RECENT AND FUTURE OUTLOOKS FOR NUISANCE FLOODING IMPACTS ON ROADWAYS ON THE UNITED STATES' EAST COAST

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ABSTRACT

Tidal floods (i.e., “nuisance” flooding) are occurring more often during seasonal high tides and/or minor wind events, and the frequency is expected to increase dramatically in the coming decades. During these flood events, coastal communities’ roads are often impassable or difficult to pass, thus impacting routine transport needs. This study identifies vulnerable roads and quantifies the risk from nuisance flooding in the Eastern United States by combining public road information from the Federal Highway Administration’s Highway Performance Monitoring System with flood frequency maps, tidal gauge historic observations, and future projections of annual minor tidal flood frequencies and durations. The results indicate that tidal nuisance flooding across the East Coast threatens 7,508 miles (12,083 km) of roadways including over 400 miles (644 km) of interstate roadways. From 1996-2005 to 2006-2015, there was a 90% average increase in nuisance floods. With sea level rise, nuisance flood frequency is projected to grow at all locations assessed. The total induced vehicle-hours of delay due to nuisance flooding currently exceed 100 million hours annually. Nearly 160 million vehicle-hours of delay across the East Coast by 2020 (85% increase from 2010); 1.2 billion vehicle-hours by 2060 (126% increase from 2010); and 3.4 billion vehicle-hours by 2100 (392% increase from 2010) are projected under an Intermediate Low sea level rise scenario. By 2056-2065, nuisance flooding could occur almost daily at sites in Connecticut, New Jersey, Maryland, the District of Columbia, North Carolina, and Florida under an Intermediate sea level rise scenario.

Keywords: Nuisance Flooding; Roadways; Congestion; Vehicle Hours of Delay; Sea Level Rise; Vulnerability

INTRODUCTION

Transportation infrastructure in coastal regions is vulnerable to coastal extreme events today; this vulnerability will increase with sea level rise (SLR), enhanced storm surge from tropical and nontropical storms, and land subsidence (*1,2*). Hurricanes have caused billions in direct damage to coastal roadways and bridges. Significant economic losses also occurred due to transport disruption during and after these storms. Currently, 60,000 miles (96,561 km) of roadways are exposed to coastal storms (see (*2*)). In the future, rising seas will cause more frequent disruptions and damage to occur, more severe events, and storm surge impacts to extend further inland.

In some coastal areas, impacts are not limited to storm events. Critical transportation infrastructure is at risk from sea level rise alone. SLR-induced coastal flooding decreases service and increases maintenance costs for existing facilities; mitigation strategies will be an increasingly critical aspect of transportation planning, design, and operations and maintenance (*3, 4,* 5). Numerous transportation agencies have identified assets vulnerable to permanent inundation for global mean sea level rise scenarios for the United States that range from 1 to 8.2 feet (0.305 to 2.5 m) by 2100 with sea level rise values along the U.S. Atlantic and Gulf Coasts likely to be greater than the global average (*6*).

Sea level rise is also contributing to an increasing frequency of tidal floods (i.e., “sunny day”, “recurrent”, “shallow coastal”, and “nuisance” flooding), occurring more often during seasonal high tides and/or minor wind events. Some portions of the U.S. coast, including much of the Atlantic coast, are seeing an accelerating frequency of such events (*7, 8*). Flooding that surpasses local emergency thresholds for minor tidal flooding (i.e., “nuisance” levels of about 30–60 cm (1–2 feet)) result in flooded infrastructure including roadways. These nuisance floods have increased 5- to 10-fold or more since the 1960s along the U.S. coastlines (*8, 9, 10, 11, 12*).

For example, cities such as Annapolis, Maryland, Norfolk, Virginia, and Miami Beach, Florida, are now flooded numerous times per year (42, 11, and 17 days in 2016, respectively) (*13*). With rising sea levels, such flooding is expected to increase dramatically in the coming decades (*8, 10, 14, 15, 16*).

The damage to coastal infrastructure from recurrent flooding is less well understood than that due to extreme coastal events or gradually SLR. In some regions, the cumulative cost of nuisance flooding could be comparable to or exceed costs from extreme coastal storm events (*9*). Dahl et al. (2017) determined that currently there are 91 communities where 10% or more of livable land area is flooded at least 26 times per year and that number will nearly double by 2035. A primary impact of nuisance flooding in communities is rendering roads impassable or difficult to pass so frequently that routine transport needs are not met. While the importance of transportation disruptions from nuisance flooding is broadly understood, few studies (*16*) have quantitatively addressed how nuisance flooding impacts roadway flooding.

The goal of this study is to broadly understand the type and extent of roadway infrastructure that are vulnerable to nuisance flooding as well as the transportation impacts now and in the future due to SLR. This study focuses on the East Coast of the United States and includes all coastal states from Maine to Florida, including the Gulf Coast of Florida and Key West. In this study, we determine the number and length of roadway segments (not including bridges, tunnels, or causeways) at risk from tidal nuisance flooding. The number of days per year that these vulnerable roadways are flooded from nuisance flood is estimated for current, mid-century, and late century. Current traffic counts are combined with the total hours per year that the roads are inundated to determine annual transportation impacts for these same periods. Results are summarized by each state and differentiated by the road type using the Federal Highway Administration functional classifications.

DATA SOURCES

Roadway data for 2015 were obtained from the Federal Highway Administration (FHWA). The FHWA requires all states (including the District of Columbia) to annually submit Geographical Information System (GIS) data on the extent, condition, performance, use, and operating characteristics of all of the Nation's public roads, regardless of ownership, to the Highway Performance Monitoring System (HPMS) (*18*). This study uses the HPMS functional class (FC), average annual daily traffic (AADT), facility type (FT), and structure type (ST) data. HPMS functional classes definitions are Interstate (FC 1), Principal Arterial (Other Freeways and Expressways) (FC 2), Principal Arterial (Other) (FC 3), Minor Arterial (FC 4), Major Collector (FC 5), Minor Collector (FC 6) and Local roads (FC 7). The Facility type (FT) provides the operational characteristic of the roadway and was used to distinguish ramps (FT 4) and individual road/roads of a multi-road facility that is/are not used for determining the primary length for the facility (FT 6). FT 6 allows states to more efficiently record interstate information. Structure type (ST) identifies roadway sections that are bridges (ST 1), tunnels (ST 2), or causeways (ST 3). All geospatial data were projected in NAD_1983_2011_Contiguous_USA_Albers, and analysis was done using ArcGIS. States included in this study include Connecticut, Delaware, District of Columbia, Florida, Georgia, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, North Carolina, Pennsylvania, Rhode Island, South Carolina, and Virginia.

Nuisance flooding areas were identified using the National Oceanic and Atmospheric Administration's (NOAA) flood frequency maps, which delineate areas based on ground elevation for which there is potential nuisance flooding. Nuisance flooding events correspond to those coastal floods that would cause 'minor' impacts to infrastructure as determined locally by the National Weather Service. Most, but not all, of the coastal tide gauges with such elevation thresholds are monitored along with riverine gauges by NOAA (*19*). NOAA used 30-cm LIDAR digital elevation data to develop these maps, which are a spatial interpolation of elevations at or below gauge-specific elevation threshold for nuisance impacts (*20*).

Verified hourly water levels were used in this study and are available from NOAA's Center for Operational Oceanographic Products and Services (*21*). Historic annual flood frequencies are based upon counts of discrete days and total number of hours per year above local minor-flood thresholds (where such thresholds exist) similar to methods of Sweet et al. (2014) (*22)*. Long-term gauges with hourly data extending prior to 1950 continue to be monitored on an annual basis by NOAA (e.g., *22*, *23*), and 21 of these tide gauges along the U.S. East Coast and Southern Florida Gulf Coast provided spatial flood frequency information for this study (see Figure 1).

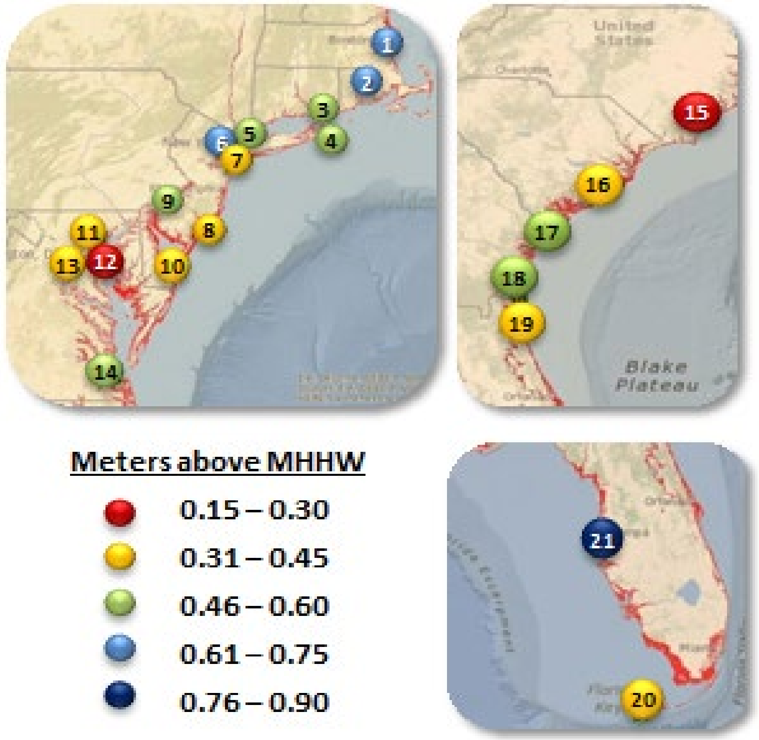

FIGURE 1 NOAA water level (tide gauge) locations numbered as listed in Table 3 and showing NOAA-defined nuisance flood levels above the 1983–2001 MHHW datum (colored dots) and coastal areas below the nuisance elevations and potentially at risk during nuisance flood events (red contours) provided by www.csc.noaa.gov/digitalcoast/tools/slrviewer (adapted from Sweet and Park 2014).

ANALYSIS METHODS

Road Segment and AADT Determination

The HPMS data were used to identify roadway segments. Because states submit their own data to FHWA for the HPMS, some aspects of the data in the HPMS may vary slightly from state to state. To account for differences in HPMS data among states, adjustments were made to ensure that data were comparable across the study region. Roadway segments that are bridges, tunnels, or causeways were identified and removed from the analysis because these assets' elevations frequently differed from the ground elevation or the elevations were not available. The definition of a road segment differed by state. For this analysis, road segments are either defined as the section of road between two ramps for FC 1 and 2 or as the road section between two intersections, not accounting for one-way roads, for FC 3 to 7. FC 1 and 2 segments were defined as a single segment between ramps, created by joining and/or splitting HPMS segments.

The AADT values reported by each state were used to estimate AADT for this study's segments. The AADT values were determined by a distance-weighted average approach. First, vehicle miles traveled (VMT) was determined for each segment (or sub-segment, if split) in the HPMS:

$$\text{VMT} = \text{AADT} * \text{Segment\_Length}_{\text{HPMS}} \tag{1}$$

where $\text{Segment\_Length}_{\text{HPMS}}$ is the distance of the HPMS-defined segment (or sub-segment). When multiple segments were joined to create a new segment for this study, the VMT values from the segments were totaled ($\text{VMT}_{\text{Total}}$) and a new, length-weighted AADT was determined as

$$\text{AADT}_{\text{weighted}} = \text{VMT}_{\text{Total}} / \text{Segment\_Length}_{\text{Total}} \tag{2}$$

where $\text{Segment\_Length}_{\text{Total}}$ is the distance of the segment created for this study.

FC 1 and 2 segments were defined as a single segment between ramps, created by joining and/or splitting HPMS segments. Some states assigned total bidirectional AADT on divided highways to one side of the road and zero to the other side. The zero side was identified using HPMS field "facility type" 6 (FT6). This was a reporting approach commonly used by CT, DE, FL, RI, and SC. For all states, first, the non-FT6 roads were split at ramps. VMT was calculated for each segment (Equation 1). Then, segments were joined, creating a single segment between each intersection with a new, length-weighted AADT (Equation 2). FT6 roads were segmented at the same points as the non-FT6 roads by finding the nearest point on the FT6 line to the vertices of the non-FT6 segments. FT6 and non-FT6 segments were paired one-to-one based on the closest FT6 segment to midpoint of the non-FT6 road, within 175 ft (53.3 m). For non-FT6 roads with a paired segment, half of the AADT was assigned to the FT6 road and half to the pair; segments without a pair remained the same. FT6 segments were then split at ramps, given a VMT factor, and joined between ramps with a new, length-weighted AADT.

In Florida's HPMS submission, ramps were frequently unconnected from highways, sometime separated by hundreds of feet. To account for this, the closest point on the nearest highway segment to the end of each ramp was determined. Highway segments were split at these points, rather than the intersection of the ramps and the road segments. Because South Carolina's

2015 HPMS submission did not include ramps, South Carolina's 2014 ramp submission was used for the South Carolina's FC 1 and 2 analysis.

FC 3, 4, 5, 6, and 7 segments were developed from the intersections of FC 3, 4, 5, 6, and 7 segments. As needed, the HPMS segments in FC 3, 4, and 5 were split at these intersections and VMT was calculated for each segment (Equation 1). Then, segments were joined, creating a single segment between each intersection with a new, length-weighted AADT (Equation 2). Because FC 6 and 7 segments did not have uniform AADT reporting, only the length and number of FC 6 and 7 segments were used in the flood risk analysis. For the states that did not submit FC 6 and 7 segments to the HPMS, statewide vulnerability summaries did not include this category of roadways.

Vulnerable Road Segments

After creating a consistent set of road segments, these roadway data were overlaid with NOAA's minor tidal flooding extent maps (henceforth referred to as "flood risk area"). Segments that were completely contained in the flood risk area or intersected the flood risk area were identified as roadways at risk from tidal nuisance flooding. The number and length of segments intersecting the flood risk area were summarized by functional class for each state. For FC 1, 2, 3, 4, and 5 segments, the AADT values in the flood risk area were calculated. Because some states reported zero for AADT on ramps, AADT on ramps in the flood risk area was not included in the delay analysis.

Tide Gauge High-Water Exceedance Projections

Projections of minor flooding were estimated using a combination of contemporary high-water exceedance probabilities and local sea level rise scenarios following methods of Sweet and Park (2014) (*8*). Empirical distributions of observed (tide plus storm surge, sea level anomalies, etc.) highest daily water levels over 1991-2009 (spanning a 19-year tidal epoch) were detrended to establish a mean sea level datum epoch centered on year 2000. Local relative sea level rise projections of Sweet et al. (2017a) (*6*), which initiate in year 2000, were used to force time-dependent shifts in the high-water distributions relative to the minor elevation thresholds (shown in Table 3). We assumed stationarity within the high-water distribution, which is typical when projecting flood probabilities (e.g., *24*, *25*), since the focus is on exceedances generally within the bulk of the distribution (< 1 year recurrence interval with very narrow uncertainty bounds) (*22*) largely dominated by repetitive annual tidal forcing and weather patterns. This analysis yielded the annual number of days of flooding and the annual total hours of flooding for each of the 21 tidal gauges. The number of historic nuisance flood days was summarized using 10-year average for 2000 (i.e., 1996-2005) and 2010 (i.e., 2006-2015). For the projected nuisance flood days and annual hours of flooding, average values were determined for 2010, 2020, 2060, and 2100 based upon the local Intermediate Low, Intermediate and Extreme sea level rise scenarios of Sweet et al. (2017a) (*6*). All counts are annual totals estimated as the decadal average decadal (10-yr) value centered on year (i.e., 2060 is 2056-2065), except 2100, which is a 5-yr average (2096 -2100).

Roadway Flood Risk

For each vulnerable roadway segment with a FC of 1 through 5, excluding ramps, the distance to the nearest tide gauge was determined using ArcGIS. Because ramps and FC 6 and 7 had nonuniform reporting of segments and AADT, these were excluded from the analysis. For each roadway segment, the annual vehicle-hours of delay (T_Delay) from nuisance flooding was determined using the flooding duration for the nearest tide gauge for each sea level rise scenario (Intermediate-Low, Intermediate, and Extreme) and each modeled year (2010, 2020, 2060, and 2100):

$$T\_Delay_{scenario,\ yr} = T\_Flood_{scenario,\ yr} * AADT\ /\ (24\ hrs\ /\ day) \qquad (3)$$

where $T\_Delay_{scenario,\ yr}$ is the annual vehicle-hours of delay for each scenario and modeled year combination and $T\_Flood_{scenario,\ yr}$ is the cumulative duration of flooding on an annual basis for each scenario and modeled year combination (hrs). The total annual vehicle-hours of delay for each state were determined by summing the delays for each segment in that state.

RESULTS

Roads At Risk From Nuisance Flooding

Tidal nuisance flooding across the East Coast of the U.S. threatens 7,508 miles (12,083 km) of roadways and nearly 15,000 individual roadway segments (Tables 1 and 2). Interstates are impacted throughout the study region. In total, over 400 interstates roadway (FC 1 and 2) segments are at risk, with an average length of 1 mile (1.61 km). Additionally, over 300 FC 1 and 2 access ramps are at risk during nuisance flooding. However, most of the roadways at risk are not interstates. Minor or local roads (FC 6 and 7) comprise the majority of the impacted segments (65%) and half of the total miles. Over 3000 miles (4828 km) of FC 3, 4, and 5 roadways, which play a critical role in local and regional connectivity, are at risk.

Florida and New Jersey have the largest percentage of roads at risk (4.7% and 4.6%, respectively). The four southernmost states (NC, SC, GA, FL) account for over 60% of the impacted miles and roadway segments. In most cases, Florida roads account for about 25% of the total of vulnerable roadways (1,823.1 miles (2,934 km)); 525 segments). While North Carolina has more impacted roadways (2,118.2 miles (3,409 km); 5,636 segments) than Florida, North Carolina has significantly more minor and local roads at risk compared to Florida. Florida has more major roads (FC 1-5) at risk. North Carolina has only 3 miles (4.8 km) of interstates roads (FC 1-2) at risk because their highways are typically located away from the coastline. Among Mid-Atlantic states (MD, DC, DE, NJ, NY, PA, VA), New Jersey has a high number and length of affected interstates. The District of Columbia (17.7 miles (28.5 km); 52 segments) has the fewest roads. The New England states (CT, MA, ME, NH, RI) have a relatively low exposure with the most impacts found in FC 3, 4, and 5 roadways. Of the five New England states, Connecticut has the greatest potential vulnerability.

The total length and number of segments of roadway at risk varies by region and state. Nine of the 16 study states have more than 1% of their reported road network at risk. Smaller states such as RI and DE have relatively few impacted roads, but their total percentage of roads at risk is quite high at 3.1 and 2.8%, respectively. Shorter coastlines and tidal rivers exposure in GA, PA, NY, MA, and NH relative to the state's entire road network keeps the overall total percentage of roads at risk below 0.6%.

TABLE 1 Miles of Roadway by State and Functional Class Located in Nuisance Flood Zones

State	Functional Class 1 & 2	Functional Class 1 & 2 ramps	Functional Class 3, 4, & 5	Functional Class 6 & 7	Total	Percent of total road miles
ME	8.7	0.8	188.6	N/A[a]	198.1	2.8%
NH	0.4	0.3	12.4	21	34.2	0.2%
MA	0	7.6	73	159	239.6	0.5%
RI	1.2	1.3	57.4	5.7	65.6	3.1%
CT	5.9	4	117.1	13.8	140.9	1.7%
NY	32	19.3	133	N/A[a]	184.3	0.6%
NJ	77.6	34.3	416.3	7.6	535.8	4.6%
PA	21	14.9	74.1	N/A[a]	110	0.2%
DE	7.7	0.7	58.5	121.5	188.5	2.8%
MD	5.8	1.7	72	548	627.6	1.7%
DC	5.3	3.3	1.2	8	17.7	1.5%
VA	18.7	11.7	145.9	234	410.3	0.6%
NC	3.2	3.3	315.2	1796.5	2118.2	1.4%
SC	31.6	6.4	262.9	288.6	627.2	0.9%
GA	65.4	4.8	53	102	225.3	0.2%
FL	121	52.9	1195.3	453.9	1823.1	4.7%
Total	405.6	167.3	3175.9	3759.6	7508.4	1.1%

[a] FC 6 and 7 roadway data were missing.

NOTE: 1 mi = 1.61 km

TABLE 2 Number of Roadway Segments by State and Functional Class (FC) Located in Nuisance Flood Zones

State	Functional Class 1 & 2	Functional Class 1 & 2 ramps	Functional Class 3, 4, & 5	Functional Class 6 & 7	Total
ME	10	3	147	N/A[a]	160
NH	1	1	56	80	138
MA	0	12	352	1139	1503
RI	4	5	89	6	104
CT	16	16	201	28	261
NY	41	43	212	N/A[a]	296
NJ	67	49	567	27	710
PA	25	24	111	N/A[a]	160
DE	11	2	107	347	467
MD	8	4	173	1218	1403
DC	7	14	6	25	52
VA	33	33	199	374	639
NC	3	9	592	5032	5636
SC	21	15	306	531	849
GA	23	13	114	364	514
FL	121	100	1198	525	1944
Total	391	343	4430	9696	14860

[a] FC 6 and 7 roadway data were missing.

Recent Observations and Future Scenarios of Nuisance Flood Frequency

Annual frequencies of days with a minor (nuisance) tidal flooding have increased rapidly over the last several decades. In fact, flood frequencies are accelerating in dozens of U.S. East and Gulf Coast communities even as local mean sea level trends are not necessarily accelerating (*22*). Acceleration in tidal flooding occurs as rising sea levels evolve the nonlinear portion of a water level distribution against a fixed elevation (i.e., nuisance flood elevation threshold shown in Figure 1 and listed in Table 3), irrespective of whether the sea level rise is linearly increasing or nonlinearly accelerating (*8*). Comparing decadal-averaged flood frequencies in 2000 (i.e., 1996-2005) to those in 2010 (Table 3), the change is substantial, with an average increase across all sites of about 90%, ranging from about a 25% increase (New London, CT) to upwards of a 350% increase (Key West, FL).

When a nuisance flood occurs, the flooding typically lasts for only part of the day, often for an hour or so near the peak of one or both of the approximately twice-daily (semi-diurnal) high tides typical along the East and Gulf Coasts. The total hours per year at or above the nuisance flood threshold at a specific location are closely related to the days per year (via a multiplication factors of 2.5 hours/day on average) (*8*) and reveal similar trends (not shown). Comparing all locations, a general pattern exists ($R^2 \sim 0.7$) as recently explained by Sweet et al.

(2017b) (*13*): where elevation thresholds are lower (i.e., Figure 1), more flood days occurs (e.g., Wilmington, NC); where thresholds are higher such as in St. Petersburg (reflecting hurricane-flood mitigation), nuisance flooding is mostly nonexistent.

With continued local relative sea level rise, the change in nuisance flood frequency (and depth and extent) is projected to grow most rapidly at all locations, as they have in the past, most notably where local sea level rise rates are higher (*7*, *8*). For example, Figure 2 shows the increases in observed nuisance floods as well as the projected nonlinear increases in nuisance flood frequency values under a range of scenarios for Charleston, SC. For the 21 tide gauges in the Eastern U.S., Table 3 provides indicators of the projected increases in flooding for the vulnerable roadways by region. Under the Intermediate scenario, the number of days per year with nuisance flooding will approach saturation (365 days per year with a flood) on average in the decade of 2060 (2056-2065) at Sandy Hook, CT, (330 days), Atlantic City, NJ, (334 days), Annapolis, MD, (354 days), Washington, DC, (342 days), Wilmington, NC, (361 days), and Key West, FL (357 days).

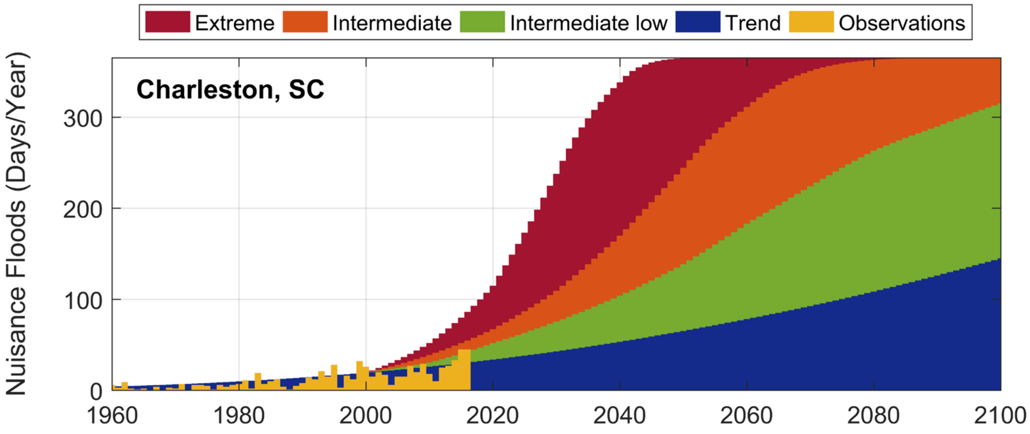

FIGURE 2 NOAA-defined nuisance flood levels for Charleston, SC (Station ID 8665530), including observations through 2016 and projections to 2100 based upon the local sea level trend and the Intermediate Low, Intermediate, and Extreme sea level rise scenarios of Sweet et al. (2017a).

The elevation threshold and amount of local sea level rise by 2060 explain 98% of the variability in the days/year metric between locations shown in Table 3 (R^2=0.98, not shown). As would be expected, the annual flood frequencies (days/year) reaches saturation sooner under the higher sea level rise scenarios (e.g., Extreme scenario). However, it should be noted that the current trajectory of local mean sea level (and derived flood frequency metric) at most locations are currently tracking the more probable scenarios (e.g., Intermediate Low scenario of Sweet et al. 2017a (*6*)).

TABLE 3 Location, NOAA Tide Gauge Identifier, NOAA-Defined Nuisance Flood Level, 10-Year Average Number of Historic Nuisance Flood Days about 2000 (i.e., 1996-2005) and 2010, and Projections for 2020, 2060, and 2100 Based on the Local Intermediate Low, Intermediate, and Extreme Sea Level Rise Scenarios of Sweet et al. (2017a). All Counts are Annual Totals Estimated as the Decadal Average Decadal (10-Yr) Value Centered on Year (i.e., 2000 is 1996-2005), Except 2100, Which is a 5-Year Average (2096 -2100)

St.	Location Name	Station ID	Nuisance Level	Observed	Obs.	Intermediate Low			Intermediate			Extreme		
			(m, MHHW)	2000	2010	2020	2060	2100	2020	2060	2100	2020	2060	2100
1	Boston, MA	8443970	0.68	2	6	10	53	115	16	155	359	40	364	365
2	Providence, RI	8454000	0.66	1	2	4	36	109	7	155	362	22	365	365
3	New London, CT	8461490	0.60	1	2	4	38	165	6	243	365	21	365	365
4	Montauk, NY	8510560	0.60	1	2	4	50	223	8	262	365	25	365	365
5	Kings Point, NY	8516945	0.52	8	15	23	106	214	37	254	363	75	365	365
6	Battery (NYC), NY	8518750	0.65	2	4	6	50	162	10	197	363	28	365	365
7	Sandy Hook, NJ	8531680	0.45	14	22	43	194	320	66	330	365	121	365	365
8	Atlantic City, NJ	8534720	0.43	13	22	49	214	330	69	334	365	127	365	365
9	Philadelphia, PA	8545240	0.49	6	11	20	137	283	32	305	364	85	365	365
10	Lewes, DE	8557380	0.41	12	21	40	192	323	57	330	365	123	365	365
11	Baltimore, MD	8574680	0.41	7	14	31	202	321	49	330	365	130	365	365
12	Annapolis, MD	8575512	0.29	24	41	87	292	351	122	354	365	224	365	365
13	Washington D.C.	8594900	0.31	21	30	72	259	336	102	342	365	196	365	365
14	Norfolk, VA	8638610	0.53	5	8	16	142	323	22	318	365	59	365	365
15	Wilmington, NC	8658120	0.25	23	43	71	275	356	108	361	365	204	365	365
16	Charleston, SC	8665530	0.38	16	25	53	183	309	70	311	365	125	365	365
17	Savannah, GA	8670870	0.46	10	17	37	139	265	51	267	365	94	365	365
18	Fernandina Beach, FL	8720030	0.59	1	2	7	48	139	11	151	362	32	364	365
19	Mayport, FL	8720218	0.44	2	6	14	94	245	23	254	365	63	365	365
20	Key West, FL	8724580	0.33	1	4	18	195	354	35	357	365	100	365	365
21	St Petersburg, FL	8726520	0.84	0	0	0	1	15	0	16	355	1	362	365

NOTE: 1 m = 0.305 ft

Impacts of Nuisance Flooding to Roadway Performance

The total annual vehicle-hours of delay for each state were mapped for each year and scenario (Figure 3). Modeled data for 2010 provide a baseline for comparison. Under baseline conditions, nuisance flooding is already causing delays in all East Coast states with the southern states having more induced vehicle-hours of delay than the northern states. Total delays currently exceed 100 million hours annually. In the future, nuisance-flooding-induced vehicle-hours of delay, or congestion, will increase for all states' coastal roads as compared to baselines conditions. Congestion also increases as scenarios become more extreme. The Intermediate Low scenario results in nearly 160 million vehicle-hours of congestion across the East Coast by 2020 (an 85% increase from 2010); 1.2 billion vehicle-hours by 2060 (126% increase from 2010); and 3.4 billion vehicle-hours by 2100 (392% increase from 2010) (Figure 2). Under the Intermediate and Extreme scenarios, vehicle-hours of delay increase 124% and 236% from 2010 to 2020, respectively. Schrank et al. (2015) (*26*) estimated that in 2014, total travel delay for the U.S. was 6.9 billion hours. Vehicle-hours of delay from nuisance flooding on the East Coast alone will exceed that level by 2100 for the Intermediate scenario and by 2060 for the Extreme scenario.

Nuisance-flooding-induced congestion varies widely by region and state. Southern states' flooding increases will occur faster that for the Mid-Atlantic or New England states. Together, the four southern states make up 36% of nuisance-flooding-induced congestion in 2020, rising to 51% in 2100 under the Intermediate Low scenario. By contrast, the seven Mid-Atlantic states make up 59% in 2020, dropping to 45% in 2100; the five New England states make up 5% in 2020, dropping to 4% in 2100. Virginia is the only state to reach 25 million vehicle-hours of delay by 2020 in the Intermediate Low scenario. However, for the more extreme scenarios in mid- to late-century, Florida will consistently experience the greatest amount of congestion of any state examined in this study. In the most conservative (Intermediate Low) scenario, Florida could see an increase of 1 billion hours of delay by 2100 compared to 2010.

DISCUSSION

FHWA now requires state DOTs and metropolitan planning organizations (MPOs) to calculate several metrics related to congestion and reliability of the national highway system (i.e., level of travel time reliability, annual hours of peak-hour excessive delay per capita, truck travel time reliability), and to set targets for these metrics and achieve progress toward targets (*27*). Nuisance flooding has the potential to significantly impact coastal states' abilities to meet their targets, if set without consideration of future changes. Because state DOTs and MPOs are not required to establish targets for the first performance period (which ends in 2021) until 2018, considering the impact of nuisance flooding – particularly at the 2020 levels predicted in this study – in target-setting may help state DOTs and MPOs set more achievable and realistic targets.

FHWA also requires state DOTs to follow a process for maintaining physical assets in a state of good repair over their lifecycle (*28*). As part of determining the lifecycle of an asset, FHWA says state DOTs should consider future climate-related changes. Nuisance flooding may cause minor damage to infrastructure that can rapidly lead to the deterioration of assets, especially when damage is increasingly recurrent, as predicted by this study (*29*).

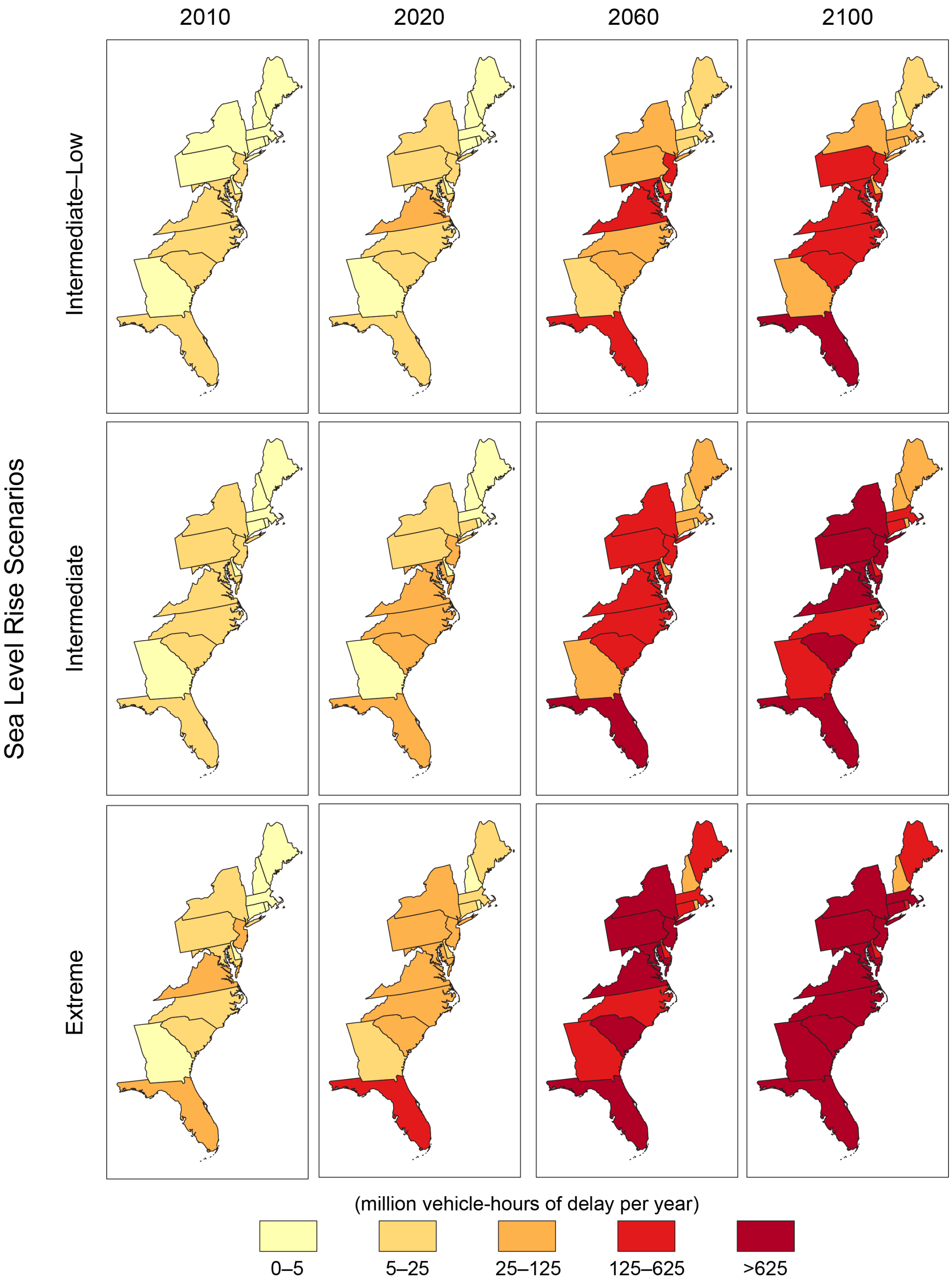

FIGURE 3 Annual vehicle-hours of delay for functional class 1-5 roads due to tidal nuisance flooding by state, year (2010, 2020, 2060, 2100) using decadal average decadal (10-yr) values except 2100, which is a 5-yr average (2096-2100) and Intermediate Low, Intermediate, and Extreme sea level rise scenarios of Sweet et al. (2017a).

This study uses a regional analysis approach to consistently identify roadways vulnerable to nuisance flooding and the current and projected impacts on transportation delays. Datasets that provide more detailed spatial information or a finer temporal resolution may improve the understanding of flooding impacts to specific road segments. This study does not include existing, planned, or potential protective structures or adaptation strategies to reduce roadway flooding. These measures could reduce the frequency and duration of flooding. All FC 1-5 (excluding ramps) road segments were considered in the roadway performance analysis; however, the distance from the nearest tide gauge varied. Forty four percent of segments were less than 25 miles (40 km) from the nearest tide gauge and 65% of segments were less than 50 miles (80 km) from the nearest tide gauge, but segments ranged from 0.02 to 343 miles (0.03 to 552 km) away As scenario-based modeling using a greater number of tide gauges becomes available, future studies will be able to more accurately predict flood timing on specific road segments.

When roads are impassable or difficult to pass determines the extent to which routine transport needs are impeded. On the East Coast, the probability of high tide occurring at a particular hour is about the same over the course of a year due to the progressive nature of the semi-diurnal tide (i.e., 12.4 oscillation). Thus, AADT values are adequate to resolve this study's annual hours of delay metric. However, AADT is not uniformly distributed throughout the day and peak hours (e.g., morning (6-10 am) and evening commute (3-8 pm) (*27*)) are likely to experience more traffic than non-peak hours. Furthermore, the timing and duration of roadway inundation will vary within the 'minor' flood area and differentially impact segments.

SUMMARY

Sea level rise and flooding due to storm surge are understood to make coastal roadways more vulnerable and less functional. This study identifies nuisance flooding as an important, additional stressor that should be considered when characterizing transportation infrastructure's vulnerability to SLR and identifying resiliency measures. This study documents the number of vehicles and hours affected on flooded roads in the NOAA-designated 'minor' flood area. The results indicate that tidal nuisance flooding across the East Coast threatens thousands of miles of roadways including hundreds of miles of interstate roadways. Over the past twenty years, the frequency of nuisance floods has nearly doubled and is projected to continue to increase at all locations. The total induced vehicle-hours of delay due to nuisance flooding currently exceed 100 million hours annually and could exceed a billion vehicle-hours by 2060. In addition to the reported delays, flooding affects transportation system performance with direct and indirect impacts to logistics, safety, local economies, and emissions.

Future analyses are needed to more broadly understand transportation impacts from tidal nuisance flooding as well as to better understand impacts in specific regions. Roads outside of NOAA's 'minor' flood area may also be increasingly vulnerable to flooding. Furthermore, the delays due to impacts to surrounding roads that may accommodate traffic that would otherwise flow on flooded roads could also be included. In some regions, there are existing, planned, or potential protective structures or adaptation strategies to reduce roadway flooding that were not considered in this study.

These measures could reduce the frequency and duration of flooding and improve a community's ability withstand or recover from tidal nuisance flooding.

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