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1 Flood Risk Assessment and Increased Resilience for Coastal Urban

2 Watersheds under the Combined Impact of Storm Tide and Heavy Rainfall

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18 Abstract

19 Low-lying coastal cities are vulnerable to flooding under the combined impact of storm tide and heavy 20 rainfall. While storm tide or heavy rainfall alone is able to directly cause widespread flooding in coastal 21 areas, often heavy rainfall and storm tide happen concurrently, and the severity of flooding is greatly 22 exacerbated. Current methods for understanding flood risk and mapping floodplains normally does not 23 clearly communicate either the individual or combined impact of these two flooding mechanisms. Flood 24 mitigation strategies typically target either rainfall-driven flooding (e.g., stormwater controls) or tidally-25 driven flooding (e.g., flood walls and tide gates). Thus, better understanding and communicating the 26 individual and combined flood risk resulting from these two mechanisms can be important to improving 27 flood resilience. To address this need, this study presents tools and methods for floodplain mapping in 28 coastal urban environments were rainfall and storm tide driven flooding can be better understood and 29 communicated. The approaches are demonstrated for a watershed in Norfolk, VA, USA as a case study 30 system using a 1D pipe/2D overland flow hydrodynamic model built for the watershed. Storm tide and 31 heavy rainfall events with return periods varying from 1 to 100-year were designed based on historical 32 observations and combined into a series of compound storm scenarios. Then these compound storm 33 scenarios were simulated using the hydrodynamic model for simulating flow through both the land 34 surface and underground pipe network systems. Results show how the capacity of the drainage system, 35 and therefore flood risk reduction, is sensitive to storm tide levels, even for less extreme events with a 1-36 year return period. The model also provides new insights into the role of stormwater infrastructure in 37 exacerbating flooding risk within communities during high sea level conditions. Results demonstrate how dividing the floodplain into different regions based on the dominate flooding mechanism (rainfall vs. 38 39 storm tide) makes it possible to better target mitigation strategies to improve flood resilience. To this end, 40 a transition zone index (TZI) is presented to help decision makers identify the change from rainfall-driven 41 to tide-driven flooding for locations within a watershed. Finally, we demonstrate how different flood 42 mitigation strategies can be tested using this modeling approach to better understand their impact on

43 increasing flood resilience within the system for portions of the floodplain impacted by rainfall-driven44 and tidal-driven flooding.

45 Author keywords: Coastal City; Urban Hydrology; Coastal Flood Mapping; Storm Tide; Heavy
46 Rainfall; 2D Hydrodynamic Modeling; Flood Resilience

47

48 **1. Introduction**

49 In the context of sea level rise and climate change, flooding is one of the most challenging issues facing 50 coastal cities today (Hallegatte et. al., 2013; Woodruff et al., 2013). Coastal cities form a vital component 51 of national and global economies; however, coastal cities and their economies are increasingly vulnerable 52 to extreme storm events (Hanson et al., 2011). As a consequence of extreme storm events, flooding 53 impacts on these low-lying, densely populated, and highly developed regions can be devastating (Gallien 54 et al., 2014; Wahl et. al., 2015; Karamouz et al., 2017; Sadler et al., 2017; Bilskie and Hagen, 2018). In 55 coastal cities, flooding is primary caused by two processes: surface runoff due to inland heavy rainfall and 56 tidal flooding from extreme high tide (Dawson et al., 2008; Archetti et al., 2011; Xu et al. 2014; Wahl et. 57 al., 2015). Heavy rainfall is more likely to cause severe flooding in urban areas with poorly functioning or 58 insufficient stormwater infrastructure (Upadhyaya et. al., 2014; Yazdanfar and Sharma, 2015). In coastal 59 cities, rainfall-driven stormwater collected by drainage system is designed to drain into the sea either by gravity-fed flow or pumping. However, during extreme high tide events, the drainage capabilities are 60 61 greatly reduced with a worse situation of backward flow. Additionally, extreme high tide alone is able to 62 directly cause widespread coastal flooding (Xu et. al., 2014; Castrucci and Tahvildari, 2018). Thus, if 63 heavy precipitation and extreme high tide happen concurrently, the severity of flood can be greatly 64 exacerbated (Zheng et al., 2013; Xu et al., 2014; Wahl et. al., 2015; Karamouz et al., 2015, 2017; Wu et 65 al., 2018). The extreme high tide discussed in this study is in the form of storm tide, which is the total observed seawater level during a storm resulting from the combination of storm surge and the 66 67 astronomical tide.

68 Prior studies have used statistical methods to explore the interdependence between storm tide and 69 heavy rainfall and their combined impact on flood risk (Zheng et. al., 2013; Xu et al., 2014; Wahl et. al., 70 2015; Batten et al., 2017; Wu et al., 2018). Zheng et al. (2013) investigated the presence of the 71 dependence between extreme rainfall and storm surge on Australian coastline using available rainfall and 72 tide level observations. They found a statistically significant dependence with regional and seasonal 73 variations for the majority of studied locations. Wahl et al. (2015) studied the likelihood of concurrent 74 storm tide and heavy rainfall for major coastal cities in the contiguous United States. It was found that the 75 probability of combined storms is higher for the Atlantic/Gulf coast relative to the Pacific coast. 76 Meanwhile, in many of the focused cities, the number of compound events has increased greatly over the 77 past century, and this trend may continue under the changing environment. Xu (2014) and Batten (2017) 78 estimated the joint probability of storm tide and extreme rainfall in their study areas and proposed design 79 guidance for future flooding preparedness. Specifically, Batten (2017), who worked on the same region, 80 coastal of Virginia, USA, as the current study, showed that over 50% of the rainfall events happened 81 when sea water level was higher than mean daily high tide. While statistical approaches are important for 82 understanding risk, they are not able to identify specific areas within a coastal community vulnerable to 83 flooding, nor are they able to quantify how modifications to the built environment, in the form of infrastructure improvements, can mitigate flooding risk. Physical models of the system are needed for 84 85 these challenges.

Coupled one-dimension (1D) pipe and two-dimension (2D) overland flood models are an efficient
way to simulate urban flooding and have been widely used for assessing urban flood risk (Leandro et al.,
2009; Seyoum et al., 2012; Russo et al., 2015; Fan et al., 2017; Xu et al., 2017; Martins et al., 2018). In
prior studies, 1D models (Ray et. al., 2011; Lian et. al., 2013; Bacopoulos et al., 2017; Karamouz et al.,
2017) or 2D models (Karamouz et al., 2017; Silva-Araya et. al., 2017) have been used to investigate the
combined impact of storm tide and extreme rainfall, but the combination of 2D/1D modeling approaches
to simulate both overland flow and flow through stormwater drainage systems for coastal watersheds is

93 novel. Coastal regions are usually located in low-relief terrains with flat or mild slopes and a large amount of storage potential, especially in coastal cities with complex topography and a large number of artificial 94 95 structures. Routing water in such regions is not as straightforward as in high-gradient regions since water 96 does not always stay within river channels. In confined channels, 1D models are able to generate good 97 estimation of flooding as long as the water remains in the channels (Marks et al., 2004; Leandro et al., 98 2009). However, for extreme storm events in urban environment, stormwater flow can easily overtops the 99 curbs in the streets, and the direction of the flow may change dramatically. In such conditions, a 2D 100 model is a more reliable tool for urban flood simulation. However, even though 2D models were used in 101 Karamouz (2017) and Silva-Araya (2017), the underground drainage system was not considered in both 102 studies. Underground drainage system is a key component of stormwater management infrastructure in coastal cities, and its efficiency could be greatly influenced by the downstream tidal boundary conditions 103 104 (Archetti at. al., 2011). Therefore, in order to simulate coastal city flooding in a realistic manner, flood 105 models need to be capable of simulating the dynamics of flow on ground surface and pipe flow in 106 underground drainage system, as well as the interaction between them. An effective way is to use a 1D 107 pipe and 2D overland coupled model. Several commercial or open-source 1D/2D modeling system are 108 available, such as, the Two-dimensional Unsteady Flow (TUFLOW) model (Syme, 2001), MIKE 21 109 (Carr and Smith, 2006), XP-SWMM, Leandro (2016), and Wu (2017). Such modeling systems can 110 support coastal flood mapping with the consideration of the individual and combined flood risk resulting from storm tide and heavy rainfall, and it can be important to improving flood resilience by testing the 111 112 impact of different potential mitigation strategies.

In prior studies, geospatial information and hydrodynamic models have been used for understanding flood risk and mapping coastal floodplains (Wang et al., 2002; Karamouz et al., 2015; Karamouz et al., 2017; FEMA, 2018). However, these methods normally do not clearly communicate the mechanisms of flooding for specific locations. In other words, it is not clear if the flooding is caused by the individual or combined impact of storm tide and heavy rainfall. This is problem in part because flood

118 mitigation strategies typically target either rainfall-driven flooding (e.g., stormwater controls) or tidally-119 driven flooding (e.g., flood walls and tide gates). To access flood risk across coastal landscapes, Bilskie 120 and Hagen (2018) proposed a methodology to delineate coastal floodplains into three flood zones, tidal 121 zone, hydrological zone, and transition zone, according to different driving forces of flooding. The 122 transition zone is defined as an area susceptible the interaction between tidal and rainfall-driven flooding. 123 Application of this method to a flooding event in southeast Louisiana shows that the excess rainfall and 124 storm surge interact nonlinearly and their compound effect is smaller than their superposition (Bilskie and 125 Hagen, 2018). Their study area was primarily located in a rural area with no effect from underground 126 stormwater drainage systems. The transition zone identified from their study is primarily located in a 127 region relatively close to the shoreline, where the tide has a significant impact on flooding. However, in 128 urban environments, the interaction between rainfall-driven flooding and tidal flooding exists on both the 129 land surface and subsurface through stormwater pipeline drainage systems. Thus, the influence of storm 130 tide is not limited to the near-shoreline region, but regions further inland as well.

131 The objective of the study is to develop methodologies to enhance the understanding of the 132 coastal city flood risk and how flood mitigation strategies in improving flood resilience. A high-133 resolution, coupled 1D pipe/2D overland hydrodynamic model was built using the TUFLOW modeling 134 system for a watershed within the Hague community of Norfolk, VA, USA. TUFLOW solves the full 2D depth averaged momentum and continuity equations for shallow water free surface flow, and incorporates 135 the full functionality of the ESTRY one-dimensional (1D) hydrodynamic network (Syme 2001). This 136 137 modeling system outputs detailed flooding information on both land surface and underground pipeline 138 system, which allows one to assess flood risk and understand the contribution of flooding from individual 139 or combined factors. The coastal floodplain mapping method proposed in Bilskie and Hagen (2018) was 140 extended for a coastal urban watershed based 2D/1D flood model simulations. The spatial extent of the 141 transition zone was identified using different combinations of storm tide and heavy rainfall events. We 142 also introduce an index to represent the likelihood of a region being susceptible to the combined impact of

storm tide and heavy rainfall. The mapping strategy assists in understanding how flood mitigation
approcah reduces flooding risk resulting from rainfall and storm tide drivers. The 1D pipe/2D overland
flood model is also a powerful tool to evaluate the efficiency of different flood mitigation strategies. As a
demonstration, two flood mitigation methods are tested in this study. The methodologies developed in
this study can aid city planners and stormwater engineers in other coastal communities to understand and
improve flood resilience by targeting both rainfall and storm tide-driven flooding.

149 The remainder of the paper is organized as follows. The methodology section provides 150 background information about the study domain and explains the urban flood model and design the storm 151 scenarios used in the study. It also includes a description of how flood zones were determined within the 152 floodplain mapping analysis and introduces the concept of a transition zone index (TZI). The results and 153 discussion section explains the model evaluation, how the lag between the peak storm tide and rainfall 154 was determined in the modeling scenarios, and flood risk determined by the model. The influence of 155 storm tide on the underground stormwater drainage system is also explored, followed by the coastal 156 floodplain mapping results and a brief exploration of how flood mitigation strategies could reduce the 157 floodplain for the study watershed. The paper concludes with key findings along with possible future 158 research to further advance the approach.

159

160 **2. Methodology**

161 *2.1 Study area*

162 Norfolk, Virginia, USA is the second most populous city in Virginia and the home of world's largest

163 naval base. Norfolk is a highly urbanized and relatively flat community with nearly all areas below

164 elevation 4.5m (North American Vertical Datum of 1988: NADV 88). The relative low elevations and

- tidal connections to the Chesapeake Bay place a significant percentage of the city at risk of tidal flooding.
- 166 The tidal flooding risk is more serious under the threat of sea level rise (SLR) and land subsidence (Li et.
- al., 2013; Sadler et. al., 2017). The study domain is located in the Hague community of the Norfolk, VA

(Figure 1). The sources of spatial datasets used in this study are provided in Table 1. The study domain
has a total area of 3.7 km², including total waterbody area of 0.1 km² and land area of 3.6 km², in which
0.7 km² is building area. Ground surface elevation of the study domain varies from 0.3m to 4.2m with an
average of 2.6m (NAVD88).

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Table 1. Spatial Datasets Collected to Build the Urban Flood model

Spatial Dataset	Provider	Sources		
LIDAR DEM	VGIN	https://www.vita.virginia.gov/integrated-services/vgin- geospatial-services/elevationlidar/		
Land Cover	VGIN	https://www.vita.virginia.gov/integrated-services/vgin- geospatial-services/land-cover/		
Basin Boundaries	Norfolk City	https://www.norfolk.gov/index.aspx?NID=1605		
Drainage System	Norfolk City	https://www.norfolk.gov/index.aspx?NID=1605		
Building Outlines	VGIN	https://www.arcgis.com/home/item.html?id=994d0afa44c0 46498f9774613671ce9a		
Road Centerlines	VGIN	https://www.vita.virginia.gov/integrated-services/vgin- geospatial-services/transportation/		

Note: VGIN: Virginia Geographic Information Network

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In this study, the tide level data was collected from the Sewells Point station (Station ID:

8638610), which is 9.7km away from the domain tidal boundary. This tide gauge has the longest tide

175 level record, dating back to 1927, in Virginia. There is no official rain gauge located inside the study

domain. Rainfall data was obtained from two weather stations run by the U.S. National Weather Services

177 (NWS) and two other weather stations run by the Hampton Roads Sanitation District (HRSD) (Figure 1).

178 On average, the NWS and HRSD stations are about 9km and 3km away from the study domain center,

respectively. The two NWS weather stations have hourly rainfall data available since 1948 and 1973,

180 respectively. The HRSD stations were installed in January 2016. For hurricane events simulated the

181 study, the NWS rainfall record was used as rainfall input for hurricanes earlier than 2016, and the HRSD

182 rainfall record was used for hurricanes after 2016.



183

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Fig. 1. Study area with tide gauge and rain gauge locations.

185 2.2 The Urban Flood Model

The study domain is located in a highly urbanized area with complex flow patterns and paths. The
interaction between overland flow and pipe flow significantly increases the complexity of flood modeling.
To overcome these difficulties, a 1D pipe/2D overland hydrodynamic flood model was built using the
TUFLOW model. TUFLOW was chosen due to its capability to represent surface flow on a 2D domain as
well as fluvial and pipe network via its 1D functionality and the dynamically link between the two. The
TUFLOW High-performance Computing (HPC) engine allows to execute the model on multiple GPU
units, which would significantly speed up model simulations.

193	The domain boundary was selected from the basin boundaries provided by the City of Norfolk,
194	and adjusted based on a high resolution LiDAR digital elevation model (DEM) and the underground
195	drainage system. There is no rainfall-driven flow, in the form of overland or pipe flow, entering into the
196	study domain from adjacent watersheds. Therefore, all rainfall-driven flooding is generated inside the
197	domain. The outlet of the domain connects to the Elizabeth River, which is a portion of the Chesapeake
198	Bay. Wave speed of tide is currently not considered in this study. So, the tide level at Swells Point was
199	considered to be the same as the outlet of the study watershed. The topography of the 2D domain was
200	defined using a $1m \times 1m$ Lidar DEM, building outlines, and road centerlines collected from the Virginia
201	Geographic Information Network (VGIN), as shown in Table 1. A land cover dataset with 1m spatial
202	resolution was obtained from VGIN to define the overland roughness. The Manning's roughness
203	coefficients for overland flow from McCuen (1998) were assigned to the 2D domain based on the land
204	cover types, as shown in Table 2. For a small watershed, flooding is primarily from short-duration
205	extreme storm events (Bryndal et al., 2017). At the same time, the current study area has an
206	imperviousness ratio of 57% and shallow groundwater level. Thus, infiltration is expected to have minor
207	influence on flooding caused by extreme storm events. Therefore, infiltration was not considered in the
208	current version of the urban flood model, which presumes saturated conditions within the watershed prior
209	to the model simulation period.

Table 2. Parameters used in the 1D pipe/2D overland hydrodynamic model

Parameters	Туре	Value
Manning's n value of 2D overland surface	Asphalt	0.012
	Concrete	0.013
	Other urban feature	0.012
	Grassland	0.15
	Shrub land	0.4
Manning's n value of 1D pipelines	Plastic pipes	0.012
	Concrete pipe	0.014
	Cast iron pipe	0.013
	Corrugated-metal pipe	0.015
	Brick	0.014

211 TUFLOW solves the full 2D depth averaged momentum and continuity equations for shallow 212 water free surface flow, and incorporates the full functionality of the ESTRY one-dimensional (1D) 213 hydrodynamic network (Syme 2001). In TUFLOW, inlets and grates are represented as pits, which allow 214 modelers to specify a depth-discharge relationship between ponding depth at pits and flow rate entering 215 drainage system. The depth-discharge relationship, controlled by the type and dimension of inlet, defines 216 the flow rate of overland stormwater entering into the pipeline system. The urban drainage design 217 manuals from Federal Highway Administration (2009) and state departments of transportation (e.g.: 218 VDOT, 2017) provide methods to calculate the draining capacity corresponding to the type and 219 dimensional of different inlets. In this study, the depth-discharge curves were determined for different 220 types of inlets based on the VDOT Drainage Manual (2017). The initial pipeline entrance and exit energy 221 loss coefficients are set as value of 0.5 and 1.0, respectively. TUFLOW is capable of automatically 222 adjusting energy loss coefficients associated with the contraction and expansion of flow into and out of a 223 structure according to the approach and departure velocities in the upstream and downstream channels. 224 Details of the energy loss adjustment technique are included in TUFLOW manual (2016) and Tullis and 225 Robinson (2008). The Manning's roughness coefficients were assigned to different types of pipelines, as 226 shown in Table 2.

227 2.3 Designing of Combined Storm Events

228 This study focuses on storm tide and heavy rainfall occurring with hurricanes on the Virginia coastline. A 229 summary of the hurricane history of central and eastern Virginia is provided by the National Weather 230 Service (NWS, 2016). Flood risk as a consequence of storm tide and heavy rainfall with the return periods 231 varying from 1 to 100-year are simulated and investigated in this study. Thus, hurricanes, resulted in both 232 storm tide and rainfall with recurrence intervals less than one year for coastal Virginia, were filtered out 233 from the list of hurricanes analyzed in this section. Historical hurricanes with rainfall and tide peak 234 recurrence intervals greater than one year are listed in Table 3. Hourly rainfall data were collected from 235 the NWS weather station 013737 due to it having the longest record in the study region. The Sewells

Points station was installed in 1927 to collect tide level data, thus only hurricanes happened after 1927 are
listed in Table 3. For the 15 hurricanes with an available rainfall record, the total amount of rainfall varies
from 16.8mm to 289.9mm. The minimal and maximum tide peaks are 0.55m and 1.95m (NAVD88),
respectively. The rainfall durations of the 15 hurricanes vary from 8 to 77 hours with the median of 22
hours. Ten out of the 15 hurricanes have rainfall durations between 16 to 30 hours. Therefore, because
rainfall events happening during hurricanes in the Virginia coastal region have average durations of about
22 hours. A 24-hour duration was selected as the design rainfall events in this study.

Yea	r Storm Event	Rainfall Duration (hrs)	Total Rainfall (mm)	Peak Tide Level (m, NAVD88)
192	8 Unnamed			1.13
193	3 Unnamed			1.95
193	6 Unnamed			1.56
195	3 Barbara			0.83
196	0 Donna	22	109.6	1.22
1964	4 Cleo	24	289.9	0.55
1964	4 Dora	30	122.0	1.19
197	1 Doria	22	78.6	0.61
198	5 Gloria	18	143.6	1.04
198	6 Charley	16	27.5	1.13
199	8 Bonnie	14	92.8	1.20
199	9 Floyd	33	166.5	1.29
200	3 Isabel	8	16.8	1.91
2004	4 Charley	15	94.6	0.80
200	6 Ernesto	27	256.6	1.19
201	1 Irene	27	207.7	1.81
2012	2 Sandy	77	151.8	1.57
201	6 Hermine	20	68.2	1.38
201	6 Matthew	21	234.7	1.27

Table 3. Historical hurricanes in Virginia with return period of rainfall or storm tide greater than one year.

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245 2.3.1 Designing of Storm Tide Events

246 The annual exceedance probability curves of extreme tide levels for the Sewells Points station were

247 generated by the U.S. National Oceanic and Atmospheric Administration (NOAA)

248 (https://tidesandcurrents.noaa.gov/est/curves.shtml?stnid=8638610). The annual exceedance probability

curves of extreme tide levels with 95% confidence intervals are included in the report. The curves were
calculated from the annual highest tide levels after the mean sea level trend was removed. The tide levels
with different return periods along with the 95% confidence intervals are obtained from the NOAA report
as shown in Table 4. The tide level was converted from the Mean Higher High Water (MHHW) datum to
NAVD88 to be consistent with the urban flood model settings.

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 Table 4. Annual exceedance probabilities and return periods of extreme tide levels and the matched historical hurricanes.

Exceedance Probability		99% (1-Yr)	10% (10-Yr)	2% (50-Yr)	1% (100-Yr)
Tide Level (m, NAVD88)		0.78	1.56	1.87	2.06
95% Confidence Intervals		0.72 - 0.81	1.35 - 1.61	1.64 - 2.33	1.76 - 2.74
Historical Hurricanes	Name	Charley (2004)	Unnamed (1936)	Isabel (2003)	Unnamed (1933)
	Tide Peak Level (m)	0.8	1.56	1.91	1.95

256

257 The tide level time series observed during historical hurricanes are taken as the references for designing storm tide events. Tide peak levels were selected as an indicator to choose historical hurricanes 258 259 as reference to design storm tide events. For storm tides with certain return periods in Table 4, the 260 matched hurricane events in Table 3 have tide peak levels that are close to the storm tide peaks and fall in 261 between the 95% confidence intervals. The tide level observations of the matched hurricanes would be 262 taken as the designed storm tide events. Take the 50-year storm tide event as an example. According to Table 4, the 50-year tide has a peak of 1.87m (NAVD88) with 95% confidence intervals from 1.64m to 263 264 2.33m. In the Table 3, Hurricane Isabel (2003) had a tide level peak of 1.91m, which is closest to the 50-265 year tide among all these hurricanes. At the same time, the tide peak level of Hurricane Isabel (2003) falls 266 in between the 95% confidence interval of the 50-year tide. Therefore, Hurricane Isabel (2003) was 267 selected as the 50-year storm tide event in this study, and its tide level observation was used to design the 268 50-year storm tide event. Designed storm tide events with return periods of 1, 10, 50, and 100 years are 269 presented in Figure 2.



Exceedance Probability	99% (1-Yr)	10% (10-Yr)	2% (50-Yr)	1% (100-Yr)
24-Hr Rainfall Intensity (mm)	74	140	202	234
90% Confidence Intervals (mm)	69 - 81	129 - 152	183 - 218	210 - 253

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The rainfall distribution used for rainfall design storms was obtained from a Natural Resources Conservation Service (NRCS) study (Merkel et al., 2015). In Merkel's study (2015), four types of rainfall distributions were developed from data in the NOAA Atlas 14. A map showing a multistate area with groups of regional precipitation distributions was presented along with tables containing 24-hour precipitation distributions in Merkel's study (2015). The current study domain is located in the region of Type C precipitation distribution. The precipitation distribution is non-dimensional between values 0 to
1.0. Designed rainfall events were generated by multiplying the Type C precipitation distributions with
the corresponding 24-hour rainfall intensities from the NOAA Atlas 14. The synthetic rainfall events with
different return periods are presented in Figure 3.





A series of compound storm scenarios were created by combining different synthetic storm tide and heavy rainfall events. The combined impact of storm tide and heavy rainfall are investigated according to the urban flood model simulation for these storm scenarios. Flood simulations on both 2D land area and 1D pipelines were generated as outputs.

296 2.4 Determine Food Zones

According to Bilskie and Hagen (2018), the coastal floodplain can be separated into three different flood zones, hydrological zone, tidal zone, and transition zone, based on the driving forces of flooding. In the tidal zone, storm tide is the primary factor of flooding and rainfall has negligible impacts. The tidal zone is usually located near a shoreline. The hydrological zone, normally located inland, is dominated by rainfall-driven flooding with only minor impacts from storm tide. The transition zone is where significant interactions exist between rainfall-driven and tidal flooding. 303 These three flood zones for a specific combined storm event are determined by the maximum water level simulations from three designed storm scenarios. In Simulation I, the storm tide is the only 304 305 input, i.e., no rainfall input. Simulation II consists of heavy rainfall input with a normal tide. Normal tide 306 means an average astronomical tide that cannot cause flooding in the study domain, and its maximum tide 307 level is lower than all drainage pipeline outlets. Simulation III consists of both storm tide and heavy 308 rainfall. Thus, flooding in Simulations I and II is driven by storm tide and rainfall, respectively, and it is 309 driven by the combined effect of storm tide and rainfall in Simulation III. In the tidal zone, rainfall has 310 negligible impacts on flooding; thus, the maximum water level simulation from Simulation III would 311 have minor differences compared to Simulation I even with the existing of rainfall impact. Therefore, the 312 tidal zone is defined as the area where the maximum water level simulations from Simulations I and III have a difference equal to or smaller than 0.01m. In the hydrological zone, storm tide has minor impacts 313 314 on flooding. Therefore, the maximum water level simulations from Simulation II and III would be fairly 315 close in the hydrological zone. In the current study, the hydrological zone is identified as the area where 316 the maximum water level simulations from Simulation II and III have a difference equal to or smaller 317 than 0.01m. The transition zone is normally located in between the hydrological and tidal zones. In the 318 transition zone, both the maximum water level simulations from Simulation I and II are smaller than 319 Simulation III with a difference greater than 0.01m.

The spatial extent of the transition zone varies with the change of storm tide and heavy rainfall combinations. Thus, simply mapping this zone does not fully describe this complex interaction between storm tide and heavy rainfall. In general, a greater tide peak or rainfall intensity would lead to a larger transition zone. For compound storms with higher tide peaks, the tidal zone and transition zone is more likely to extend further inland. Meanwhile, the increase of rainfall intensity would shrink the spatial extent of the tidal zone. To quantify this interaction, we defined the transition zone index (TZI) as

$$TZI = \frac{M}{N}$$
(1)

where, M is the number of simulations with transition zones sharing a same location, and N is the total
number of simulations. TZI can be computed for any watershed based on the simulations from all the
compound storm scenarios, as demonstrated in this study. A high TZI locates an area in the watershed
where flooding is the product of interactions between storm tide and heavy rainfall. The higher the TZI,
the stronger the interaction between these two primarily mechanisms for coastal flooding. TZI helps to
identify regions in the watershed that would be impacted by flood mitigation approaches that target either
storm tide driven flooding or rainfall driven flooding.

333 **3. Results and Discussion**

334 *3.1 Model Evaluation*

335 Observations of the depth, extent, and duration of flooding in urban coastal landscapes are very rare; 336 however, such data are essential to evaluate the performance of urban flood models (Smith et al., 2012). Data sources, such as photographs taken of flooded areas, newspaper reports and personal interviews, 337 338 flood information collected from social media, and crow-sourced drone footage, can be converted to 339 inundation information for model evaluation (Smith et al., 2012; Middleton et al., 2014; Fohringer et al., 340 2015; Loftis et al., 2017). However, these data sources are often sparse and not available for the current study domain. In the current study, the data source used for flood model evaluation is a crowdsourced 341 flood report dataset from the City of Norfolk, VA. This record includes flooded street locations in Norfolk 342 343 starting from Hurricane Nicole on 30 September 2010 (Salder et al., 2018).

In the flood report record, only the date and location of reports were stored instead of the precise time and flood depth. Therefore, the maximum inundation maps on the date when flood locations were reported were compared with the flood report locations as an indication of model performance. During a storm event, stormwater may cause ponding on the most parts of the study domain. Ponding depth is selected as the indicator for inundation area mapping in this study. The inundation maps shown in this paper only include area with ponding depth greater than 0.1 m. This value was selected to distinguish

between dry land and flooded locations during storm events. It is assumed that the impact of flood isnegligible for flood management purpose when the water depth is smaller than 0.1m.

352 The model performance was evaluated on Hurricanes Irene (2011), Hermine (2016), and Matthew 353 (2016) (Figure 4). If simulated ponding exists in a 20m buffer of a flood reported location, this flood 354 report was assumed to validate the model simulation. All flood reported locations of Hurricanes Irene and 355 Matthew are consistent with the inundated areas from the simulations. During Hurricane Hermine, 25 356 flood locations were reported, and 22 (88%) locations matched with the flood model simulation. The 357 remaining three flood locations are about 250 m away from the shoreline as shown in Figure 4(b). The 358 ponding depth at these three locations varies from 0.05 m to 0.09 m, which is lower than the cutoff depth 359 selected for inundation area mapping. The crowdsourced flood report dataset contains unique and 360 valuable street-level flood information, but there are still limitations of this dataset. As can be expected 361 when using crowd-sourced data, the flood report dataset has an unknown amount of subjectivity and bias because the flood locations are reported by individuals (Sadler et al., 2018). Nonetheless, using the best 362 available information, it is reasonable to suggest that the urban flood model has predictive skill at 363 364 simulating flooded roads for three different extreme weather events.



Fig. 4. Ponding depth on time of maximum inundation area and flood report locations for hurricanes (a)
Irene (2011), (b) Hermine (2016), and (c) Matthew (2016)

368 *3.2 Time Lag between Storm Tide and Rainfall*

The storm scenarios were created by combining the synthetic rainfall and storm tide events; however, we needed a method to match the time axis of rainfall and storm tide events. Usually, there is a time lag between storm tide and rainfall events, and the time lag has a significant impact on flood risk (Zheng et al., 2013). In this section, we show how the time lag between the tide peak and rainfall peak influence flood risk in the study domain.

Time lag is defined as

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$$T_{Lag} = T_{Tide \ Peak} - T_{Rainfall \ Peak} \tag{2}$$

where $T_{Tide Peak}$ is the time of tide peak and the $T_{Rainfall Peak}$ is the time of rainfall peak. In this analysis, the 10-year rainfall is selected as an intermediate rainfall intensity. The 1 and 10-year storm tides were chosen to represent a short duration (less than 6 hours) and a long duration (greater than 6 hours) storm tide, respectively. For each combination of storm tide and heavy rainfall, 17 synthetic storm 379 scenarios with time lags varying from -8 to 8 hours were created and simulated. The maximum inundation 380 areas (MIA) in percentage of the total land area and the maximum flood volumes (MFV) on land are 381 shown in Figure 5. The tide levels at the time of rainfall peak for each scenario are provided on the upper 382 row of Figure 5. For both the 1-year tide and 10-year tide cases, the MIAs appear when tide peaks and 383 rainfall peaks happen simultaneously, i.e., time lags equal to zero. The MFVs occur when rainfall peaks 384 are one hour ahead of tide peaks (time lags equal to one). From Figure 5, we found that both MIA and 385 MFV have positive correlations with tide levels at the time of rainfall peaks. When the absolute values of 386 time lag are greater than 4 hours, rainfall peaks happen at low tide periods, and both MIA and MFV are relatively small. For scenarios with absolute values of time lag less than 4 hours, the MIA and MFV 387 388 increase rapidly with the increase of tide levels at rainfall peaks. Using MIA and MFV as indicators, it the 389 worst flooding appears to happens when the time lags are between -1 to 2 hours. In the current study, the 390 compound storms with simultaneous storm tide and rainfall are chosen to represent the worst-case 391 scenarios, where the worst-case scenarios are determined by using the MIA as the indicator of flood 392 severity.



393 394 Fig. 5. Influence of time lag between storm tide and rainfall on flood risk with the examples of 10-year rainfall event pairing with 1-year and 10-year storm tide events. 395

396 3.3 Flood Risk

397 The flood ponding depth at the time of maximum inundation area for each storm scenario is presented in 398 Figure 6. Among all storm scenarios, the maximum ponding depth of 1.49 m appeared during the compound storm of 100-year rainfall and 100-year tide. For storm scenarios with fixed rainfall intensity, 399 400 for example, 1-year rainfall, the inundation area and ponding depth near the shoreline increase rapidly as 401 the storm tide return period increases. Several inland flood-prone areas are isolated from overland tidal 402 flooding; however, for a specific rainfall intensity, both the inundation area and ponding depth in these 403 areas experience a significant increase as the storm tide return period increases. Flooding in these flood-404 prone areas are greatly influenced by the impact of storm tide on underground pipeline system, which will 405 be discussed in detail in the Section 3.5.



MIAs and MFVs for different compound storm scenarios are provided in Figure 7. The storm scenario with the 1-year rainfall and 1-year storm tide would flood 12.7% of the land area with a MFV of about 76,000 m^3 . The storm scenario with the 100-year rainfall and 100-year storm tide, according to the model, would cause MIA of 38.9% and MFV of about 457,000 m^3 . From Figure 7, the results show that MIA is more sensitive to the change of rainfall return period compared to tide return period. For example, under the 1-year storm tide condition, MIA increases from 12.7% for 1-year rainfall to 32.1% for 100year rainfall. In contrast, for the 1-year rainfall event, MIA increases from 12.6% to 22.7% for 1 and 100-

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416 year storm tides, respectively. From Figure 7, MFV is susceptible to the change of both rainfall intensity 417 and storm tide severity. The simulations from certain storm scenarios have a similar amount of MIAs or 418 MFVs but different spatial extents. For example, the difference between MIAs for the storm scenario with 419 the 10-year rainfall and 1-year tide and the storm scenario with the 1-year rainfall and 50-year tide is only 420 0.7%. However, Figure 7 shows that these two scenarios, while having a similar MIA, have large 421 differences in the spatial extent of inundated areas. As expected, the flooded area of the event with a 1-422 year rainfall and 50-year tide is primarily concentrated near the shoreline while the event with 10-year 423 rainfall and 1-year tide has flooded areas more inland with relatively shallow ponding depths.



426

427 3.4 Influence of Storm Tide on Underground Drainage System

428 The study domain has a complex drainage system, which plays a key role in the stormwater management. 429 Model results and local knowledge of the drainage system both suggest that the efficiency of the drainage system is highly sensitive to the tide levels at the outfalls. During storm tide events, the pipeline outfalls 430 431 can be partly or even fully submerged. In a submerged state, both the head difference between upstream 432 and downstream pipes and the capacity of the system are reduced, which slows the draining of stormwater 433 through the system.

434 In the study domain, the ground elevation of several roads and streets near the shoreline is higher 435 than surrounding areas. These connected roads and streets form a barrier impeding overland tidal flooding 436 entering into inland regions. The area in between the shoreline and these elevated roads and streets is 437 defined as the shoreline floodplain. Inside the shoreline floodplain, inundation is the combined 438 consequence of overland tidal flooding, local rainfall-driven flooding, and surcharge flow from the 439 underground pipeline system. The inland region is free from overland tidal flooding. Thus, the inundation 440 in the inland region is a consequence of local rainfall-driven flooding and surcharge flow from 441 underground pipelines. Therefore, in the inland region, the flood severity for a fixed rainfall event is 442 determined by the efficiency of the underground pipeline system, which is highly sensitive to the tide levels at outfalls. To explore the relationship between tide level and the efficiency of the drainage system, 443 444 the flood severity in the inland region is analyzed under the impact of different storm tide events. In this 445 section, the compound storm scenarios with 1-year rainfall and storm tide varying from normal tide to 446 100-year tide were simulated and analyzed. Normal tide means an average astronomical tide that cannot 447 cause flooding in the study domain, and its maximum tide level is lower than all drainage pipeline outlets. 448 As shown in Figure 8, the maximum extent of the shoreline floodplain for these compound storm 449 scenarios are covered by the shoreline floodplain mask, and the inland region is outside the mask. The 450 focus pipes connect the inland region with the shoreline floodplain.





Figure 8. Locations of shoreline floodplain and focus pipes

453 The time series of total discharge in the focus pipes and the total amount of flood volume in the 454 inland region for the simulated compound storm scenarios are present in Figure 9. From Figure 9 (a), 455 there is no backward flow through the focus pipes under the normal tide and 1-year storm tide conditions. 456 Before hour 12, the total discharge time series have nearly identical trends under these two conditions. 457 However, the peak of total discharge under the 1-year storm tide condition is about 10% lower than the 458 normal tide condition. Meanwhile, from Figure 9 (b), the maximum inland flood volume for the 1-year 459 storm tide is about 5% higher than the normal tide. The pipeline outlets elevation is higher than the 460 normal tide peak, but lower than the 1-year storm tide peak. Therefore, the 1-year storm tide has a 461 blockage effect on the drainage system and would slow down the draining of inland stormwater.

When the recurrence intervals of storm tide are equal to or higher than 10 years, backward flow would occur at the beginning period of the storms. This means these storm tide events are able to reach to the pipelines in the inland region. Under the 10-year tide condition, the total volume of backward flow through the focus pipes is $37,000m^3$. This volume would occupy a large portion of the storage space of pipeline system and slow down the draining of runoff from the inland region. The blockage effect results in the peak of total discharge under the 10-year tide condition decreased by 22% compared to the normal tide condition, and the maximum inland flood volume increased by 34%.

The total volumes of backward flow are $310,000m^3$ and $210,000m^3$ under the 50 and 100-year 469 470 storm tide conditions, respectively. In the current paper, designed storm tides are selected based on the 471 peak water levels; for example, the 100-year tide is 0.04m higher than the 50-year tide. However, the duration of the 50-year tide is about 5 hours longer than the 100-year tide, which is the reason that the 50-472 year tide caused greater volume of backward flow. The water head near the peaks of 50 and 100-year 473 474 storm tide events are higher than several flood-prone areas in the inland region. Thus, in the simulation, a 475 portion of the backward flow would exit the pipeline system and cause inundation in these areas. From 476 Figure 9 (b), the maximum flood volumes under the 50 and 100-year tide conditions have more than 70% 477 increase compared to the normal tide condition. Therefore, the surcharge flow on top of the blockage 478 effect on pipeline system greatly exacerbate the flooding in inland region.



Figure 9. Influence of tide level on the efficiency of the underground pipeline system: (a) total flood
volume of inland area under the condition of different storm tide scenarios; (b) total discharge in focus
pipes.

483 *3.5 Coastal Floodplain Mapping*

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The coastal floodplain mapping method is demonstrated by three simulations generated from the 484 50-year rainfall and 50-year storm tide. In Simulation I, the 50-year tide is the only input, i.e., no rainfall. 485 486 Simulation II consists of 50-year rain and normal tide. Simulation III consists of 50-year rainfall and 50-487 year tide. For the focused transect in Figure 1, the maximum water level simulations for these three 488 simulations, along with the land surface elevation profile, are presented in Figure 10. In the tidal zone, the maximum water levels from Simulations I and III have a difference less than 0.01m, which means the 489 impact from rainfall is negligible. In the hydrological zone, the difference between maximum water level 490 491 simulations from Simulations II and III is less than 0.01m. This indicates that storm tide has minor impact 492 in the hydrological zone, and rainfall is the dominating factor. The transition zone is normally located 493 between the tidal zone and hydrological zone. In transition zone, the maximum water level from 494 Simulation III is higher than both Simulations I and II.



496 Fig. 10. Land surface elevation profile and simulated maximum water levels across the selected transect for497 three storm scenarios.

For Simulation III, the spatial extent of different flood zones are identified, as shown in Figure 11. The total inundation area is $1.17km^2$, which is about 32.5% of the land area. The inundation area includes 7% of the tidal zone, 43% of the hydrological zone, and 50% of the transition zone. The tidal zone is located in a narrow region near the shoreline. The hydrological zone is primarily distributed in inland region. The transition zone, as originally proposed by Bilskie and Hagen (2018), is located relatively close to the shoreline. However, in this study and in contrast to the Bilskie and Hagen (2018) study, due to the existing of pipeline system, the transition zone can reach to much further inland areas. This is because the strong interaction between rainfall-driven and tidal flooding exists for both the ground surface and underground drainage systems.



Fig. 11. Flooding zones identified for storm scenario consists of 50-year storm tide and 50-year heavy rainfall



become surcharge flow and exacerbate flooding severity. The high TZI areas are normally located in the 515 516 middle region between shoreline and inland area. The inland region has zero or relatively small TZI, 517 which means rainfall is the dominating factor of flooding. Thus, in the inland region, stormwater control 518 measures (e.g., detention pond or rain garden) are effective flood mitigation strategies. In the near-519 shoreline region, storm tide is the primary driving factor of flooding because of the small TZI. Therefore, 520 tide control measures (e.g., tide gates or flood walls) can be effective to reduce flood risk. For the high 521 TZI areas, both stormwater and tide control measures can potentially help to reduce the flood risk, and the 522 efficiency and mechanisms can be evaluated and explored using the 1D pipe/2D overland flood model.



523 524

Fig. 12. Transition zone index estimated based on all compound storm scenario simulations



526 In order to demonstrate how the model can be used to aid decision makers when decided between

527 strategies for improving flood resilience within a system, two mitigation strategies were explored for the

528 case study watershed. In both cases, the TZI maps help decisions makers to anticipate regions within the 529 watershed that will be improved based on the mitigation strategy selected. The first strategy is to install 530 flap gates at certain locations within the drainage system to block backflow from high tide. This strategy is aimed at improving flood resilience for areas in the tidal zone with a low TZI value. The second 531 532 strategy is to increase the useable capacity of a detention pond within the watershed to increase its 533 capability for flood control. This strategy is targeted areas in the Hydrological Zone with low TZI value 534 could be impacted by either of these two mitigation strategies in complex ways. The ponding depth 535 reduction ratio is defined as the criteria for quantifying the improved resilience of the flood mitigation 536 methods. The ponding depth reduction ratio is defined as

Ponding Depth Reduction Ratio =
$$\frac{MPD_{Modified} - MPD_{Original}}{MPD_{Original}} \times 100\%$$
(3)

Where, the *MPD_{Modified}* is the maximum ponding depth simulation from the urban flood model
including flood mitigation method, and the *MPD_{Original}* is the maximum ponding depth simulation from
the original version of the urban flood model with no flood reduction measure.

540 Two methods of using flap gates are discussed in this section. The first method (Version I) is to 541 install flap gates at the 17 outfalls of the drainage system. However, during extreme high tide, overland 542 tidal flooding can reach to near-shoreline region to inundate several pits and manholes, and sea water 543 would enter into the drainage system through these pits and manholes. The region inundated by overland 544 tidal flooding is defined as the tidal floodplain. To further reduce the volume of backward flow from tide, 545 the second method (Version II) is to install flap gates at all pipes covered by the 100-year tidal floodplain. 546 The Version I and II methods were tested on storm scenarios with 1-year rainfall combined with 10 or 547 100-year storm tide events. The maximum ponding depths were simulated from the urban flood models 548 with and without flap gates. The ponding depth reduction ratio were calculated as shown in Figure 13. 549 Overall, the reduction of maximum ponding depth can be observed from the simulation in several

550 flood-prone regions after flap gates are installed, also flap gates have greater influence for a more extreme

551 storm tide event. Under the combined impact of the 1-year rainfall and 10-year tide event, the Version I 552 method is able to reduce the ponding depth by 2% to 5% for several flood-prone areas, and 5% to 15% in 553 a small portion of these flood-prone area. Under the same event, the Version II method generates large 554 area with a reduction ratio between 5 to 15%. For the storm scenarios with 100-year tide, the ponding 555 depth reduction appear more expansive compared with the 10-year tide. However, the reduction ratio 556 from the Version I method is limited to the range of 2 to 15%, and the majority of that is between 2 to 557 5%. For the Version II method, the maximum ponding depth shows a significant reduction in the 558 upstream flood-prone area. In this case, a large area experiences a ponding depth reduction ratio between 559 5 to 30%, and several areas have a reduction ratio greater than 30%.



561 Fig. 13. Ponding depth reduction ratio between simulations with and without flap gates: (Version I) flap gates installed at drainage system outfalls; (Version II) flap gates installed in pipes inside the 100-year 562 tidal floodplain. (Tested storm scenarios: 1-year rainfall with 10 and 100-year storm tide events). 563 564 The detention pond in the study domain is a permanent pool of standing water that provides long-565 term water quality enhancement of stormwater runoff. Stormwater can also be temporarily stored in the 566 detention pond for downstream flood control. The detention pond has a total capacity of about 24,000m³ 567 and a bed elevation of -1.83m (NAVD88). The detention pond has a normal water level of about 0.35m (NAVD88) and detention storage of about 15,600m³. The flood control ability of the detention pond is 568 569 determined by its usable capacity at the beginning of storm events. To enlarge the usable capacity, 570 stormwater control structures can be installed to lower the water level in advance of a forecasted storm. For example, if the water level is lowered to -1m (NAVD88), the detention pond would gain 7,000m³ 571 572 extra usable capacity for flood control.

573 Two initial water level (IWL) scenarios were tested in this section. For the first scenario (IWL I), 574 the IWL was lowered to -1m above NAVD88. The second scenario (IWL II) had an IWL of -1.83m, the 575 bed elevation, meaning the detention pond is dry under the IWL II condition. The IWL II is tested and 576 discussed to represent a best-case scenario for flood risk reduction. The storm scenarios with the joint 577 occurrences of 1 and 10-year rainfall with 1-year tide are selected to analyze the efficiency of flood 578 mitigation when the detention pond is in IWL I and II conditions.

579 The ponding depth reduction ratios between the maximum ponding depth simulations with 580 lowered IWLs and normal water level of the detention pond are calculated and presented in Figure 14. 581 Generally, lowering the detention pond IWL only influences the flooding in local regions near the pond, 582 and the ponding depth reduction ratios on IWL I and II conditions are very similar for both tested storm 583 scenarios. This is because the usable capacities of the detention pond have relatively small difference (about 2,000m³) between IWL I and II conditions. With a 1-year rainfall event, the detention pond does 584 not reach to its full capacity under both IWL conditions, and the maximum ponding depths in the region 585 586 downstream the pond decrease by 2 to 15%. For a 10-year rainfall event, the detention pond does exceed

bankfull levels, and the maximum ponding depths in the downstream region near the pond decrease by 5
to 15%, and a portion of this region has more than a 15% ponding depth reduction ratio. A 2 to 15%
reduction ratio occurs in the further downstream. The most significant flood mitigation appears on the
southeastern portion of the detention pond drainage area due to increased capacity to store rainfall runoff
generated from this area.



Fig. 14. Ponding depth reduction ratio between the maximum ponding depth simulations on lowered
initial water levels and normal water level of the detention pond: (IWL I) initial water level lower to -1m;
(IWL II) initial water level lower to -1.84m. (Tested storm scenarios: 1 and 10-year rainfall with 1-year
tide event).

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598 **4. Conclusions**

599 An overarching objective of this study was to develop methodologies to enhance the understanding of

flood risk within coastal urban watersheds. To this end, we modeled how overland flooding in an urban

601 watershed with stormwater drainage infrastructure is affected by storm tide and rainfall events with

varying return periods. The study area is located in Norfolk, VA, USA, a city prone to recurrent flooding

603 challenge, was the case study system for the study. The 1 to 100-year storm tide events were designed 604 based on storm tides that happened during historical hurricanes impacting the Virginia coastline. A series 605 of rainfall events with return periods varying from 1 to 100-year were designed based on the NOAA Atlas 606 14 precipitation frequency estimates (Bonnin et. al., 2006). These design storm tide and rainfall events 607 were combined to a series of compound storm scenarios. A coupled 1D pipe/2D overland hydrodynamic 608 model was built for the study watershed using the TUFLOW model. The model outputs included detailed 609 flooding information on both land surface and underground pipeline system, which allows to assess flood 610 risk and understand the contribution of flooding from individual or combined factors. Floodplain maps 611 and a new transition zone index (TZI) were created to communicate regions of the watershed under risk 612 of flooding due to tide and rainfall-driven mechanisms. The 1D pipe/2D overland flood model and floodplain visualizations are a powerful tool to evaluate the efficiency of different flood mitigation 613 614 strategies, as a demonstrated for two flood mitigation methods.

615 Results show how the capacity of stormwater drainage system is highly sensitive to storm tide 616 levels. Based on model simulations, event with a 1-year tide is able to partially submerge the pipeline 617 outlets and has an impact on the pipeline capacity. Storm tide events with return periods greater than or 618 equal to 10 years would significantly reduce the drainage capacity. Extreme storm tide events, for 619 example a 50 and 100-year tide, would cause flooding within the watershed due to the backing-up and 620 day lighting of sea water traveling through stormwater drainage infrastructure. Even for smaller tide 621 events, model simulations show that rainfall driven flooding combined with reduced capacity of the 622 drainage infrastructure caused by tailwater conditions can cause significant flooding in inland regions. 623 Due to the low gradient of the stormwater drainage infrastructure, which is common in many coastal 624 urban areas, this interaction between rainfall-driven flow and sea water flow traveling through the pipe 625 system can influence flooding far into the watershed.

626 This study provides a methodology that can be repeated for other coastal urban watersheds to627 better understand the influence of storm tide and rainfall-driven flooding through floodplain maps. The

628 coastal floodplain mapping method proposed in Bilskie and Hagen's study (2018) was applied to the 629 urban watershed in the current study. In Bilskie and Hagen's study (2018), the study area is located in a 630 rural area, and the interaction between rainfall-driving and tidal flooding is primarily within the region close to the shoreline. However, in this study, we extended on past work to include the stormwater 631 632 drainage system, showing that the transition zone can reach much further inland due to the underground 633 stormwater drainage system. The transition zone index (TZI) was defined to represent the likelihood of a 634 location under the impact of strong interaction between tidal and rainfall-driven flooding. In areas with 635 low TZI, flood risk is primarily caused by individual factors. Therefore, flood mitigation measures 636 targeting to individual flood mechanisms can be effective ways to reduce flood risk in these parts of the 637 watershed. For the high TZI areas, both stormwater and tide control measures can potentially assist to 638 reduce the flood risk, and the efficiency and mechanisms can be evaluated and explored using the 1D 639 pipe/2D overland flood model.

640 Lastly, the flood model and floodplain visualization is a powerful tool to evaluate the efficiency 641 of different flood mitigation strategies. As a demonstration, two flood mitigation methods were tested in 642 this study: one targeting rainfall-driven flooding and the second targeting tidal-driven flooding. The 643 model simulations show how both methods would be able to reduce the flood risk for certain flood-prone 644 regions of the watershed. Because the floodplain map helps to visualize regions of the watershed where tide, rainfall, or a combination of these two mechanisms cause flooding, it is easier to see how mitigation 645 646 strategies improve flood resilience. This methodology can be of a significant value to cities and 647 communities as they work to improve resilience for a host of services that can be impacted by flood risk. The presented model will be used in a future study to explore several aspects of compound storm 648 649 tide and rainfall-driven flooding. In this study, only tide level data is considered at the boundary as the 650 tide input while tidal flow velocity may have a significant effect on tidal flooding and the function of 651 drainage system. Future research should focus on coupling a hydrodynamic storm surge model with the 652 inland hydrodynamic model to account for these processes. Furthermore, this study is focused on present

- sea level. However, climate change impacts include increases in rainfall intensity and relative sea level
- rise (RSLR), which could substantially increase the severity of flood risk in the study area. Future
- assessments using this model will aim to quantify the impacts of changing climatic conditions on flooding
- 656 risk.
- 657

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797 Appendix A

The watershed is urbanized and flow has complex patterns and paths through building areas. 798 799 These buildings dissipate energy by forcing the flow to change its direction and speed. In prior studies, 800 the buildings in the 2D model domain have been represented by increasing the roughness coefficient, 801 blocking out of buildings, applying energy loss coefficient in building areas, and setting the buildings as 802 porous elements (Hunter et. al., 2008; Syme, 2008; Chen et. al., 2012). In this study, one assumption is 803 that no water would enter into buildings during simulations. Therefore, the method of blocking out of 804 buildings is the only satisfactory option based on this assumption. As shown in Figure A1, the areas inside building outlines are deactivated from the 2D domain. To make sure no stormwater from rainfall 805 806 lost by deactivating the buildings areas, a building representation method is proposed in this study, 807 including three major steps: I) deactivate areas inside building outlines from the 2D domain; II) build 808 polygons that includes groups of buildings; and III) apply the rainfall falling on the building areas to the 809 buffered polygon around each group of buildings. The building roofs are designed to drain rain water 810 rapidly and completely. The assumption behind the building representation method is that rain water can drain out of building roofs without any loss of rain water and no delay time from transferring the water 811

812 from precipitation to ground. This method is reasonable for the study domain where most of its buildings813 are residential houses with relatively small roof areas.

