Inundation of Stormwater Infrastructure is Common and Increases Risk of Flooding in Coastal Urban Areas

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Key Points:

- Proxy measurements show that inundation of coastal stormwater networks from high receiving water levels is common along the US east coast
- Water level measurements and modeling in coastal North Carolina showed frequent stormwater network inundation at typical water levels
- Stormwater network inundation increases risk of overland flooding in coastal urban areas

Abstract

Stormwater infrastructure can mitigate precipitation-driven flooding when there are no obstructions to draining. Coastal areas increasingly experience recurrent flooding due to elevated water levels from storms or tides, but the inundation of coastal stormwater infrastructure by elevated water levels has not been broadly assessed. We conservatively estimated stormwater infrastructure inundation in municipalities along the Atlantic United States coast by using areas of high tide flooding (HTF) on roads as a proxy. We also modeled stormwater infrastructure inundation in four North Carolina municipalities and measured infrastructure inundation in one. Over 600 east coast municipalities had road area impacted by HTF, and over 1/3rd had >1% road area impacted. Modeling results and water level measurements indicated that extensive inundation of underground stormwater infrastructure frequently occurs during typical water levels. These results suggest that stormwater infrastructure inundation is common and increases the occurrence of urban flooding along the east coast of the US.

1 Introduction

Coastal flooding is a longstanding issue which has been exacerbated by climate change (Kulp & Strauss, 2019; Nicholls et al., 1999; Wahl et al., 2015; Woodruff et al., 2013). Flooding due to extreme storm events such as hurricanes is increasing, and these extreme storms can cause massive amounts of damage to coastal communities (Hallegatte et al., 2013; Hinkel et al., 2014). While sea level rise is predicted to increase the impact of extreme storm events on coastal areas, it is also increasing the incidence of recurrent nuisance flooding known as "high tide flooding" (HTF) (Sweet et al., 2020, 2018). Many cities in the United States (US) already experience multiple days of HTF a year, with the number of flood days rapidly increasing (Sweet et al.,

2018). During dry weather, this recurrent nuisance flooding can be disruptive to local infrastructure and economies (Hino et al., 2019; Jacobs et al., 2018). Combined with typical storm conditions, high tide flooding can impede stormwater drainage and result in more significant compound flooding (Rosenzweig et al., 2018; Shen et al., 2019; Wahl et al., 2015; R.L Wilby, 2007).

Stormwater drainage networks aim to prevent flooding from stormwater runoff, but sea level rise threatens to reduce the efficacy of coastal stormwater networks (Rosenzweig et al., 2018; Titus et al., 1987; R.L Wilby, 2007). The goal of reducing precipitation-driven flooding has conventionally been achieved using an underground pipe network that quickly conveys stormwater runoff to a receiving waterbody using gravity (Burns et al., 2012; Hale, 2016). Older stormwater networks were designed to accommodate conditions at the time of their construction under the assumption that future conditions and variability will be similar to those in the past, but climate change has invalidated this assumption (Milly et al., 2008). Relative sea level rise in some coastal areas of the US has increased mean sea level by up to a foot since the 1960s (Eggleston & Pope, 2013; Zervas, 2009), so many coastal stormwater networks are increasingly inundated by typical high tide water levels or rising groundwater levels (Rotzoll & Fletcher, 2013; Sadler et al., 2020; Shen et al., 2019; Su et al., 2020; Wdowinski et al., 2016). Stormwater network inundation reduces how well the system drains during storm events (Shen et al., 2019; Wahl et al., 2015), but recurrent stormwater network inundation by saltwater also corrodes stormwater infrastructure (Bjerklie et al., 2012), promotes saltwater intrusion to groundwater (Su et al., 2020), and can mobilize fecal bacteria from co-located sanitary sewer lines (Su et al., 2020).

Inundation of underground stormwater networks has been reported in multiple cities in the US (Hino et al., 2019; Sadler et al., 2020; Shen et al., 2019; Wdowinski et al., 2016), but a broad characterization of stormwater network inundation has not been conducted. Recent studies of compound flooding show how both stormwater network inundation and precipitation influence coastal flooding, but most of these studies focus on small areas or specific extreme storm events to recreate real-world flooding conditions using hydrodynamic models (Gallien et al., 2014; Hasan Tanim & Goharian, 2020; Sadler et al., 2020; Shen et al., 2019). These flooding estimates are extremely useful for the modeled study areas, but the limited spatial or temporal resolution of flooding estimates may limit their utility to identify vulnerable infrastructure hotspots at larger spatial scales or during dry-weather conditions. Regional- or national-scale estimates of stormwater network inundation do not exist, but these estimates, or even proxies, of stormwater network inundation would be helpful in characterizing the extent and scale of the issue. For broad estimates of stormwater network inundation to identify vulnerable infrastructure during dry- or wet-weather conditions, static inundation ("bathtub") models that use a digital elevation model (DEM) to estimate inundation at discrete water levels may serve as useful tools for managers. Static inundation models have limitations, such as over-estimating flooding extent relative to hydrodynamic models (Castrucci & Tahvildari, 2018; Gallien et al., 2014), but their simplicity makes them well-suited for use as a diagnostic tool at large spatial scales.

In this study, we used simple proxies, static inundation models, and water level measurements to estimate stormwater network inundation at varying spatial scales. Through modeling, we also tested how stormwater networks influence flooding when receiving waters are elevated and how stormwater network inundation relates to current NOAA coastal flood thresholds. To identify locations along the eastern US coast where stormwater network

inundation may occur, we used buffered road data from the OpenStreetMap and NOAA high tide flooding estimates to find roads within incorporated municipalities that experience HTF, and thus likely also have subterranean inundation of the stormwater network draining the road. To characterize inundation of the stormwater network in the coastal town of Beaufort, NC, we measured water levels in stormwater infrastructure over a period of 8 months and compared them to water levels from a nearby NOAA tide gauge (Figure S1). We then used a static inundation model both with and without a coupled pipe network model to estimate stormwater network inundation and overland flooding across a range of water levels in Beaufort and three other cities in NC (Wilmington, Nags Head, and New Bern)(Figure S1).

2 Materials and Methods

2.1 High tide flooding on roads along the US east coast

We used publicly available national-scale road and high tide flooding datasets to find areas where the two datasets overlapped in incorporated municipalities along the east coast of the US. We suggest that areas where roads are inundated during high tide flooding can act as a conservative proxy for areas where stormwater network inundation occurs during high tide events. This estimate can be considered conservative because without stormwater network infrastructure data, we cannot estimate the extent of inundation in pipes that are underground. Therefore, the only way to estimate the incidence of underground stormwater network inundation at a national or regional scale is to detect the end results of stormwater network inundation, which is overland flooding caused by surcharge from the stormwater network or overland flooding that is actively entering the stormwater network. This assumption would likely

not apply in lower-density or rural areas if there is no stormwater network present, but we believe that this assumption is reasonable within the boundaries of incorporated municipalities.

The east coast of the US is comprised of fifteen states, ranging from the Atlantic coast of Florida to Maine, and these fifteen states were selected as the extent for the stormwater network inundation estimate. Census bureau incorporated municipality boundaries were downloaded for each state in order to constrain the estimate to urban areas, where the underlying assumption of the coincidence of roads and stormwater networks is likely strongest. High tide flooding estimates from NOAA were downloaded for each state (Sweet et al., 2020), and these estimates consist of approximately 3-meter resolution raster data sets that indicate areas where "minor flooding" occurs based on a common impact threshold derived from the local tidal range (Minor flood threshold (m) = 1.04 * (Mean Higher High Water – Mean Lower Low Water) + 0.5) (Sweet et al., 2018). Road data for each state were downloaded from the open-source OpenStreetMap (https://www.openstreetmap.org). The OpenStreetMap road dataset was selected rather than the Census Bureau's TIGER dataset because the OpenStreetMap dataset explicitly identifies bridges and tunnels. Bridges and tunnels were removed from the roads dataset because including bridges and tunnels could create false positives for the inundation estimates, where the bridge or tunnel appears to overlap high tide flooding extent when it is actually over (bridges) or under (tunnels) the inundated area; most bridges are removed from the DEMs used to calculate high tide flooding estimates.

Processed road data consisted of GIS polylines, and a 5-meter buffer was created around all polylines to create polygons that approximated road surfaces (i.e., 10 meter width). Waterbody outlines from the National Hydrography Dataset (NHD) (i.e., ocean/sea, rivers, ponds, reservoirs) were used to remove any portions of buffered roads that intersected them to

further remove false positive areas. Polygons representing buffered roads were then used to extract high tide flooding estimates. The extracted high tide flooding estimates were then used to clip the buffered road network, so that the attributes associated with the buffered road polygons could be analyzed (i.e., road type). Areas of overlap among buffered roads where road area would be counted multiple times were extracted and dissolved to create polygons labeled simply "intersection". These intersection areas were erased from the buffered road polygon dataset to remove the overlapping polygon areas, and then the intersection areas were merged with the edited buffered road polygon dataset.

This analysis resulted in areas where high tide flooding estimates intersect roads, assuming a 10m wide road. Based on the assumptions outlined above, these data represented areas where stormwater network inundation may occur, either from surcharge from the stormwater network due to tidal flooding or from tidal flooding overtopping stormwater network inlets.

2.2 Site Description

We measured various stormwater network water levels and modeled inundation in Beaufort, a small town located in coastal North Carolina on a peninsula between the mouths of the Newport and North Rivers (Figure S1). The downtown area of Beaufort is located directly adjacent to Taylor's Creek, a channel that receives either brackish flow from the Newport/North rivers or saline water from the Atlantic Ocean via Beaufort Inlet. Taylor's Creek has a mean semi-diurnal tidal range of 3.11 ft (NOAA gage 8656483). The downtown area has moderate urban land use and uses conventional subsurface piping to convey stormwater from impervious surfaces directly to Taylor's Creek. The town has no stormwater backflow measures, and often

157 documents "sunny day" high-tide flooding and compound flooding during storm events (Sweet
158 et al., 2020). A recent survey of the stormwater network by a civil engineering firm produced
159 measurements for most of the downtown area (shown in bold in Figure S1).

160 Stormwater network inundation was also modeled in Wilmington, New Bern, and Nags
161 Head, North Carolina. Each dataset had sporadic missing values for pipe or structure elevations,
162 but New Bern had a large section of upland new development that was excluded due to missing
163 survey elevations. All three cities (and Beaufort) have some distinctly different characteristics,
164 but they all have all have flooding issues and large areas of development that rely on subsurface
165 stormwater conveyance directly to a receiving waterbody. Wilmington is both the largest city
166 and the city with highest elevation and relief. Wilmington's downtown area is directly adjacent
167 to the Cape Fear River and has a mean semi-diurnal tidal range of 4.28 ft above the river stage
168 (NOAA gage 8658120), but it also has extensive suburban land use on the southern and eastern
169 sides of the city that are affected by mean 3.98 ft semi-diurnal tides from the Atlantic Ocean
170 (NOAA gage 8658163). New Bern is further inland and lies on the western side of the Neuse
171 River. The Neuse River near New Bern can experience large amounts of riverine or storm surge
172 flooding during hurricanes due to its eastward-facing orientation, and this occurred recently in
173 2018 during Hurricane Florence that led to damages costing hundreds of millions of dollars.
174 Nags Head is located on the Outer Banks, east of Manteo and Roanoke Island. On its western
175 side, Nags Head is affected by wind-driven tides within the Pamlico sound, while its eastern side
176 is affected by mean 3.22 ft semi-diurnal tides (nearby NOAA gage 8651370) from the Atlantic
177 Ocean.
178

179 2.3 Water level

180 Two stormwater outfalls in Beaufort were selected for water level monitoring (Figure S1,
181 OS-outfall and MP-outfall), and water level within the pipes was measured every 30 minutes
182 from June 2017 to February 2018 (8 months) using a Teledyne Isco low-velocity flow sensor
183 (pressure transducer for level) . In late November (for 3 months), we began measuring water
184 level in a storm drain upstream from the MP site (Figure S1, MP-upstream).

185 A NOAA water level gauge located in Beaufort on Taylor's Creek, and data were
186 downloaded from this station to compare to our measured water levels. Using NOAA water level
187 data and the surveyed invert elevations of our monitored sites (NAVD88), the water level in each
188 monitored site was estimated every 30 minutes, coincident with the measured water levels within
189 the pipes. Pipe diameter measurements for the two monitored outfalls and one storm drain were
190 used to calculate the percent cross-sectional area inundated at the pipe ends for each time step of
191 measured water level.

192

193 2.4 Inundation Modeling

194 Stormwater network GIS data were obtained from each individual municipality by
195 request. In total, we contacted 14 municipalities in coastal North Carolina and received data from
196 8 municipalities. After data QC, we determined that only 5 municipalities had adequate data for
197 the purpose of inundation modeling, and the main selection criteria were data coverage of the
198 majority of the city and elevation or depth data for stormwater inverts. We chose four
199 municipalities with good quality data: Beaufort, Wilmington, Nags Head, and New Bern.

200 We then created an R package, *bathtub* (https://acgold.github.io/bathtub/), that
201 implements a 2D static inundation model coupled with a 1D pipe network model to estimate

stormwater network inundation at discrete water levels. The R package uses GIS data representing the stormwater network features (e.g., pipes, drop inlets, junction boxes, etc.), and creates a model object consisting of 3 simple feature objects (*sf* R package, Pebesma, 2018): 'pipes', 'nodes' (pipe ends), and 'structures' (e.g., drop inlet, junction box, etc.). Network connectivity derived from the spatial topology is stored in the 'nodes' layer. In the case of the occasional missing invert elevation at a node, the value is conservatively interpolated from nearby nodes by dropping the invert elevation a minimal amount (0.1 feet) from the nearest up-network value.

For the 2D inundation model, we used methods and source data used by NOAA to model overland inundation (SLR viewer: https://coast.noaa.gov/slr/). We utilized 1/9th arcsecond (~ 3 m) NOAA SLR DEMs (https://coast.noaa.gov/slrdata/) and converted the vertical datum of the elevation values from NAVD88 to the local mean higher high water (MHHW) datum using a conversion raster created with the NOAA VDATUM application (https://coast.noaa.gov/htdata/Inundation/TidalSurfaces). For Nags Head only, the conversion factor between NAVD88 and MHHW was propagated up the stormwater network because there were large differences in conversion factors between the western side (Pamlico Sound) and eastern side (Atlantic Ocean) of the barrier island. For each distinct water level modeled, areas lower than that elevation were selected, and clumps of cells smaller than a specified area were removed. This filtering of small clumps of cells ensured that modeled inundation only represented areas connected to the receiving water body.

This estimate of overland flooding was used as a starting point for the 1D pipe model, with all nodes (pipe ends) that intersected the overland flooding extent selected and marked as "impacted" at that water level. The specified water level was propagated up-network by

evaluating every node connected to the initially-selected nodes by a pipe and selecting nodes with invert elevations below the specified water level. This propagation continued until no additional nodes were selected for the specified water level. All selected nodes and both pipes and structures connected to them were marked as "impacted", and using the diameter of each pipe end and the depth of each structure, the percent inundation of each object was calculated. Overland ponding was estimated using the original MHHW DEM by selecting all cells under the specified elevation and selecting only clumps of cells not connected to downstream waters but intersected structures that were estimated to be surcharging (water elevation > surface structure elevation).

Error estimates for model results were calculated using the z-score mapping method (Schmid et al., 2014), which produces a p-value that indicates the likelihood of inundation at a particular water level for each DEM pixel or stormwater network component. For the 2D model, error estimates incorporated the root mean squared error (RMSE) of the source DEM and the error associated with converting elevations from NAVD88 to MHHW. For this study, RMSE of the source NOAA DEM was 20 cm while estimated error (as standard deviation) of the conversion factor was 10 cm. In computing z-scores for stormwater network components, the measurement error of network invert elevations (estimated at 10 cm) was added to the error components from the 2D model if invert elevations were derived from depth measurements. If invert elevations were directly measured, the only additional error included was error from the conversion between NAVD88 and MHHW. P-values derived from z-scores allowed for predicted impacted infrastructure to be classified as "high confidence" (80% confidence, $p < 0.2$) or "low confidence" (20% confidence, $p < 0.8$).

Using the *bathtub* R package, we modeled inundation in all four study cities between the water levels of -3 ft and 4 ft MHHW by 0.25 ft increments. To estimate flooding caused by stormwater network surcharge, the number of inlet structures impacted at each water level estimated by the 2D-1D model were compared to the number of inlet structures impacted by only the 2D component of the model that represents overland flooding with no subsurface modeling.

3 Results

3.1. High tide flooding on roads along the US east coast

High tide flooding on roads was estimated to occur to some extent in 656 incorporated municipalities along the US east coast, indicating that inundation of stormwater infrastructure may occur in many of these municipalities during high tide unless backflow measures exist (Figure 1). The metro areas of Miami, FL, New York City, NY, and Boston, MA had the largest estimated extent of high tide flooding on roads, partially because of the overall large amount of roads (Figure 1a,b, Figure 2). The majority of estimated impacted roads are classified as service (e.g., parking lots, alleys, etc.) or residential roads, but larger and higher-traffic roads (tertiary – trunk) were also estimated to be impacted in larger metro areas (Figure 1b,c).

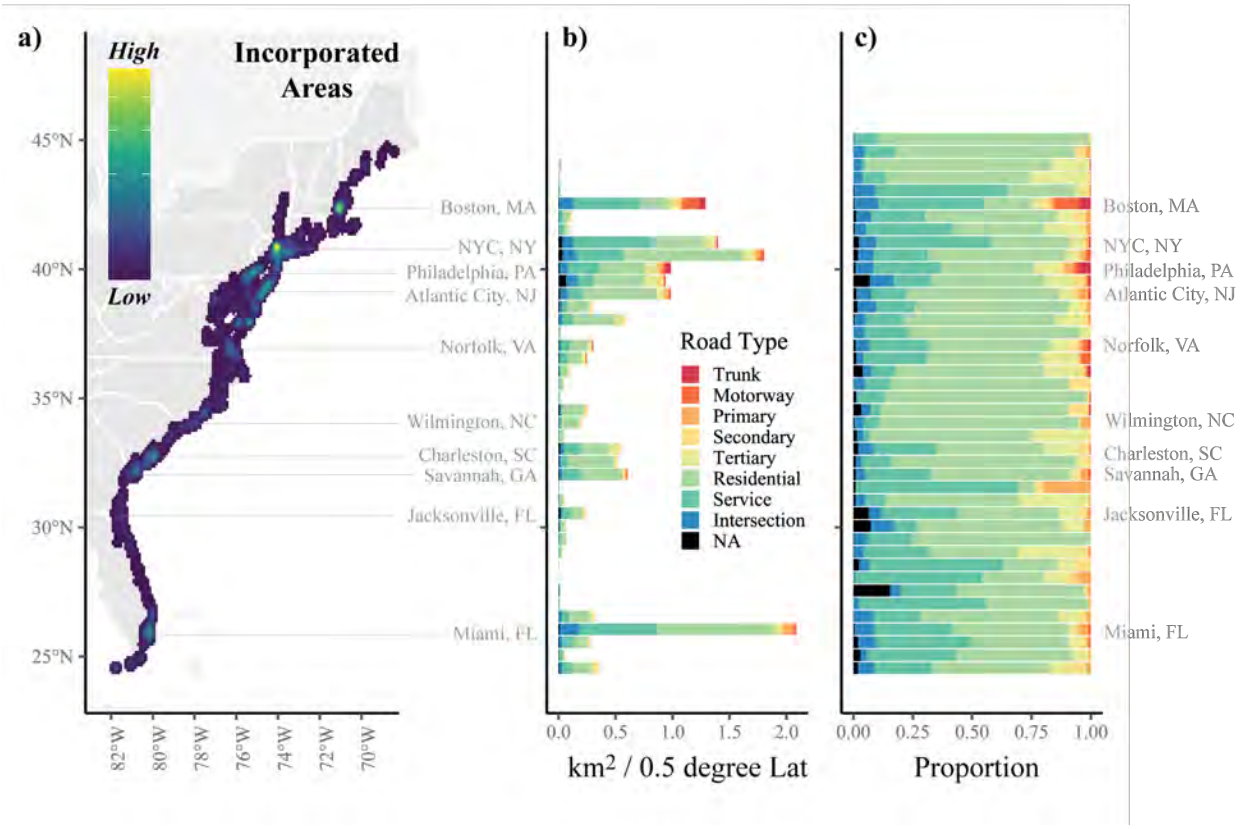

Figure 1. Area of high tide flooding on city roads. **a)** Density map of areas where high tide flooding overlaps roads in incorporated areas, **b)** road area overlapping estimated high tide flooding extent binned by 0.5 degrees of latitude, and **c)** proportion of impacted road area separated by road type.

Using estimates of total road area for each incorporated municipality, we found that the median percent of total road area impacted by HTF decreased as total road area increased ($\rho = -0.25$, $p < 0.001$, Figure 2), and the relative impact of HTF on roads varied greatly between municipalities, ranging from just over 0 to 94.5% of total road area impacted by HTF. While a majority of municipalities along the US east coast that currently experience HTF on roads had relatively small amounts of total road area impacted by HTF (median = 0.28%, Figure 2), approximately 1/3rd of the municipalities had greater than 1% of total road area impacted by HTF and approximately 13% of the municipalities had greater than 5% of total road area impacted HTF (Figure 2). Of the four municipalities measured or modeled in this study, Beaufort had the

highest percent of total road area impacted by HTF (1.17%), followed by Nags Head (1.04%), Wilmington (0.23%), and New Bern (0.19%).

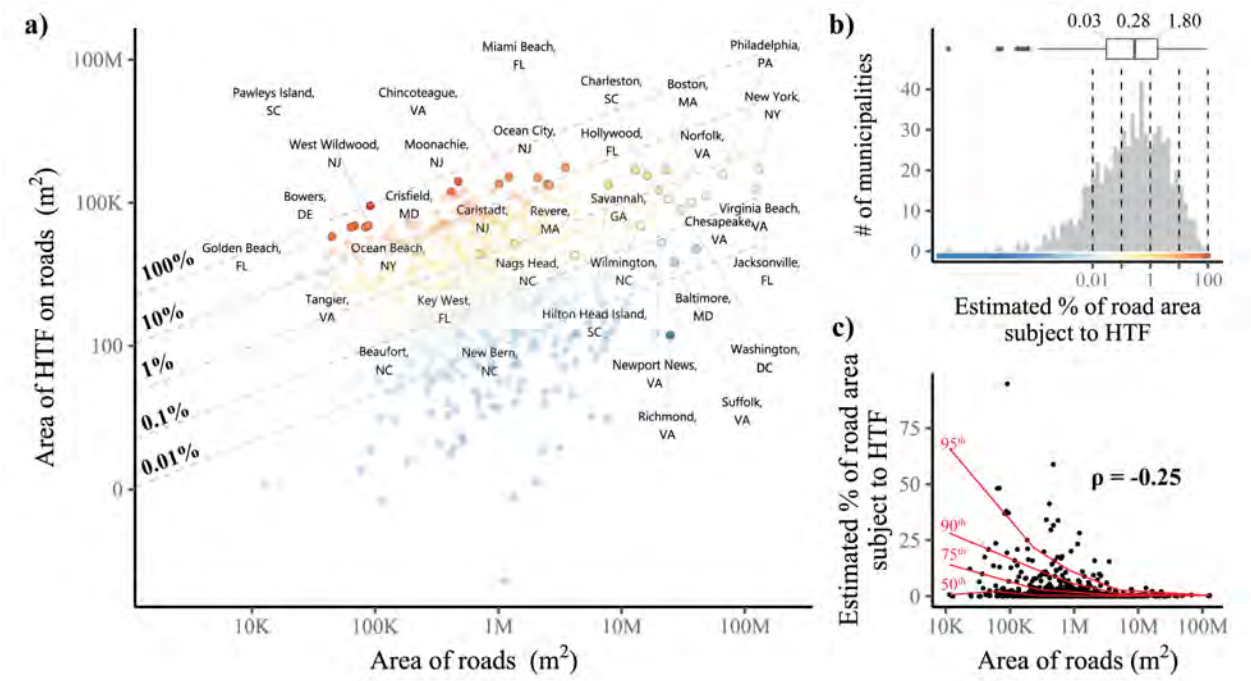

Figure 2. High tide flooding on city roads compared to total road area. **a)** Road area affected by high tide flooding (HTF) versus total road area for municipalities along the US east coast that experience some degree of HTF. Dotted lines and color indicate the estimated percent of road area subject to HTF in each municipality. Selected municipalities labeled, including the four study municipalities. **b)** Histogram of percent of total road area impacted by HTF. **c)** Percent of total road area impacted versus total road area with smooth quantiles (red).

3.2 Measured water levels

In Beaufort, NC, the two monitored stormwater outfalls experienced some degree of tidal inundation every tidal cycle throughout the 8-month monitoring period. (data shown for December 2017 in Figure 3). The upstream monitored storm drain (MP-upstream) was located more than 200 meters up-network from the corresponding outfall (MP-outfall), but MP-upstream also experienced significant tidal inundation during more extreme high-tide events (Figure 3). Water level in each monitored outfall was predicted based on NOAA water level from a nearby

297 gauge and the invert elevation of the infrastructure. Predicted water level measurements
298 corresponded well with observed water levels (r^2 = 0.72 – 0.95), as did cumulative distribution
299 functions of predicted and observed pipe inundation percent (Figure S2). The predicted water
300 levels for the MP-upstream site were slightly higher than the measured water levels, and the
301 predicted cumulative distribution of inundation percent over-predicted the occurrence of small
302 amounts of inundation in the storm drain (Figure S2).
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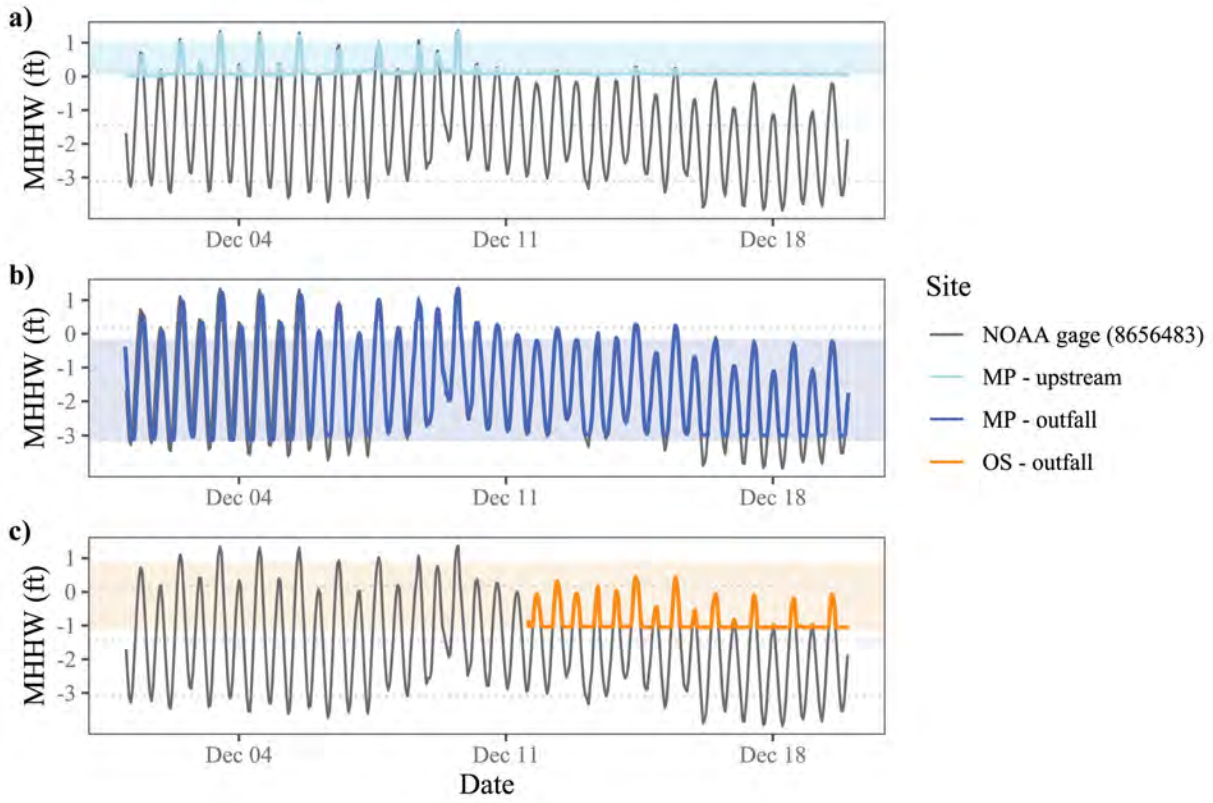

304

305 **Figure 3.** Snapshot of measured water levels in pipes. Example of water level measured in
306 selected pipes (color lines) and a NOAA tide gage in Beaufort, NC (grey line) in December
307 2017. Shaded areas represent the dimensions of the pipe, showing that the monitored pipes were
308 frequently filled with water from the receiving water body. Water level from OS – outfall (panel
309 a) is missing on the graph prior to Dec 11 due to equipment malfunction.
310

3.3. Inundation modeling

Modeling the impacts of a range of water levels on stormwater infrastructure inundation for the Town of Beaufort showed that the stormwater network likely has extensive inundation at typical water levels (mean sea level = -1.83 MHHW, mean high water = -0.29 ft MHHW)(Figure 4). At lower water levels, the inundation estimates are completely subsurface (Figure 4, Figure 5a), but beginning around 1.5 – 2 ft MHHW (near NOAA HTF threshold), portions of the stormwater network reach full capacity and result in surcharging and ponding on roadways (Figure 4, Figure 5c). Model simulations that do not incorporate conveyance via the stormwater network show overland flooding due to shoreline overtopping at 2.25 ft MHHW (Figure 5b), and the estimated number of stormwater inlets impacted by solely overland flooding ("no pipes" line in Figure 4) is consistently smaller than the estimated number of inlets that are at full capacity (Figure 4).

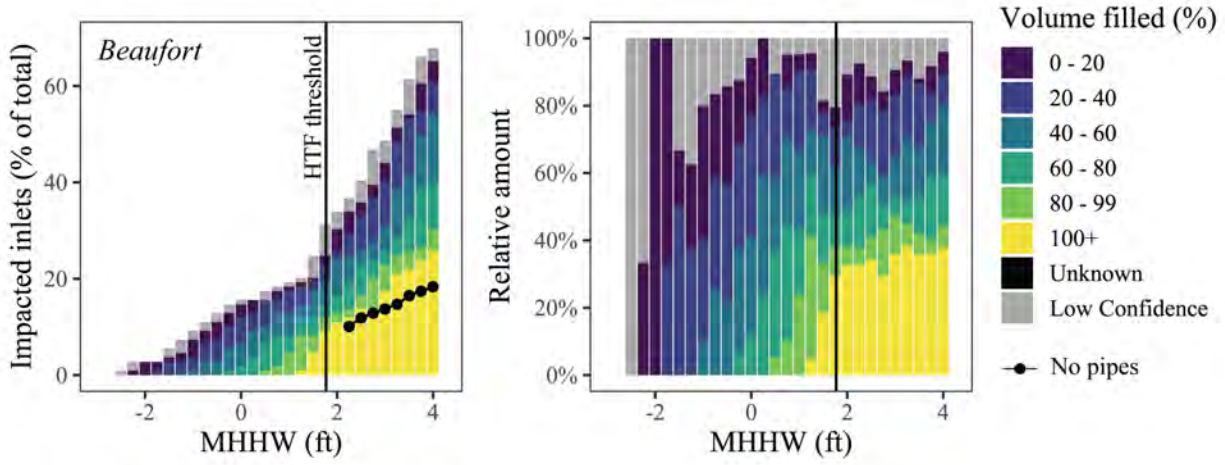

Figure 4. Model results for Beaufort, NC. Estimated impact of water level on stormwater inlets in Beaufort, NC across a range of water levels modeled with (stacked bars) and without (black dots/line) incorporating the stormwater network. NOAA HTF threshold for Beaufort is shown as black vertical bar (1.77 ft). Yellow bars ("100+" volume filled) indicate full/surcharging inlets.

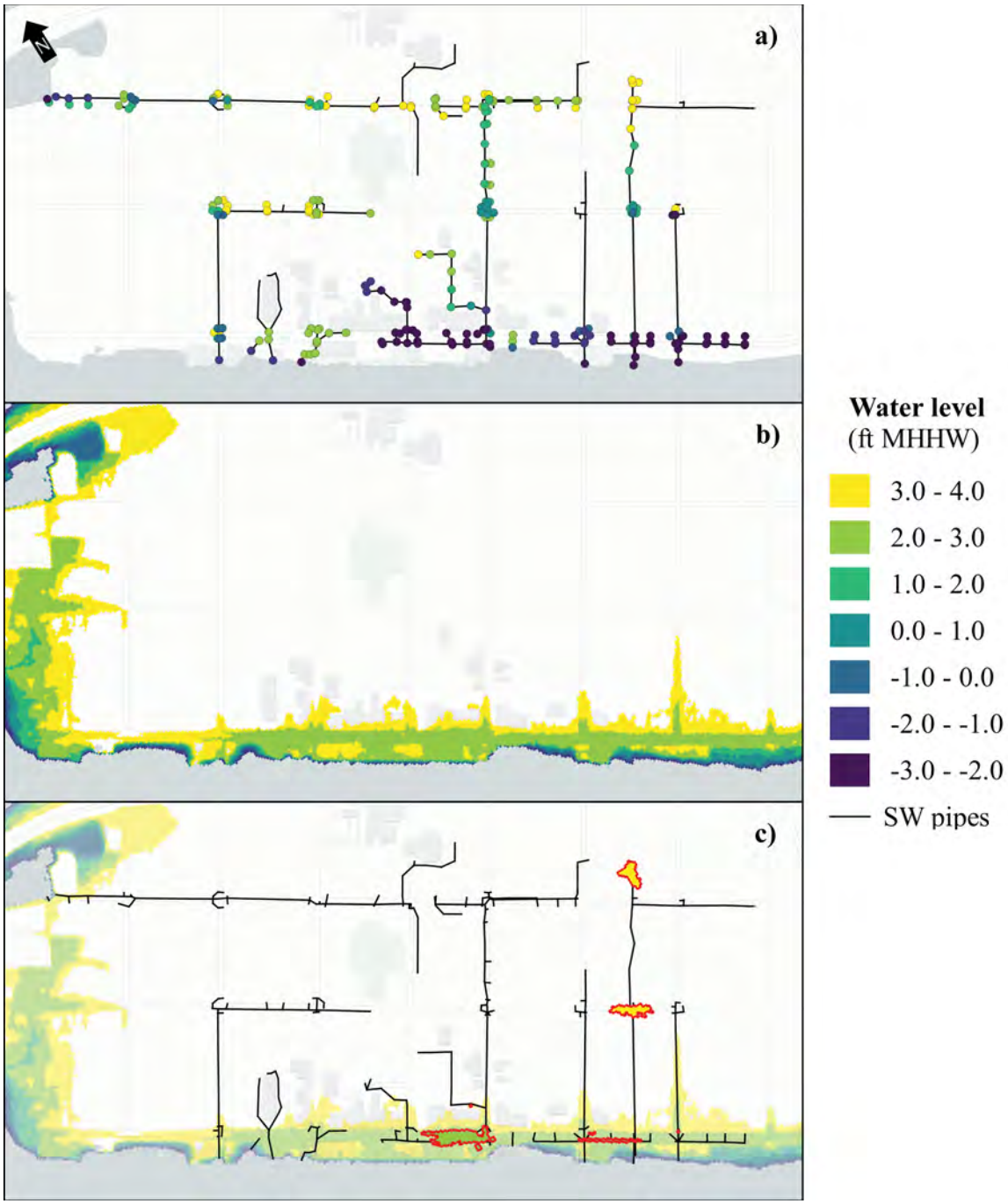

Figure 5. Spatial model results from Beaufort, NC. **a)** Water level of first impact (any degree of inundation) for pipe ends, **b)** overland flooding ignoring the stormwater network connected to Taylor's Creek for each water level, and **c)** extent of ponding at each water level due to surcharge from stormwater network (red border) and overland flooding (transparent).

Inundation modeling in Wilmington, New Bern, and Nags Head showed that stormwater network inundation likely also occurs often in these cities at typical water levels, but the percent

of infrastructure impacted is lower than in Beaufort (Figure 6 – note the different vertical scales for each municipality). As in Beaufort, all of the study cities had extensive estimated subsurface inundation at typical water levels, and most estimated inundation did not result in overland flooding (Figure 6). Comparing model simulations that incorporate the stormwater network with model simulations that do not showed that estimates of stormwater inlet surcharge in Wilmington and New Bern aligned well. Similar to Beaufort, though, the estimated number of surcharging/full structures in Nags Head as estimated by model simulations that incorporate the stormwater network was much higher than predicted by flooding estimates that do not incorporate the stormwater network (Figure 6).

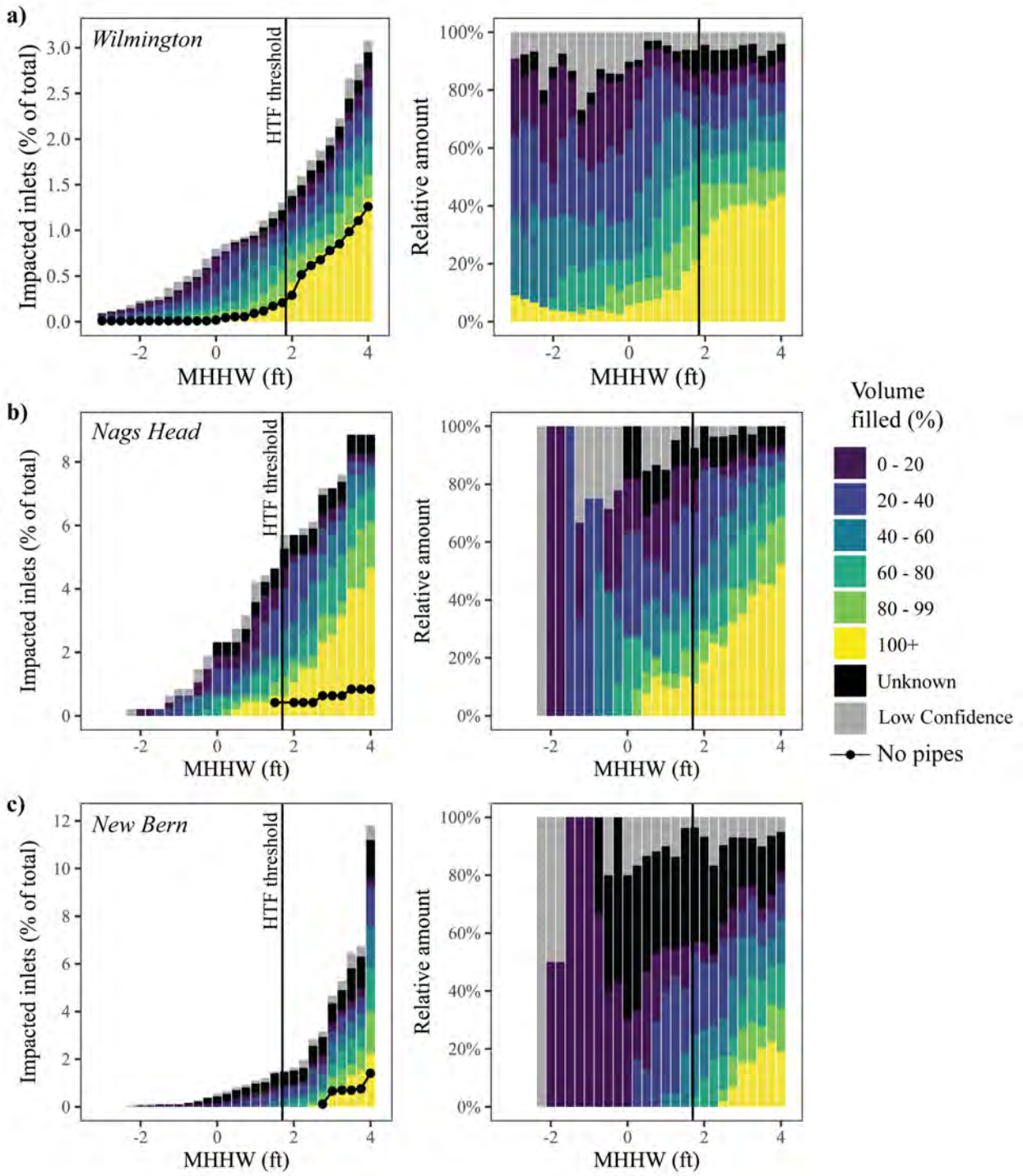

Figure 6. Model results from Wilmington, Nags Head, and New Bern, NC. Estimated impact of water level on stormwater inlets across a range of water levels in **a)** Wilmington, **b)** Nags Head, and **c)** New Bern, NC. Impacts were modeled with (stacked bars) and without (black dots/line) incorporating the stormwater network. NOAA HTF threshold (1.84 ft – Wilmington) and

approximate HTF threshold (1.7 ft – Nags Head and New Bern) shown as black vertical bar. Yellow bars ("100+" volume filled) indicate full/surcharging inlets.

4 Discussion

Inundation of stormwater infrastructure can have a large local impact on the frequency and magnitude of urban flooding, but this phenomenon remains difficult to characterize. Using national high tide flooding and road data, this study demonstrated that tidal inundation on coastal roads, and thus stormwater infrastructure, occurs in municipalities along the east coast of the US. Measuring stormwater infrastructure inundation at a local scale in Beaufort, NC, gauged stormwater outfalls were inundated by the tide daily while the monitored upstream storm drain was inundated during extreme high tides. Predictions of pipe water level based on local NOAA water level data and pipe elevations showed that predicted outfall water levels corresponded well with measured water levels, but predicted water levels for the upstream storm drain were slightly higher than measured water levels, highlighting an acknowledged weakness of static inundation models. Using a 2D static inundation model coupled with a 1D stormwater network model (see Methods), we found that all four study municipalities likely experience frequent inundation of underground stormwater infrastructure that impairs their ability to convey stormwater. Inundation of the underground stormwater network occurred at water levels far below local NOAA "minor flooding" thresholds (~ 1.75 ft above MHHW), suggesting that current and future estimates of high tide flooding extent and frequency may drastically underestimate urban flood risk due to reduced stormwater capacity. While stormwater networks aim to drain stormwater runoff, model results from Beaufort and Nags Head showed that the stormwater network can act as a conduit for elevated downstream waters to flood low-lying inland areas that would otherwise be disconnected from receiving waters. Overall, this study shows that stormwater network

inundation in coastal US municipalities is common and can increase the risk of overland flooding.

4.1. Impacts of network inundation

The measured and estimated stormwater network inundation in this study demonstrate the frequency of stormwater network inundation and the associated decrease in network drainage during wet weather along the east coast of the US. It is well-known that elevated water levels are a major driver of coastal urban flooding during extreme storm events such as hurricanes (Shen et al., 2019), but this study further shows that stormwater networks may often have reduced capacity to convey runoff during typical weather conditions and water levels far below local NOAA "minor flooding" thresholds frequently used to characterize high tide flooding (e.g., Sweet et al., 2018). Storm surge is not required to impair stormwater network drainage; typical high tides can affect network drainage during wet weather even absent overland flooding due to tides. Although Beaufort had the largest estimated impact at typical water levels (< 1 ft MHHW), it is important to note that it was the smallest of the four study municipalities with most of the surveyed infrastructure in the downtown portion of the municipality along a developed waterfront. A low percent of impacted stormwater inlets in another municipality could still mean a large impact in specific lower-lying spots within the municipality, especially if the municipality also encompasses inland area with higher elevations (e.g., Wilmington).

Inundation estimates of infrastructure in the study cities, especially Beaufort and Nags Head, also suggest that the stormwater network may act as conduit for receiving waters to flood low-lying areas at high water levels. Both of these municipalities had approximately 1% of their total road area impacted by HTF, suggesting that this specific issue may be widespread given that 1/3rd of the incorporated municipalities along the US east coast that experience HTF on

roads had similar or greater levels of HTF impact on total road area. This overland flooding that is counterintuitively exacerbated by stormwater networks could have negative impacts during both dry and wet weather. During dry weather, this overland "nuisance" flooding could have negative economic impacts for local businesses by limiting access (Hino et al., 2019). During wet weather, this overland flooding would effectively reduce the ability of the surrounding area to drain, depending on the amount of precipitation. An example of this high-tide flooding via the stormwater network is evident in Beaufort, where a section of road adjacent to Taylor's Creek (Front St.) is predicted to flood at 1-2 ft MHHW (Figure 5b). These model results align with high tide flood reports at this location (Figure S3) and NOAA estimates of high tide flooding during dry weather (https://bit.ly/30MWUGi).

During dry weather, the inundation of subsurface pipes with brackish or saltwater at typical tidal water levels can degrade them (Bjerklie et al., 2012) and promote saltwater intrusion and the transmission of fecal bacteria from nearby sewer lines (Su et al., 2020). We did not directly measure or model either of these effects, but during water level data collection in Beaufort, we did find qualitative evidence of network degradation in the form of oysters and barnacles growing within the stormwater network or cracked pipes (Figures S4-S6). The issue of stormwater and sanitary sewer degradation from inundation likely exists in Beaufort, as a previous study in the area measured high levels of human-sourced fecal indicator bacteria in piped stormwater runoff (Parker et al., 2010).

4.2 Issues characterizing network inundation

While inundation of stormwater networks appears widespread and common in our study area, directly characterizing the scale of the issue of stormwater network inundation remains a challenge due to issues of data quality and availability.

Good quality stormwater network data is key to assessing the impacts of inundation on the stormwater network, but inadequate funding likely hinders the collection of stormwater infrastructure survey measurements. For example, in NC, many municipalities raise the majority of funding for stormwater management directly through local stormwater fees (Riggs & Kirk, 2019). While stormwater fees are a common means of raising funding for stormwater projects, they often do not generate enough funding for necessary stormwater infrastructure projects (Riggs & Kirk, 2019; Zhao et al., 2019). Approximately 18% of stormwater fees tracked over the past decade in NC have not been increased during that time period, and 36% of the fees that have been increased did not keep pace with inflation despite rising budget needs (Riggs & Kirk, 2019). Also, municipality size and property values likely both contribute to higher stormwater fees (Kea et al., 2016), thus allowing more populous cities or areas with higher property values to collect more money for stormwater projects than smaller towns with lower property values, despite the fact that smaller towns are more likely to have a higher degree of road impacts from HTF (Figure 2c).

If municipalities do, in fact, have adequate stormwater network data to assess the possible impacts of inundation, there are currently no centralized state or federal databases to house the data. A public database of stormwater network data would have a positive impact on planning efforts to increase resilience to extreme storm events and sea level rise by allowing comparisons of network inundation between municipalities and additional modeling of flood risks. Comparisons of network inundation risk could help determine which municipalities are most at risk and in need of additional funding for updates. Broad access to stormwater network datasets would also allow more researchers access to undertake more sophisticated modelling of real-world flooding conditions during storm events (e.g., Shen et al., 2019). Stormwater networks are

heterogeneous due to differences in development or landscape properties, so infrastructure data from more municipalities could improve the accuracy of large-scale estimates that rely on assumptions of stormwater network characteristics. For the current study, we assume that HTF on municipal roads is an indicator of stormwater network inundation that drains the surrounding area, and additional infrastructure data from more municipalities would allow this assumption to be tested more broadly.

4.3 Addressing network inundation in the short- and long-term

The threat of coastal flooding is increasing due to rising seas and the effects of climate change on precipitation patterns (Kulp & Strauss, 2019; Nicholls et al., 1999; Sweet et al., 2020, 2018; Wahl et al., 2015; Woodruff et al., 2013), and many low-lying coastal areas will need to adapt quickly to both increased stormwater network inundation and excessive stormwater runoff.

For stormwater network inundation in the short term, the most direct engineering solution is to install tide gates that prevent flow up-network when receiving water levels are elevated. These tide gates reduce tidal inundation (Sadler et al., 2020; Shen et al., 2019), and there are even efforts to make these tide gates responsive to current and predicted inundation to increase their efficacy (Sadler et al., 2020). Though this retrofit to the current stormwater network may be effective in the short- to medium-term, predicted increases in sea level and groundwater will inevitably lead to continuously inundated outfalls in vulnerable locations and decreased surface storage of stormwater further inland (Davtalab et al., 2020; Rotzoll & Fletcher, 2013).

Addressing the long-term issue of coastal urban flooding, which includes both stormwater network inundation and excess stormwater runoff volumes, will require substantial investment in planning and upgrading drainage systems (Robert L Wilby & Keenan, 2012). A discussion of this broader adaptation and planning effort is outside the scope of the current study,

but these strategies broadly include updating infrastructure to address network inundation (e.g., backflow prevention, pumping), decentralized or low impact development to manage stormwater (e.g., stormwater harvesting), landscape-scale planning to incorporate surface storage of flood waters, and possibly managed retreat or buyouts of vulnerable areas (Rogers et al., 2020; Rosenzweig et al., 2018; Robert L Wilby & Keenan, 2012).

Future investigation is needed to further characterize the extent of coastal stormwater network inundation to inform planning efforts, and the simple modeling framework presented here can be used as an initial step for both municipalities and researchers.

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