are not possible, it can hardly be purely coincidental that the loss occurred during the storm surge. The likely mechanisms involve physical erosion during the storm surge that enlarged existing open or low-resistance patches, which themselves may have been formed because of ongoing SLR.

While the dominant role of the 2018 storm in the conversion to open water on the Neuse marsh islands is clear, the role of climate change in Florence is more uncertain. No post-storm attribution study was conducted because of a lack of adequate model tools for the situation, but a forecasted attribution study was performed (Reed et al., 2020). Using a numerical model, Reed et al. (2020) estimated a mean total forecasted rainfall increase of about 5 % (4.9 ± 4.6 %) attributable to anthropogenic climate change. The study also attributed a small increase in forecasted storm size of 1 to 2 %.

Peak river stages upstream of New Bern as reflected at gaging stations and in anecdotal reports occurred between 19 and 23 September, well after the water levels near New Bern had receded. This, plus evidence of ~3 m storm surges in the lower estuary early in the storm (Fig. 7) indicates that submergence of the marsh islands was attributable to storm surge rather than fluvial flooding. The extremely high rainfall, runoff, and river flow associated with Florence is plausibly linked to climate change and "new normal" or moving baseline, as is the slow

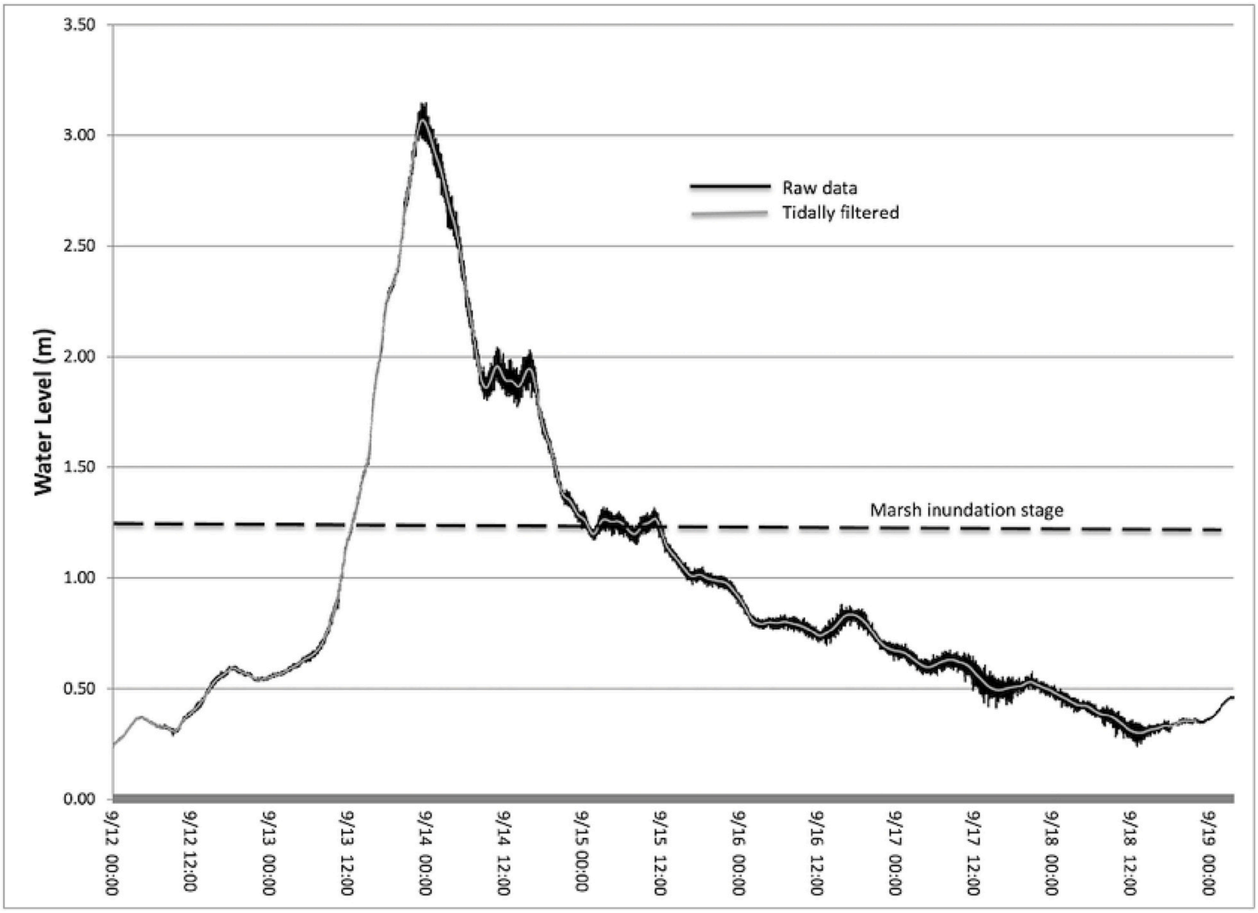

Fig. 7. Water level data from USGS water level sensor NCCRA12508 (see location on Fig. 6) in elevation above mean sea level. The sawtooth line represents unfiltered measurements; the central line is tidally filtered.

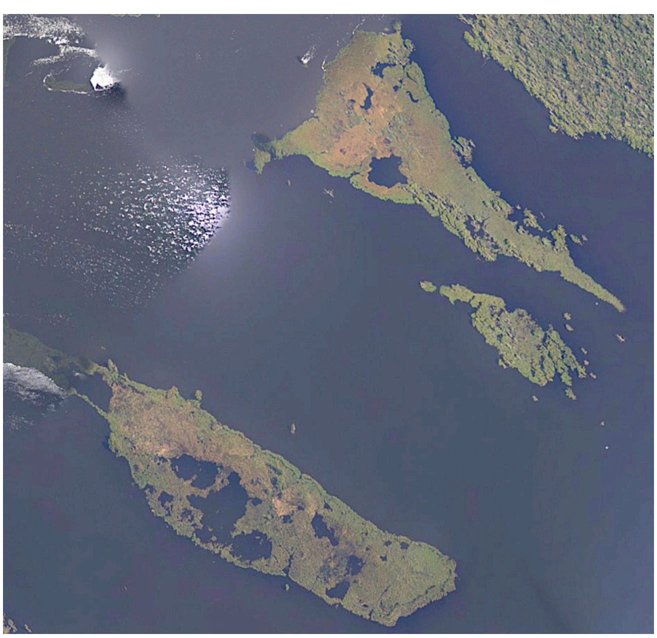

Fig. 8. 15 September 2018 image from the National Geodetic Survey damage assessment flights (https://storms.ngs.noaa.gov/storms/florence/index.html#11/36.2112/-75.4695).

forward movement and extremely large spatial extent of the storm (Phillips, 2022b). However, the high storm surges were because the Neuse estuary and Pamlico Sound are wind-dominated and highly sensitive to wind effects, and the specific track of the storm, which exposed the Neuse to predominantly NE winds for an extended period (by contrast, an area near the track of the cyclone's eye will experience changes in wind direction as the rotating circulation passes). At landfall near Wrightsville Beach, NC, the eye was about 130 km southwest of New Bern. The large area of the storm and its post-landfall track to the west kept the Neuse area exposed to the northeasterly circulation on the right side of the storm.

Overall impacts of Florence on the lower Neuse, Phillips (2022a) maintained, were partly attributable to climate change, but also to particulars of the storm track and characteristics of the estuary that are independent of the trend toward larger, slower, wetter tropical cyclones. Single-day precipitation records were set at six stations in North and South Carolina during Florence, with 419 mm recorded at Kinston and 300 to >400 mm totals throughout the Neuse region, with estimated recurrence intervals of >200 yr and associated river flooding (Feaster et al., 2018; Stewart and Berg, 2019). However, the rainfall had negligible impacts on the marsh islands—as stated above, storm surge was the main factor in the marsh conversion.

5. Discussion and conclusions

The attribution of meteorological events and episodes to climate change is hardly simple or straightforward, though scientific process is rapid (Qian et al., 2022). Attribution for landscape responses to meteorological events is complicated even further by a whole new set of variables related to landscape factors, and issues of resistance, resilience, sensitivity, and geographical and historical contingency. Still more layers of uncertainty are associated with landscape change apparently or possibly driven or affected by climate change, and in considering effects of the combined effects of ramp or press disturbances (gradual or chronic climate change) vs. the pulse disturbances of individual events. Other complicating factors include indirect effects of climate, and disentangling climate from the other factors affecting geomorphological, hydrological, pedological, and ecological responses.

As climate change is a global phenomenon manifested in a context of regional and local factors, general testing and validation strategies are as varied as geomorphological problems themselves. Thus, issues of evidence, testing, and uncertainty are as varied as geomorphology itself, and there are no problems or principles completely unique to climate attribution studies. Key issues particularly associated with climate change attribution include the role of single events or episodes (tropical cyclones, floods, etc.) vs. longer-term climate change (e.g., general warming, cooling, wetting, drying), and the interaction of the two, such as changing storm climatology. There also typically exists multiple causality, so that climate change or individual weather and climate events are rarely the sole cause of geomorphological changes.

The protocol for climate attribution of landscape responses presented here is based on identification and testing of plausible climate, climate-related, and non-climate causes or influences on observed landscape responses. A significant degree of uncertainty is virtually inevitable in landscape response analysis. However, the dominant processes or controls (as opposed to every potentially relevant variable) can be identified.

Because it is based on commonsense deployment of familiar approaches in the historical and interpretive branches of Earth and ecological sciences, the protocol can be thought of as an *aide memoire* or checklist, as opposed to a novel methodology. One advantage is that the approach explicitly considers negative results (for climate and other factors), which is important in advancing our understanding of climate change impacts (East et al., 2022).

5.1. Landscape response attribution—Neuse River marsh islands

The steps in the LRA protocol are plausibility, timing, identification of possible causal factors, testing, and interpretation. Is it plausible that the marsh loss is attributable to climate-related factors? Relative SLR has been suspected, implicated, or proven in coastal wetland loss in numerous other cases, including some in the region. Evidence of SLR effects exists, as well as credible indications that the Hurricane Florence event was influenced by climate change. The plausibility test is passed, along with the timing test. The long-term gradual size reduction of the islands coincides with historical relative SLR, and the major observed marsh-to-open-water conversion occurred during the 2018 Hurricane. In the “other causes” step, sediment supply, vegetation damage or destruction, human impacts, and faunal disturbance were identified. In the testing stage, no evidence was found for factors other than SLR, Hurricane Florence, and anthropic ditching. Based on this, the interpretation is given below.

A net reduction in size and conversion of marsh to open water since at least the mid-twentieth century can be attributed to relative SLR. The submergence is driven primarily by general climate warming, with no positive evidence for any additional or alternative drivers. Thus, strong positive inference exists for a climate cause. The only other factor with supporting evidence is human modification in the form of ditches, around which conversion was concentrated—however, the post-2018 marsh loss also occurred in unditched portions of the Neuse River marsh islands. The rapid recent marsh loss is clearly attributable to Hurricane Florence, particularly the storm surge. There is some weak positive inferential support for a role of climate change in the storm, but with respect to the marsh island impacts, geographically and synoptically contingent factors not linked to climate, such as the wind-dominated nature of the Pamlico Sound and Neuse River estuaries and the specific track of the storm relative to the Neuse are more important.

Overall, the landscape response can be confidently linked to climate factors, exacerbated by direct human impacts of marsh ditching, and strongly influenced by local place factors and the specific storm track. A role for recent and ongoing climate change is apparent, but not necessarily paramount, in determining the landscape response.

The nature of LRA studies such as the case study here is that they are inherently local. While Hurricane Florence had significant geomorphological, hydrological, ecological, and economic impacts over a large area, the high and prolonged storm surge was unique to the Neuse River area (Stewart and Berg, 2019; Phillips, 2022a). Ditching in wetlands as a general phenomenon is not rare, but evaluating its impacts on wetland deterioration requires consideration of specific local conditions. The other potential causes, such as sediment supply and biological effects, are certainly relevant to other coastal wetlands, but the testing and interpretation in the LRA protocol is location specific.

The general phenomena of wetland loss caused by SLR, with erosion and conversion occurring episodically in storm events, are common to coastal marshes along the U.S. Atlantic and Gulf Coasts, and in other locations. Likewise, marsh loss caused by fragmentation into marsh and open water is common. The Neuse River case study is not unusual—and is probably typical—in identifying a combination of climate and other factors strongly influencing landscape response, and in providing an indication of whether climate is a dominant control or process, rather than a quantitative estimate of climate contributions.

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.

Data availability

Data will be made available on request.

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