

# Impact of Compound Flood Event on Coastal Critical Infrastructures Considering Current and Future Climate

Mariam Khanam<sup>1</sup>, Giulia Sofia<sup>1</sup>, Marika Koukoulou<sup>1</sup>, Rehenuma Lazin<sup>1</sup>, Efthymios I. Nikolopoulos<sup>2</sup>, Xinyi Shen<sup>1</sup>, and Emmanouil N. Anagnostou<sup>1</sup>

<sup>1</sup>Civil and Environmental Engineering, University of Connecticut, Storrs, CT 06269, USA

<sup>2</sup>Mechanical and Civil Engineering, Florida Institute of Technology, Melbourne, FL 32901, USA

*Correspondence to:* Anagnostou, Emmanouil N. (emmanouil.anagnostou@uconn.edu)

**Abstract.** The changing climate and anthropogenic activities raise the likelihood of damages due to compound flood hazards, triggered by the combined occurrence of extreme precipitation and storm surge during high tides, and exacerbated by sea level rise (SLR). Risk estimates associated with these extreme event scenarios are expected to be significantly higher than estimates derived from a standard evaluation of individual hazards. In this study, we present case studies of compound flood hazards affecting critical infrastructure (CI) in coastal Connecticut (USA) based on actual and synthetic (considering future climate conditions for the atmospheric forcing, sea level rise, and synthetic hurricane tracks) hurricane events, represented by heavy precipitation and surge combined with tides and SLR conditions. We used the Hydrologic Engineering Center's River Analysis System (HEC-RAS), a two-dimensional hydrodynamic model to simulate the combined coastal and riverine flooding on selected CI sites. We forced a distributed hydrological model (CREST-SVAS) with weather analysis data from the Weather Research and Forecasting (WRF) model for the synthetic events and from the National Land Data Assimilation System (NLDAS) for the actual events, to derive the upstream boundary condition (flood wave) of HEC-RAS. We extracted coastal tide and surge time series for each event from the National Oceanic and Atmospheric Administration (NOAA) to use as the downstream boundary condition of HEC-RAS. The significant outcome of this study represents the evaluation of changes in flood risk for the CI sites for the various compound scenarios (under current and future climate conditions). This approach offers an estimate of the potential impact of compound hazards relative to the 100-year flood maps produced by the Federal Emergency Management Agency (FEMA), which is vital to developing mitigation strategies. In a broader sense, this study provides a framework for assessing risk factors of our modern infrastructure located in vulnerable coastal areas throughout the world.

## 1 Introduction

The impacts of hurricanes such as Harvey, Irma, Sandy, Florence, and Laura are characteristic examples of hazardous storms that have affected the society and environment of coastal areas, and have damaged infrastructure, through the combination of heavy rain and storm surge. The increased frequency of such events raise concerns about compound flood hazards previously considered independent of one another (Barnard et al., 2019; Leonard et al., 2014; Moftakhari et al., 2017; Wahl et al., 2015; Zscheischler et al., 2018; Winsemius et al., 2013; Hallegatte et al., 2013; de Bruijn et al., 2017; de Bruijn et al., 2019, Bevacqua et al., 2019).

36 Concurrent with the rise in event intensities, the elevated damage and disruption caused by compound flooding (CF)  
37 to critical infrastructure (CI) and services, including electrical systems, water, and sewage treatment facilities, and  
38 other utilities that underpin modern society, have substantial adverse socioeconomic impacts, especially in low-lying  
39 coastal areas, where almost 40 percent of people in the United States live (NOAA, 2013).

40 The growing record of significant impacts from extreme events around the world (Chang et al., 2007; McEvoy et al.,  
41 2012; Ziervogel et al., 2014; FEMA, 2013; Karagiannis et al., 2017) adds an urgency to the need for reassessing CI  
42 management policies based on compound impact, to help ensure flood safety and rapid emergency management  
43 (Pearson et al., 2018). The uncertainty of the current evolution of compound events translates into an even greater  
44 uncertainty concerning future damage to CI (de Bruijn et al., 2019, Marsooli et al., 2019).

45 Recent studies have underlined the importance of understanding and quantifying the flood impacts on critical  
46 infrastructure, and their broader implications in risk management and catchment-level planning (Chang et al., 2007;  
47 McEvoy et al., 2012; Ziervogel et al., 2014; de Bruijn et al., 2019; Pearson et al., 2018; Pant et al., 2018; Dawson,  
48 2018). Some authors have estimated the frequency of compound flooding and provide approaches to risk assessment  
49 based on the joint probability of precipitation and surge (Bevacqua et al., 2019; Wahl et al., 2015). The spatial extent  
50 and depth of compound flooding can vary in frequency (Quinn, et al., 2019) if any of the component of CF is not taken  
51 into consideration while evaluating flood frequency. Both storm surges and heavy precipitation, and their interplay,  
52 are likely to change in the future (Field et al., 2012, Dottori et al., 2018; Blöschl et al., 2017; Muis et al., 2016; Marsooli  
53 et al., 2019; Vousdoukas et al., 2018). Nonetheless, the effects of CF, considering the climate change impact, have not  
54 been thoroughly explored yet.

55  
56 To deal with CF threats and challenges to coastal communities, there is a need to develop efficient frameworks for  
57 performing systematic risk analysis based on a wide range of actual and what-if scenarios of such events in current  
58 and future climate conditions. In this study, we focused on coastal power grid substations as critical infrastructure and  
59 investigated the impacts of compound flood hazard scenarios associated with tropical storms. We present a hydrologic-  
60 hydrodynamic modeling framework to evaluate the integrated impact of flood drivers causing CF by synthesising  
61 current and future scenarios. This study enables the quantitative measurement of CF hazard casted on critical  
62 infrastructures in terms of flood depth and flood extent by observing actual storm-induced floods and drawing  
63 information from synthetic scenarios. To project the combined flood hazard in future climate conditions, we integrated  
64 the effects of SLR, tides, and synthetic hurricane event simulations into the flood hazard exposure.

65 Even though past research on the assessment of damages to the power system components or other related  
66 infrastructures has proposed design and operation countermeasures and remedies (i.e. Kwasinski et al. 2009; Reed et  
67 al. 2010; Abi-Sarma and Henry, 2011; Chang et al., 2007; de Bruijn et al., 2019; Pearson et al., 2018; Pant et al., 2018;  
68 Dawson, 2018), these studies lack a comprehensive hazard assessment on power grid components, and potential  
69 changes due to climate change.

70 The scenario-based analysis of this study formed the basis on which to address two questions:

71 *(1) What are the characteristics of the tropical storm-related inundation, considering the compound effect of riverine*  
72 *and coastal flooding coinciding or not with peak high tides*

73 (2) Will future climate (including SLR and intensification of storms due to warmer sea surface temperatures) bring a  
74 significant increase in flood impact for the power-grid coastal infrastructures?

75 The proposed framework offers a multi-dimensional strategy to quantify the potential impacts of tropical storms, thus  
76 enabling for a more resilient grid for climate change and the increasing incidence of severe weather.

77 We investigated these questions based on eight case studies of CI in Connecticut (USA), distributed on the banks of  
78 coastal rivers discharging along the Long Island Sound.

## 79 **2 Materials and methods**

### 80 **2.1 Study sites**

81 This study focused on seven coastal river reaches (Fig. 1, Table 1), where eight power grid substations lie in proximity  
82 to riverbanks and are prone to flooding caused by both coastal storms (such as hurricanes) that combine heavy  
83 precipitation and high surge. These power grid substations are coded on the map CI1 through CI8.

84 For each river reach adjacent to a CI, we developed a hydrodynamic model domain, and we applied a distributed  
85 hydrological model for predicting river flows from the upstream river basin. Table 1 shows the specification of each  
86 river reach, associated drainage basin, the correspondent domain extent for the hydrodynamic simulations, and the  
87 hydrological distance [distance along the flow paths] of each power grid substation from the coastline. This distance  
88 was derived using the 30m National Elevation Dataset (NED) for the continental United States (USGS 2017).

89 Among the case study sites, two CIs are relatively inland [CI3 and CI4] (table 1: see hydrologic distance. Figure 1:  
90 see coastal boundary), nonetheless all the sites are included within the Coastal Area as defined by Connecticut General  
91 Statute (CGS) 22a-94(a) [[https://www.cga.ct.gov/current/pub/chap\\_444.htm#sec\\_22a-94](https://www.cga.ct.gov/current/pub/chap_444.htm#sec_22a-94)]. The considered rivers  
92 belong to watersheds ranging from 10 to 300 km<sup>2</sup> basin area, which are sub-basins of the Connecticut River basin.  
93 The hydrodynamic model simulation domains ranged from 3.7 to 8.3 km in river length and 2.2 and 20.7 km<sup>2</sup> in area.

### 94 **2.2 Simulation framework**

95 To evaluate the effect of compound events, we selected four tropical storms: two actual hurricanes (Sandy and Irene)  
96 that hit Connecticut, and two synthetic scenarios based on actual hurricanes Sandy and Florence. Both Irene (August  
97 21–28, 2011) and Sandy (October 22–November 2, 2012) reached category 3, but they made landfall in Connecticut  
98 as category 1 hurricanes. The synthetic simulations (Chapt. 2.2.1) include different atmospheric conditions leading to  
99 landfall scenarios with greater impacts. The Sandy synthetic scenario represents hurricane Sandy under future climate  
100 and sea surface conditions (Lackmann 2015), while the synthetic scenarios for Florence were based on simulated  
101 surge-tide condition and future SLR (see Chapt. 2.2.1 and 2.3).

102 To investigate the impact of floods of the various scenarios, we devised a combined hydrological (Chapt. 2.2.2) and  
103 hydrodynamic (Chapt. 2.2.3) modeling framework (Figure 2), forced with weather reanalysis and geospatial data for  
104 the actual events, and a numerical weather prediction model (subsection a) for the synthetic events (that is, synthetic  
105 hurricane Florence and future hurricane Sandy).

### 106 **2.2.1 Atmospheric simulations**

107 To simulate the two synthetic Sandy and Florence hurricane events, we used the Weather Research and Forecasting  
108 (WRF) system (Powers et al., 2017; Shamarock et al., 2007). For the synthetic hurricane Florence event, we used a  
109 hurricane track forecast by the National Oceanic and Atmospheric Administration (NOAA), that as of September 6,  
110 2018, according to the Global Forecast System (GFS) forecasts of the National Center for Environmental Prediction  
111 (NCEP), showed landfall in Long Island and Connecticut on September 14 as a category 1 hurricane (Higgins 2000).  
112 We based synthetic hurricane Sandy event on future climate conditions (post-2100).

113 For the soil type and texture input in the WRF model for both synthetic storm simulations, we used the USGS  
114 GMTED2010 30-arc-second (Danielson and Gesch 2011) Digital Elevation Model for the topography, the Noah-  
115 modified 21-category IGBP-MODIS (Friedl et al., 2010) for land use, and vegetation input, and the Hybrid  
116 STATSGO/FAO (30-second) (FAO 1991) for soil characteristics.

117 To simulate the synthetic hurricane Florence with WRF, we used the GFS forecasts at  $0.25^\circ \times 0.25^\circ$  spatial resolution  
118 as initial and boundary conditions. We used a three-grid setup with a coarse external domain of 18 km spatial resolution  
119 and two nested domains with 6 km and 2 km horizontal grid spacing, respectively. Two-way nesting was activated for  
120 both inner domains. Vertically, the domains stretched up to 50 mb with 28 layers. We parameterized convective  
121 activity on the outer (resolution of 18 km) and the first nested (resolution of 6 km) domain using the Grell 3D ensemble  
122 scheme (Grell and Devenyi 2002). Further details on the model setup are presented in Table 2.

123 For the future hurricane Sandy scenario, we used the hurricane Sandy simulations under future climate conditions  
124 (after 2100) by Lackman (2015), who used a three-grid setup at spatial resolutions of 54, 18, and 6 km. We defined  
125 initial and boundary conditions by altering the European Centre for Medium-Range Weather Forecasts (ECMWF)  
126 interim reanalysis (Dee et al., 2011) data, based on five General Circulation Model (GCM)-projected, late-century  
127 thermodynamic changes derived from the IPCC (Intergovernmental Panel on Climate Change) AR4 A2 emissions  
128 scenario (Meehl et al., 2017). A complete description of the modeling framework is provided by Lackman (2015).

### 129 **2.2.2 Hydrological modeling**

130 To account for the river inflow (upstream boundary condition), we applied a physically-based distributed hydrological  
131 model [CREST-SVAS (Coupled Routing and Excess Storage–Soil–Vegetation–Atmosphere–Snow)] described in  
132 Shen and Anagnostou (2017).

133 To simulate river discharges for the synthetic hurricanes (Florence and future Sandy), we used the WRF simulations  
134 at 6-km/hourly spatiotemporal resolution, as described above. To force the hydrological model for the actual events  
135 (Sandy and Irene), we used data from Phase 2 of the North American Land Data Assimilation System (NLDAS-2)  
136 (Xia et al., 2012) dataset. NLDAS-2 is a gridded dataset derived from bias-corrected reanalysis and in situ observation  
137 data, with a one-eighth-degree grid resolution and an hourly temporal resolution, available from January 1, 1979, to  
138 the present day. We derived the precipitation from daily rain gauge data over the continental United States, and all  
139 other forcing data came from the North American Regional Reanalysis (NARR) by NCEP (Higgins 2000), to which  
140 we applied bias and vertical corrections. To reduce the computational effort, we performed the hydrological simulation  
141 using a hydrologically conditioned 30 m spatial resolution DEM (USGS 2017).

142 The hydrologic simulation include the use of land use and land cover information retrieved from the Moderate  
143 Resolution Imaging Spectroradiometer (“MOD12Q1” from MODIS) (Friedl et al., 2015). To compensate for the  
144 coarse resolution (500 m) of these data, we obtained imperviousness ratios using Connecticut’s Changing Landscape  
145 (CCL) database and the National Land Cover Database (NLCD) at 30 m resolution. In CREST-SVAS, the land surface  
146 process was simulated by solving the coupled water and energy balances to generate streamflow at hourly time steps  
147 at the outlet of the studied watershed. CREST-SVAS was calibrated and validated for the whole Connecticut river  
148 basin [that contains all the investigated sites] with an NSCE of 0.63 (Shen and Anagnostou, 2017). We further  
149 validated the model considering hourly flows in two locations within the Housatonic River and Naugatuck River  
150 watersheds with an NSCE of 0.69 (Hardesty et al., 2018). The quality measures indicate a satisfactory model  
151 performance at the watershed scale over the topographic region that collectively include our study sites.

### 152 **2.2.3 Hydrodynamic modeling**

153 To assess the flood hazard in terms of extent and the maximum depth of the flood, we implemented the Hydrologic  
154 Engineering Center’s River Analysis System (HEC-RAS), developing two-dimensional model domains around the CI  
155 location. Except for CI4 and CI5, which are within the same simulation domain, each substation has an independent  
156 domain.

157 The inundation maps are derived using a 1m LIDAR DEM (CtECO 2016) taken as base maps for the study reaches.  
158 To better represent the impacts of urban establishments on inundation dynamics, solid urban features such as houses  
159 and buildings, which obstruct the flow of stormwater, were added to the bare-earth DEM. For this, we considered the  
160 building footprints from (CtECO, 2012) and identified positions of buildings and houses in the DEM by increasing  
161 the elevation of the pixels within the building footprint polygons by an arbitrary height of 4.5 m, assuming one-story  
162 buildings.

163 The considered locations have no bathymetric (underwater topography) data represented in the DEM. In general, the  
164 impact of inclusion/exclusion of bathymetry data on the hydrodynamic model simulations will vary according to the  
165 river size and event severity (Cook & Merwade 2009). For the investigated events in this study flood risk is mainly  
166 dominated by defence overflow and defence breaching. This means that we do not require detailed bathymetric  
167 information in the upstream main channel, thereby considerably simplifying the modeling problem (Bates et al. 2013).  
168 Therefore, we did not represent the flow of water in the main channel. Rather boundary conditions were given as time  
169 series of water surface elevation imposed along the defence crests.

170 To reduce the computation time, we created a 2D mesh grid at 10 m background resolution, enforced with breaklines  
171 to intensify the riverbank and other areas with a large elevation gradient up to 1 m resolution. The upstream boundary  
172 condition was provided by CREST-SVAS, and the downstream boundary condition (coastal water level, including  
173 coastal tide, storm surge, and sea level) was derived from National Water Level Observation Network (NWLON)  
174 data, provided by NOAA. These data are available as actual observations and predictions at intervals of six minutes  
175 to one hour. Figure 3 provides an example of one of the sites, showing the upstream and downstream boundaries,  
176 along with a map overlay of flooded areas of five (SD1–SD5) scenarios (see below) for CI2. We initiated the

177 simulation with a warmup period of 12 hours to achieve stability. We chose the full momentum scheme in HEC-RAS  
178 and extracted hourly output from the simulation.

179 The model parameters were calibrated to obtain realistic water depths and extents, as compared to reference data  
180 collected for Sandy. To validate the hydrodynamic model simulations, we used surveyed HWMs (high water marks)  
181 (Koenig et al., 2016) collected by the United States Geological Survey (USGS) after hurricane Sandy at 15 selected  
182 locations spread across the simulation domains. HWMs are frequently used to calibrate and validate model outputs  
183 and satellite-based observations of flood depth (Bunya et al., 2010; Cañizares and Irish 2008; Cariolet, 2010; Chang  
184 et al., 2007; Hostache et al. 2009; McEvoy et al., 2012; Pearson et al., 2018; Schumann et al., 2008; Schumann et al.,  
185 2007; Schumann et al., 2007; Ziervogel et al., 2014). As for the flood extent, we further validated the model against  
186 the most accurate available information on the 2D extent and maximum depth of storm surge for Sandy (FEMA, CT  
187 DEEP, 2013), created from field-verified HWMs and Storm Surge Sensor data from the USGS.

188 An HWM does not necessarily indicate the maximum flood depth; rather, it can be a mark from a lower depth that  
189 lasts long enough to leave a trail. Based on this understanding, we compared the HWMs against the simulated flood  
190 depths within a 10x10m radius around the high water marks, also to avoid issues due to the presence of buildings in  
191 the DEM (Boxplots in Fig. 4). The simulated depths demonstrated reasonable agreement with the collected HWM  
192 values (Figure 4), with the model showing a slight overestimation. In this case, the systematic error fell within values  
193 of expected precision, implying a consistent positive bias in the simulations not strong enough to hinder the results.  
194 Figure 5 shows a visual comparison for CI1 and CI2 between the simulated inundation (Fig.5 a, c), and the reference  
195 extent (Fig. 5 d,e). A slight overestimation of the flood level, ranging between 0.2 and 0.4 m, with a precision of 0.2  
196 m or less, is observed for the inundation depths at the displayed locations, which is consistent with the results obtained  
197 locally, at the HWM locations (Fig. 4). Taking into consideration the accuracy of the inundation depth, the declared  
198 DEM accuracy (vertical RMSE ~0.3m), and the simplified modeling problem concerning bathymetry, the accuracy of  
199 the flood extent assessment was judged satisfactory.

200

### 201 **2.3 Compound scenarios**

202 We modeled four types of synthetic compound event scenarios, as well as actual events by (1) simulating the synthetic  
203 hurricanes; (2) introducing a climate change factor, in the form of SLR (~0.6 m), as projected for 2050, as a prediction  
204 for intermediate low probability (CIRCA 2017); (3) shifting the surge timing to make the surge peak-level occurring  
205 at local high tide; and (4) combining the SLR with the high tide condition. The combination of these four event types  
206 yielded nine simulations, hereby coded as IR or SD for hurricanes Irene and Sandy, and FL for the synthetic hurricane  
207 Florence.

208 Two scenarios were created for hurricane Irene. IR1 was the actual hurricane Irene, that made landfall in Connecticut  
209 during high tide, and IR2 was the IR1 scenario with future SLR added to the tidal water level as a downstream  
210 boundary condition in HEC-RAS.

211 For hurricane Sandy, we generated five scenarios. SD1 was the actual Sandy. For SD2, we shifted the peak high tide  
212 to coincide with the maximum storm surge recorded, as derived from the local NOAA stations (hereafter referred to

213 ‘shifted tide water levels’). We further added SLR to the shifted tide water levels from SD2 to create the third scenario  
214 (SD3). The remaining two scenarios for hurricane Sandy represented future climate conditions. Specifically, SD4 was  
215 the future hurricane scenario simulated with the GFS (Chapt. 2.2.1) and shifted tidal water level. SD5 was the future  
216 Sandy with shifted tide water levels and SLR.

217 For the synthetic hurricane Florence event, we simulated two scenarios. FL1 was the synthetic Florence event, based  
218 on the GFS track that gave landfall in Connecticut and Long Island (Chapt. 2.2.1). FL2 was the same synthetic event,  
219 with SLR added to the coastal water levels.

220 Table 3 shows, for each scenario, the basin-averaged event accumulated precipitation (mm) and the simulated peak  
221 flow (m<sup>3</sup>/s) used as an upstream boundary condition in HEC-RAS, along with the recurrence interval of the peak  
222 flows derived using a Log-Pearson probability distribution fitted using yearly maxima from the long-term simulated  
223 flows (1979-2019) from CREST. This shows how significant the precipitation forcing was for each considered  
224 scenario. For CI1, for example, the future Sandy (SD4/5) scenario, with a peak flow of 242.4 m<sup>3</sup>/s, was the most  
225 extreme event with a recurrence interval of 316 years, followed by Irene (158.5 m<sup>3</sup>/s) and Florence (51.3m<sup>3</sup>/s) with  
226 a recurrence interval of 56 and 2 years respectively, whereas, for CI8, Florence and future Sandy had similar  
227 magnitudes with peak flows of 93.1m<sup>3</sup>/s (6) and 94.7m<sup>3</sup>/s (6), respectively. In table 3, we have summarised the  
228 maximum total water level (tide & surge) used in the model at the downstream of the study sites for all the scenarios.  
229 This table represents the change in the severity of the coastal component of the compound scenarios concerning added  
230 challenges like shifted tide and SLR. For example, for CI3, the total water level increases 1m with the shifted tide  
231 (SD2/ SD4), and with SLR it becomes 4.4 m.

## 232 **2.4 Compound flood hazard analysis**

233 We investigated the compound effect of the different events by comparing flood area extents and flood depths for  
234 each event. For the flood area extent, we used as a baseline the 100-year flood maps provided by FEMA. The distance  
235 correlation index (dCorr) (Székely et al; 2007) has been used to identify the correlation of the differences between  
236 simulated and FEMA extent and compound events’ parameters [flow and total water level peak]. dCorr values range  
237 from 0 to 1 expressing the dependence between two independent variables. The closer the value to 1 is the stronger  
238 the dependency would be, and zero implies that the two variables in question are statistically independent. dCorr can  
239 depict the non-monotonic associations of the variables and declare the dCorr value is zero if only the variables are  
240 statistically independent.

241 For the flood level differences, we considered the overall distribution of water depths across the domain of the CI sites  
242 and investigated the time series of water depth at each location (Figure 6 is an example of the simulated flood depth  
243 during the scenarios of Sandy (SD1- SD5) over time for CI2).

244 To evaluate the flood hazard in terms of flood depth, we computed a Cumulative Distribution Function (CDF) to  
245 shows the probability that the flood depth will attain a value less than or equal to each measured value. We estimated  
246 the CDF using all the depth values of all the grid of simulation domain, for the time step when the inundation was  
247 maximum. We evaluated the depth empirical exceedance probability (Hanman et al., 2016; Lin et al., 2016; Warner  
248 and Tissot 2012) within the whole domain, considering the maximum depth at each pixel, as suggested in (Pasquier

249 et al. 2019, Hamman et al. 2016). The benefits of this empirical approach are that it overcomes sensitivity to the  
250 choice of the distribution and does not require a definition of the distribution parameters. By comparing the empirical  
251 distributions, we can investigate how changes in the scenario characteristics modify the frequency of the maximum  
252 inundation depths.

253 The study further looked at whether the depth of water at a station would change for various scenarios. Figure 6 shows  
254 an example of the flood depth over simulated time at CI3 for the scenarios of Sandy. Pre-defined critical water levels  
255 were investigated for each station, as hypothetical values representing the height between the floor and the critical  
256 electric system in the station. Specifically, we considered 0.5 m, 1.5 m, and 2.5 m for threshold levels. As a measure  
257 of the potential threat to the electric infrastructure, we determined the percentage of time that the flood level was over  
258 each specific threshold (Figure 7). This data was then used to assess potential flooding problems associated with on-  
259 site inundation: we associated the changes in risk posed to the CI from the different examined scenarios based on the  
260 changes in those percentages.

## 261 **3 Results and Discussion**

### 262 **3.1 Flood extent**

263 The inundation extents shown in figure 6 represent an aggregation of the overall runs rather than a specific simulation  
264 time, and it represents the extent reached when all pixels had the maximum inundation depth. Total flood extent ranged  
265 between less than 1 km<sup>2</sup> to more than 7 km<sup>2</sup>, with a minimum extent of 0.4 km<sup>2</sup> for the actual Sandy (SD1) at C8, and  
266 a maximum extent of 7.1 km<sup>2</sup> for the future Sandy (SD5) at C3. The results showed consistent agreement that the  
267 flood extent increased with increasing intensity of the event and an increase in the recurrence intervals of the flows  
268 (Table 3).

269 Changes across the study sites relative to the FEMA 100-year flood extend (Table 4, Figure 7a–c) ranged from –87.8%  
270 (for CI8 for SD1) to 192.2% (for CI2 for IR2). Overall, the sites with a return period of fewer than 100 years, showed  
271 consistently less flooding than that of the FEMA map, a finding best represented by the comparison of actual events,  
272 such as IR1.

273 Since the model performance shows a good agreement with the actual flood extents, and the HWMs (Chapt.2.2.3),  
274 our results suggest that FEMA’s flood maps do not fully capture the flood extent at least for some locations. Similar  
275 findings were reported in Jordi et al. (2019), Wang et al. (2014) and Xian et al. (2005), where tens of meter-scale  
276 absolute differences were found between the FEMA estimated flood extent for hurricane Sandy. The strength of  
277 correlation (dCorr) between changes in the upstream (flow peak) or downstream (surge peak) components, and the  
278 absolute differences with FEMA extent, gives an idea of the importance of each single driver of change. For the cases  
279 investigated in this study, the percentage difference mostly depends on the surge: surge height explains more than  
280 80% of the variation in the differences to FEMA extent (dcorr=0.8 in median). CI6 appears to be the sites where the  
281 surge has the strongest correlation with the absolute difference in flood extent, as compared to FEMA maps. The  
282 differences with FEMA maps are less related to the peak flows (median correlation 0.5, with max correlation recorded  
283 for CI3). As expected, the correlation with surge increases at the decreasing of the hydrologic distance to the coast,

284 while the correlation with the flow increases the further a site is from the coast, even though this relationship is not  
285 linear.

286 As we proceeded with the synthetic scenarios, adding compound and future climate, the results indicated the additional  
287 impacts of the joint flood drivers (shifted tide, surge, SLR).

288 For the same event, peak storm-tide levels occurring near local high tide (i.e. SD2) resulted in more flooding than that  
289 of events happening at low-tide (like actual Sandy, SD1). Climate change related SLR exacerbates extreme event  
290 inundation relative to a fixed extent (FEMA) with variability that ranged from 8.3% (CI4/5) to as high as 425% (CI8).  
291 CI8 is the site hydrologically closer to the coast (see hydrologic distance in Table 1), making it the most susceptible  
292 to the altered scenario. Nonetheless, the shifted tide increased the inundation relative to the FEMA 100-year flood  
293 map also for CI2 and CI4/5.

294 The effects of compound events emerged drastically with the combination of both shifted tide and SLR. With the  
295 exception of CI3 and CI8, all other CIs showed an increase in the percentage change from FEMA (Table 4). In  
296 comparison to SD1, SD3 exhibited increased inundation for all the CIs. The inundated area was about 146% more  
297 (1.9 km<sup>2</sup>) for SD3 than SD1 (0.9 km<sup>2</sup>) for CI1, for example. The river flood peak for hurricane Sandy had a recurrence  
298 interval of about two years, but the flood hazard associated with this event became more devastating if simulated in a  
299 compound way, including SLR and shifted tide. This result suggests that events of lower river flood severity (from  
300 less rain accumulations) can produce aggravating impact, as the intensity of major storm surges increases due to shifted  
301 timing and SLR.

302 For the synthetic hurricane Florence and hurricane Irene, we saw an increased flooded area in comparison to FEMA  
303 (Table 4); for CI2, for example, the increase was almost 200% from IR1 to IR2. Again, this result confirms that  
304 accounting for river peak flow frequency alone does not effectively capture the severity of a flood hazard in the case  
305 of coastal locations.

306 For all the study sites for future Sandy, we saw consistent increases in flood extent (Table 4) from SD2 to SD4 and  
307 SD3 to SD5. Between SD2/SD3 and SD4/SD5, the only difference was the future projection of the flow. In comparison  
308 to the FEMA map, the percentage change ranged from -22.3 to +123.7. CI1, CI7, and CI8 for SD4 have less inundation  
309 than the FEMA 100-year map. This may be an indication of the significance of individual flood components specific  
310 to one site. For those sites, river flow might not be the most significant component of the flood. When we look at the  
311 hydrologic distances in table 1 CI1 and CI8 are closer to the coastline, making them more prone to coastal flooding  
312 than fluvial flooding. When we looked at SD5 (which added SLR), all the sites except CI8 showed more flooding than  
313 the FEMA 100-year flood map. Although CI8 had an increase of 22% in inundation compared to SD4.

314 When we compare the worst-case future events (SD5 and IR2) to actual events (SD1 and IR1), we can see major  
315 changes in flood extents. The flood extent in all locations increased by about 60% on average for future Sandy with  
316 both SLR and coinciding tide (SD5) in comparison to the actual Sandy (SD1), with the highest impact in CI8 (+148%).  
317 Looking at Irene, the worst-case future scenario (IR2) increased the flood extent by about 30% on average for all  
318 locations compared to the actual event (IR1), with the highest impact in CI2 (101%). Among all the events, Florence  
319 had the lowest expected changes, between the current climate scenario (FL1) and the future one (FL2). One must note  
320 that hurricane Florence had no actual impact in the study area; the simulation for this event was based on a hurricane

321 track forecast by GFS, which if materialized would have produced a flood inundation of almost 5 km<sup>2</sup> in CI3, and this  
322 extent could have increased by about 20% in the worst-case future scenario (FL2) that includes shifted tide and SLR.  
323 Five of the CIs were outside the FEMA 100-year flood zone, but they present flooding for FL1 and SD3. For FL2 all  
324 of the study sites were more vulnerable (positive % change), as compared to the FEMA map. Similar findings are  
325 presented for SD5, with the exception of CI8.

326

### 327 **3.2 Flood depths over the domain**

328 While flooding occurs in all the presented scenarios, both extent and depth vary greatly between the different  
329 simulations. Depth is important to consider while preparing for risk management as it is used in determining flood  
330 damage.

331 The CDFs of water depth for the whole domain (Figure 8), confirm that the water depths derived for coupled events  
332 (i.e. high tide coinciding with surge peak, or SLR and future climate) are generally higher than those derived from  
333 events with independent drivers. Note that for some cases (i.e. IR1 and IR2, for CI2 in Fig. 8) water depths increase  
334 very consistently as SLR increase. Large changes in the CDFs appears for lower water depths. Thus, regions with  
335 generally lower hazard (depth), will likely experience larger impacts under SLR. Results also confirm that scenarios  
336 with simultaneous high values for all these parameters implicated a higher vulnerability of the CIs. Comparing these  
337 changes in pairs [i.e. IR1 vs IR2, or SD1 vs SD3] also highlights that compound scenarios changes in the frequency  
338 of extreme values that go far beyond the average are much more pronounced than the related changes of the median  
339 depths (cumulative probability=0.50). In particular, it may be asserted that more expressed changes in extremes could  
340 lead to corresponding “hazard shift” for all CIs, as represented in Figure 8.

341

342 These results suggest that fluvial flow is not the only driver determining flood risk. Actual Irene (IR1) and synthetic  
343 Florence (FL) had higher river flood return periods than did actual Sandy (SD1) (Table 2). Nonetheless, the CDFs of  
344 the flood depth showed different behavior in terms of severity. For CI1, for example, IR1 had higher probabilities for  
345 lower depth, followed by SD1 and FL1. In CI8, SD1 had higher probabilities for lower values of depth. These findings  
346 highlight that neither the severity of rainfall, nor the magnitude of river flow controls the flood characteristics, which  
347 are, rather, controlled by additional factors, such as storm surge, high tides, topography, and location of the site. CI7,  
348 for example, which is more coastal than the other CIs, presented increasing flood depth due to tidal timing.

349 As expected, and as previously highlighted when considering the flood extent (Table 4), climate played an important  
350 role in flood hazard changes. Furthermore, the effect of SLR was also evident for all the events (IR, SD, and FL),  
351 increasing the flood depth for the same exceedance probability. For CI6, for example, the 50% exceedance  
352 corresponded to ~1 m depth of floodwater for IR1, increasing to ~1.5 m for IR2. For the CI4 and CI5 sites, for  
353 exceedance of 20%, actual Irene produced ~2 m of flood depth, whereas with SLR it was ~2.5 m. Another way to put  
354 it is that, for CI4/5, IR1 had an exceedance of ~20% for a flood depth of 2 m, whereas IR2 had an increased exceedance  
355 level of 40%. Similarly, for 50% exceedance, FL1 and FL2 corresponded to 1.5 m and 2 m depth of floodwater,  
356 respectively, and we saw the trend for the Sandy event scenarios (SD2–SD3; SD4–SD5) as well.

357 This analysis highlighted that the timing of a storm is also crucial. The changes from SD1 to SD2 showed very well  
358 the impact of the shifted tide for all the sites. For CI3, for example, the 1 m flood depth had an exceedance of ~88%  
359 for SD2, whereas it was only ~23% for SD1.

360 Analysis of the overall flood depth across the whole domain shows that the coincidence of fluvial flood, high tide, and  
361 storm surge results in a significant increase in flood risk. SD3 and SD5 had all the components of a compound flood  
362 and comparing them with SD1 gave us a clear idea of how severe a compound event can be in the future. CI3, for  
363 example, had exceedance levels of almost 30%, 85%, and 90%, respectively, for SD1, SD3, and SD5 for a flood depth  
364 of 1 m. This suggests the compound effect increases the intensity of the flood hazard.

### 365 **3.3 Local risk for CI**

366 Much of the flood damage in CI is incurred by components being submerged for a long period. Investigating the  
367 duration of the flood depth at the CI location (Figure 9) should be considered in planning for any protective measures,  
368 such as elevating or waterproofing equipment. If a critical infrastructure shows 0%, it means that for that  
369 scenario/event the water didn't reach the substation at all, at least during the simulated timeframe. This could be due  
370 to the water flooding other upstream locations, and therefore draining away from the station, or because the topography  
371 of the landscape actually prevented water from reaching the area for some specific events.

372 According to our analysis, none of the scenarios has an actual impact on CI1. For the other CIs, comparing individual  
373 events we could see an increase in risk due to the compound hazard scenarios—that is, shifted tide and SLR. Important  
374 to note is that, for most of the sites, the compound risk due to SLR and tide timing was always higher for the lower  
375 water-level thresholds (0.5 m). This implies a higher risk for CI components currently positioned closer to the ground.  
376 Damage to the CI components is dictated by both the flood depth and the duration of submergence. The suggested  
377 high values of risk [increase percentage in inundation duration] (Figure 9) further imply differences in the timing of  
378 repairs. In the cases of CI7 and CI8 (Figure 9), the CIs remained submerged with 0.5 m of water for about 20% of the  
379 event period for actual Sandy, but for the worst-case future Sandy scenario, the location was flooded for more than  
380 90% of the event duration. This demonstrates the increased flood risk to which future climate conditions expose CI.

381 Another important insight was provided by the hurricane Florence scenarios. As mentioned earlier, Florence did not  
382 affect the study area, although an early GFS storm forecast track predicted landfall in Long Island and Connecticut.  
383 For this event, the estimated measure of risk was about 20%, and it was shown to increase to up to 40% for the lower  
384 water depth (0.5 m) threshold in some locations. The result of the simulated scenario allows for an assessment of  
385 potential damage and for an identification of equipment that might be affected by future events under current climatic  
386 conditions. In this regard, comparing the results for the different CIs during the Sandy scenarios revealed an interesting  
387 pattern. While we might have expected a greater impact over the whole domain when shifting the tide (Figure 9, Table.  
388 3), we found different impacts in the CI locations. Notably, the risk appeared lower when the tides were shifted (Fig.  
389 9) for some of the CIs (for example, CI5 and CI7). This can be explained by the fact that higher water levels in the  
390 domain were changing the water flows, allowing the flood to follow different drainable ways. This can be a very  
391 useful piece of information for deciding whether to and where to take measures in terms of flood occurrence and  
392 potentially relocating CIs to avoid catastrophic compound flood events.

393 From table 1 we can see that CI8 is the closest to the coastline followed by CI7, CI6, and CI5. From figure 9 we can  
394 see that all the CIs that are closer to the coastline are susceptible to changes in the downstream water level condition  
395 (Shifted tide/ SLR) (Table 3). CI4 is the farthest from the coast followed by CI3. Both the CIs show minimal response  
396 to changes in the coastal water level compared to CI5/ CI6/ CI7. This analysis gives us conclusive evidence of risk  
397 associated with the location of the CI from the coastline.

#### 398 **4 Concluding Remarks**

399 Preparing for the challenges posed by climate change requires understanding of current actual, possible and future  
400 scenario of tropical storm impacts, and a correct understanding of the hazard imposed by compound flooding. In this  
401 work we have developed and implemented a modeling framework that allows to address this task, focusing on coastal  
402 electric grid infrastructure (substations). To date, the design of these facilities typically has assumed the current  
403 climatic conditions. However, a changing climate, as well as co-occurrence of compound drivers, and the resulting  
404 more extreme weather events mean those climate bands are becoming outdated, leaving infrastructure operating  
405 outside of its tolerance levels.

406 We explored a range of actual and synthetic hurricane scenarios, offering a system that could inform short- and long-  
407 term decisions. For the short-term decision, the framework allowed to investigate the characteristics of the hurricane-  
408 related inundation, considering the compound effect of riverine and coastal flooding coinciding, or not, with peak high  
409 tides. Generally, hurricanes affect large areas, and the specific locations at which damage will occur are often difficult  
410 to anticipate. Simulation of different scenarios can provide system operators with the ability to prepare for damage  
411 and respond quickly once it has occurred—for example, by pre-positioning repair crews. Furthermore, by simulating  
412 the impact using possible storm paths, the framework allows us to understand the potential impacts on the CI. The  
413 framework proposed in this study evaluates the extent of flood nearby a critical coastal infrastructure caused by  
414 possible extreme compound events. Each type of infrastructure system has specific elements vulnerable to specific  
415 water levels; we map those hazard infrastructure intersections where risks will be exacerbated by climate change or  
416 compound events.

417 The findings of this study can support flood mitigation; the FEMA 100-year map is used for designing infrastructure  
418 and for making decisions on flood mitigation and flood insurance. Nonetheless, these maps must be updated because  
419 flood risk is not static; changes in hydrology, topography, and land development all have an impact on flood  
420 conditions. The results show that the vulnerability of each substation is linked to the different storms' characteristics,  
421 and how they vary depending on the distance from the coast—that is, inland substations are less affected by surge and  
422 SLR and more affected by rainfall accumulation events (such as Irene). The findings of this study highlight that rising  
423 seas will allow storm surges to inundate areas farther inland and that flood hazard is likely to grow as seas rise and  
424 storm surges become deeper. The results also highlight that tide-surge-SLR effects modeled using only coastal models  
425 in isolated open environments without considering fluvial effects on the flooding, or riverine models without  
426 appropriate downstream boundary conditions cannot capture the risk from tide-surge-SLR effects. The variability in  
427 flood extent among scenarios implies that the modeling of individual flood drivers separately can mischaracterize the  
428 true risk of flooding to coastal communities and critical infrastructure, introducing uncertainties that make the design

429 of long-lived infrastructure much more difficult. Significant losses can result in when the designs are inadequate and  
430 ill-adapted to climate conditions.

431 This study also shows that, for some locations, FEMA maps significantly underestimate the actual storm surge risk to  
432 structures near the shore relative to structures further inland, and it generally does not account for the impacts posed  
433 by simultaneous conditions, such as high tide and river flows, or for future climate impacts.

434 The inundation maps, as well as the depth distributions, highlight how climate change is expected to lead to increased  
435 flooding in many sites, due to rising sea levels and changing precipitation patterns. The impacts will be felt most  
436 acutely along the coasts, but our results show a significant increase also for the more inland locations, as heavy and  
437 more frequent rain events increase the risk of flash floods and riverine flooding events. The provided framework can  
438 produce inundation maps that would allow improving the CIs' resiliency in the face of natural disasters, independently  
439 from the mapping done for insurance purposes. Critical infrastructures are usually positioned by following the FEMA  
440 100-year flood zone map. Areas outside the designated zones generally either do not have flood mitigation plans, and  
441 stand without any protection, or plans based on critical flood depths derived from FEMA zone areas. In this study,  
442 however, we see an increase in the exposed (flooded) areas for future climate scenarios, as well as some under- and  
443 overestimation as compared to FEMA maps. We also show how the flood depth exceedance probability at a location  
444 can essentially increase during compound flooding and shift due to climate changes. This further suggests the need to  
445 develop, update improved criteria for recognizing the effects of existing and planned protection measurements, such  
446 as relocating equipment or CIs, where warranted.

447 Future research should consider improved estimation methods, including more detailed information on the variability  
448 of river properties (i.e. depth and width). Future works should also relate the frequency of inundation depths to return  
449 periods of precipitation, river flows, and surges, as well as differentiate among the individual effects of the components  
450 to determine the role of each in flooding impact. This can be a very useful piece of information for deciding whether  
451 and where to take measures in terms of flood occurrence and the potential relocation of CI to avoid catastrophic  
452 compound flood events.

453 Notwithstanding these challenges, the findings of this study highlight that, whenever possible, risk assessments across  
454 different critical locations directly or indirectly affecting critical infrastructure should be based on a consistent set of  
455 compound risks. The proposed analysis suggests planning and management strategies for critical infrastructure should  
456 rely on historical flooding data, together with future storm scenarios and climate and SLR projections. The overall  
457 impact on each critical structure in terms of flood extent and depth is unique. This will ultimately allow the building  
458 of resilience into different components of critical infrastructure to enable the system to function even under disaster  
459 conditions or to recover more quickly.

460  
461 **Acknowledgments:** This work was supported by Eversource Energy.

462 **Author contributions:** MKh, GS, XS, EA conceived the study. XS and EA contributed to the conception of the  
463 hydrologic model. RL contributed to the production and analysis of the hydrologic model outputs. MKo and EN  
464 contributed to the analysis, and interpretation of the climatic data. MKh and GS contributed to the automation of the

465 hydraulic model and the interpretation of its results. All authors participated in drafting the article and revising it  
466 critically for important intellectual content. All authors give the final approval of the published version.

467 **Competing interests.** The authors declare that they have no conflict of interest.  
468

## 469 **References**

- 470 Abi-Samra, N. and Henry, W.: Actions Before and After a Flood – Substation Protection and Recovery from Weather  
471 Related Water Damage, *IEEE Power & Energy Magazine*, pp. 52–58, Mar/Apr. 2011.
- 472 Ahearn E.A., (2004). Scientific Investigations Report 2004-5160, <https://doi.org/10.3133/sir20045160>
- 473 Barnard, P. L., Erikson, L. H., Foxgrover, A. C., Hart, J. A. F., Limber, P., O'Neill, A. C., ... Jones, J. M.: Dynamic  
474 flood modeling essential to assess the coastal impacts of climate change. *Scientific Reports*, 9(1), 4309.  
475 <https://doi.org/10.1038/s41598-019-40742-z>, 2019.
- 476 Barnard, P. L., Hoover, D., Hubbard, D. M., Snyder, A., Ludka, B. C., Allan, J., Kaminsky, G. M., Ruggiero, P.,  
477 Gallien, T. W., Gabel, L., McCandless, D., Weiner, H. M., Cohn, N., Anderson, D. L. and Serafin, K. A.: Extreme  
478 oceanographic forcing and coastal response due to the 2015–2016 El Niño, *Nat. Commun.*, 8(1), 14365,  
479 doi:10.1038/ncomms14365, 2017.
- 480 Bates, P. D., Dawson, R. J., Hall, J. W., Horritt, M. S., Nicholls, R. J., Wicks, J., & Hassan, M. A. A. M. (2005).  
481 *Coastal Engineering*, 52, 793–810.
- 482 Bevacqua, E., Maraun, D., Voudoukas, M. I., Voukouvalas, E., Vrac, M., Mentaschi, L., Widmann, M.: Higher  
483 probability of compound flooding from precipitation and storm surge in Europe under anthropogenic climate change.  
484 *Sci. Adv.* 5, eaaw5531, 2019.
- 485 Blöschl, G., Hall, J., Parajka, J., Perdigão, R. A. P., Merz, B., Arheimer, B., Aronica, G. T., Bilibashi, A., Bonacci,  
486 O., Borga, M., Čanjevac, I., Castellarin, A., Chirico, G. B., Claps, P., Fiala, K., Frolova, N., Gorbachova, L., Gül, A.,  
487 Hannaford, J., Harrigan, S., Kireeva, M., Kiss, A., Kjeldsen, T. R., Kohnová, S., Koskela, J. J., Ledvinka, O.,  
488 Macdonald, N., Mavrova-Guirguinova, M., Mediero, L., Merz, R., Molnar, P., Montanari, A., Murphy, C., Osuch, M.,  
489 Ovcharuk, V., Radevski, I., Rogger, M., Salinas, J. L., Sauquet, E., Šraj, M., Szolgay, J., Viglione, A., Volpi, E.,  
490 Wilson, D., Zaimi, K. and Živković, N.: Changing climate shifts timing of European floods, *Science* (80-. ),  
491 357(6351), 588–590, doi:10.1126/science.aan2506, 2017.
- 492 Bradbrook, K., Lane, S., Waller, S. and Bates, P.: Two-dimensional diffusion wave modelling of flood inundation  
493 using a simplified channel representation, *Int. J. River Basin Manag.*, 2, 211–223 [online] Available from:  
494 [https://research-information.bris.ac.uk/en/publications/two-dimensional-diffusion-wave-modelling-of-flood-](https://research-information.bris.ac.uk/en/publications/two-dimensional-diffusion-wave-modelling-of-flood-inundation-usin)  
495 [inundation-usin](https://research-information.bris.ac.uk/en/publications/two-dimensional-diffusion-wave-modelling-of-flood-inundation-usin) (Accessed 13 October 2020), 2004.
- 496 Bunya, S., Dietrich, J. C., Westerink, J. J., Ebersole, B. A., Smith, J. M., Atkinson, J. H., ... Roberts, H. J.: A High-  
497 Resolution Coupled Riverine Flow, Tide, Wind, Wind Wave, and Storm Surge Model for Southern Louisiana and  
498 Mississippi. Part I: Model Development and Validation. *Monthly Weather Review*, 138(2), 345–377.  
499 <https://doi.org/10.1175/2009MWR2906.1>, 2010.

500 Cañizares, R., & Irish, J. L.: Simulation of storm-induced barrier island morphodynamics and flooding. *Coastal*  
501 *Engineering*, 55(12), 1089–1101. <https://doi.org/10.1016/J.COASTALENG.2008.04.006>, 2008.

502 Cariolet, J.-M.: Use of high water marks and eyewitness accounts to delineate flooded coastal areas: The case of Storm  
503 Johanna (10 March 2008) in Brittany, France. *Ocean & Coastal Management*, 53(11), 679–690.  
504 <https://doi.org/10.1016/J.OCECOAMAN.2010.09.002>, 2010.

505 Chang, S. E., McDaniels, T. L., Mikawoz, J., & Peterson, K.: Infrastructure failure interdependencies in extreme  
506 events: power outage consequences in the 1998 Ice Storm. *Natural Hazards*, 41(2), 337–358.  
507 <https://doi.org/10.1007/s11069-006-9039-4>, 2007.

508 Chou M.-D., and Suarez, M. J.: An efficient thermal infrared radiation parameterization for use in general circulation  
509 models. *NASA Tech. Memo.* 104606, 3, 85pp, 1994.

510 Cook A., Merwade, V., (2009) Effect of topographic data, geometric configuration and modeling approach on flood  
511 inundation mapping. *Journal of Hydrology*, 377, 1–2, 20, 131-142 <https://doi.org/10.1016/j.jhydrol.2009.08.015>

512 CtECO.: 2012 Impervious Surface Download, <http://www.cteco.uconn.edu/projects/ms4/impervious2012.htm>, 2012.

513 CtECO.: Connecticut Elevation (Lidar) Data, <http://www.cteco.uconn.edu/data/lidar/index.htm>, 2016.

514 D.A. Reed, M.D. Powell and J.M. Westerman, “Energy Supply System Performance for Hurricane Katrina,” *Journal*  
515 *of Energy Engineering*, pp. 95–102, Dec. 2010.

516 Danielson, J.J. and Gesch, D.B.: Global multi-resolution terrain elevation data 2010 (GMTED2010) (p. 26). US  
517 Department of the Interior, US Geological Survey, 2016.

518 Dawson, R. J., Thompson, D., Johns, D., Wood, R., Darch, G., Chapman, L., Hughes, P. N., Watson, G. V. R., Paulson,  
519 K., Bell, S., Gosling, S. N., Powrie, W. and Hall, J. W.: A systems framework for national assessment of climate risks  
520 to infrastructure, *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, 376(2121), doi:10.1098/rsta.2017.0298, 2018.

521 de Bruijn, K. M., Maran, C., Zygnerski, M., Jurado, J., Burzel, A., Jeuken, C. and Obeysekera, J.: Flood resilience of  
522 critical infrastructure: Approach and method applied to Fort Lauderdale, Florida, *Water (Switzerland)*, 11(3),  
523 doi:10.3390/w11030517, 2019.

524 de Bruijn, K., Buurman, J., Mens, M., Dahm, R. and Klijn, F.: Resilience in practice: Five principles to enable societies  
525 to cope with extreme weather events, *Environ. Sci. Policy*, 70, 21–30, doi:10.1016/j.envsci.2017.02.001, 2017.

526 Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A.,  
527 Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani,  
528 R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Hólm, E.V., Isaksen, L., Kållberg, P., Köhler,  
529 M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P.,  
530 Tavolato, C., Thépaut, J.-N. and Vitart, F.: The ERA-Interim reanalysis: Configuration and performance of the data  
531 assimilation system. *Quart. J. Roy. Meteor. Soc.*, 137, 553–597, doi: <https://doi.org/10.1002/qj.828>, 2011.

532 Dottori, F., Szweczyk, W., Ciscar, J. C., Zhao, F., Alfieri, L., Hirabayashi, Y., Bianchi, A., Mongelli, I., Frieler, K.,  
533 Betts, R. A. and Feyen, L.: Increased human and economic losses from river flooding with anthropogenic warming,  
534 *Nat. Clim. Chang.*, 8(9), 781–786, doi:10.1038/s41558-018-0257-z, 2018.

535 FAO.: The digitized soil map of the world, World Soil Resource Rep. 67, FAO, Rome. FAO-UNESCO (1971–1981),  
536 Soil Map of the World (1:5,000,000), vol. 1–10, UNESCO, Paris, France. FAO-UNESCO (1974), Soil Map of the  
537 World (1:5,000,000), vol. 1 legend, UNESCO, Paris, France, 1991.

538 FEMA, CT DEEP (2013). Coastal Hazards Map Viewer Information  
539 <http://www.cteco.uconn.edu/viewers/coastalhazards.htm#surge>

540 FEMA.: Reducing Flood Effects in Critical Facilities. HSFE60-13-(April), 1–11, 2013.

541 Friedl M. A., Sulla-Menashe D., Tan B., Schneider A., Ramankutty N., Sibley A., & Huang X.: MODIS Collection 5  
542 global land cover: Algorithm refinements and characterization of new datasets. Remote Sensing of Environment,  
543 114(1), 168 10.1016/j.rse.2009.08.016–182), 2010.

544 Friedl, M., Sulla-Menashe, D.: MCD12Q1 MODIS/Terra+Aqua Land Cover Type Yearly L3 Global 500m SIN Grid  
545 V006. NASA EOSDIS Land Processes DAAC. <https://doi.org/10.5067/MODIS/MCD12Q1.006>, 2015.

546 Gerald, A. M., Covey, C, Delworth, T., Latif, M., McAvaney, B., Mitchell, J. F. B., Stouffer, R. J., and Taylor, K. E.:  
547 The WCRP CMIP3 multimodel dataset: A new era in climate change research. Bulletin of American Meteorological  
548 Society, 2007.

549 Grell, G. A., and Dévényi, D., A generalized approach to parameterizing convection combining ensemble and data  
550 assimilation techniques, Geophys. Res. Lett., 29(14), doi:10.1029/2002GL015311, 2002.

551 Hallegatte, S., Green, C., Nicholls, R. J., Corfee-Morlot, J.: Future flood losses in major coastal cities. Nat Clim Chang  
552 3:802–806. doi: 10.1038/nclimate1979, 2013.

553 Hamman, J. J., Hamlet, A. F., Lee, S.-Y., Fuller, R. and Grossman, E. E.: Combined Effects of Projected Sea Level  
554 Rise, Storm Surge, and Peak River Flows on Water Levels in the Skagit Floodplain, Northwest Sci., 90(1), 57–78,  
555 doi:10.3955/046.090.0106, 2016.

556 Hamman, J. J., Hamlet, A. F., Lee, S.-Y., Fuller, R., & Grossman, E. E.: Combined Effects of Projected Sea  
557 Level Rise, Storm Surge, and Peak River Flows on Water Levels in the Skagit Floodplain. Northwest Science,  
558 90(1), 57–78. <https://doi.org/10.3955/046.090.0106>, 2016.

559 Hardesty, S., Shen, X., Nikolopoulos, E., & Anagnostou, E.: A Numerical Framework for Evaluating Flood Inundation  
560 Hazard under Different Dam Operation Scenarios—A Case Study in Naugatuck River. Water, 10(12), 1798.  
561 <https://doi.org/10.3390/w10121798>, 2018.

562 Higgins, R.W.: Climate Prediction Center (U.S.S). Improved United States Precipitation Quality Control System and  
563 Analysis; NCEP/Climate Prediction Center Atlas, NOAA, National Weather Service, National Centers for  
564 Environmental Prediction, Climate Prediction Center: Camp Springs, MD, USA, 2000.

565 Hostache, R., Matgen, P., Schumann, G., Puech, C., Hoffmann, L., & Pfister, L.: Water Level Estimation and  
566 Reduction of Hydraulic Model Calibration Uncertainties Using Satellite SAR Images of Floods. IEEE Transactions  
567 on Geoscience and Remote Sensing, 47(2), 431–441. <https://doi.org/10.1109/TGRS.2008.2008718>, 2009.

568 Jordi, A., Georgas, N., Blumberg, A., Yin, L., Chen, Z., Wang, Y., Schulte, J., Ramaswamy, V., Runnels, D. and  
569 Saleh, F.: A next-generation coastal ocean operational system, Bull. Am. Meteorol. Soc., 100(1), 41–53,  
570 doi:10.1175/BAMS-D-17-0309.1, 2019.

571 Karagiannis, G.M., Chondrogiannis, S., Krausmann, E. and Turksezer, Z.I.: Power grid recovery after natural  
572 hazard impact. Science for Policy report by the Joint Research Centre (JRC), European Union.  
573 <https://doi.org/10.2760/87402>, 2017.

574 Koenig, T.A., Bruce, J.L., O'Connor, J.E., McGee, B.D., Holmes, R.R., Jr., Hollins, Ryan, Forbes, B.T., Kohn, M.S.,  
575 Schellekens, M.F., Martin, Z.W., and Peppler, M.C.: Identifying and preserving high-water mark data: U.S.S  
576 Geological Survey Techniques and Methods, book 3, chap. A24, 47 p., <http://dx.doi.org/10.3133/tm3A24>,  
577 2016.

578 Kwasinski, W.W. Weaver, P.L. Chapman and P.T. Krein, "Telecommunications Power Plant Damage Assessment for  
579 Hurricane Katrina – Site Survey and Follow-Up Results," IEEE Systems Journal, vol. 3, no. 3, pp. 277–287, Nov.  
580 2009.

581 Lackmann, G. M.: Hurricane Sandy before 1900, and after 2100. Bull. Amer. Meteor. Soc., 96, 547-560, doi:  
582 10.1175/BAMS-D-14-00123.1, 2015.

583 Leonard, M., Westra, S., Phatak, A., Lambert, M., Van Den Hurk, B., McInnes, K., ... Stafford-Smith, M.: A  
584 compound event framework for understanding extreme impacts. WIREs Clim Change, 5, 113–128.  
585 <https://doi.org/10.1002/wcc.252>, 2014.

586 Lin, N., Kopp, R. E., Horton, B. P., & Donnelly, J. P.: Hurricane Sandy's flood frequency increasing from year 1800  
587 to 2100. Proceedings of the National Academy of Sciences of the United States of America, 113(43), 12071–12075.  
588 <https://doi.org/10.1073/pnas.1604386113>, 2016.

589 Marsooli, R., Lin, N., Emanuel, K., & Feng, K.: Climate change exacerbates hurricane flood hazards along US  
590 Atlantic and Gulf Coasts in spatially varying patterns. Nature Communications, 10(1).  
591 <https://doi.org/10.1038/s41467-019-11755-z>, 2019.

592 McEvoy, D., Ahmed, I., Mullett, J.: The impact of the 2009 heat wave on Melbourne's critical infrastructure. Local  
593 Environ 17:783–796. doi: 10.1080/13549839.2012.678320, 2012.

594 Meehl, G. A., C. Covey, K. E. Taylor, T. Delworth, R. J. Stouffer, M. Latif, B. McAvaney, and J. F. B. Mitchell: The  
595 WCRP CMIP3 multimodel dataset: A new era in climate change research. Bull. Amer. Meteor, 2007.

596 Mlawer, E. J., Taubman, S. J., Brown, P. D., Iacono, M. J. and Clough, S. A.: Radiative transfer for inhomogeneous  
597 atmospheres: RRTM, a validated correlated-k model for the longwave. J. Geophys. Res., 102, 16663–16682.  
598 doi:10.1029/97JD00237, 1997.

599 Moftakhari, H. R., Salvadori, G., AghaKouchak, A., Sanders, B. F., & Matthew, R. A.: Compounding effects of sea  
600 level rise and fluvial flooding. Proceedings of the National Academy of Sciences of the United States of America,  
601 114(37), 9785–9790. <https://doi.org/10.1073/pnas.1620325114>, 2017.

602 Muis, S., Verlaan, M., Winsemius, H. C., Aerts, J. C. J. H. and Ward, P. J.: A global reanalysis of storm surges and  
603 extreme sea levels, Nat. Commun., 7, doi:10.1038/ncomms11969, 2016.

604 NOAA.: NOAA's STATE OF THE COAST: National Coastal Population Report, 2013.

605 O'Donnell, J.: Sea Level Rise Connecticut Final Report. [https://circa.uconn.edu/wp-](https://circa.uconn.edu/wp-content/uploads/sites/1618/2019/02/SeaLevelRiseConnecticut-Final-Report.pdf)  
606 [content/uploads/sites/1618/2019/02/SeaLevelRiseConnecticut-Final-Report.pdf](https://circa.uconn.edu/wp-content/uploads/sites/1618/2019/02/SeaLevelRiseConnecticut-Final-Report.pdf), 2017. (last accessed January 10,  
607 2020)

608 Pant, R., Thacker, S., Hall, J. W., Alderson, D. and Barr, S.: Critical infrastructure impact assessment due to flood  
609 exposure, *J. Flood Risk Manag.*, 11(1), 22–33, doi:10.1111/jfr3.12288, 2018.

610 Pasquier, U., He, Y., Hooton, S., Goulden, M. and Hiscock, K. M.: An integrated 1D–2D hydraulic modelling  
611 approach to assess the sensitivity of a coastal region to compound flooding hazard under climate change, *Nat. Hazards*,  
612 98(3), 915–937, doi:10.1007/s11069-018-3462-1, 2019.

613 Pearson, J., Punzo, G., Mayfield, M., Brighty, G., Parsons, A., Collins, P., Jeavons, S. and Tagg, A.: Flood resilience:  
614 consolidating knowledge between and within critical infrastructure sectors, *Environ. Syst. Decis.*, 38(3), 318–329,  
615 doi:10.1007/s10669-018-9709-2, 2018.

616 Powers, J. G., Klemp, J. B., Skamarock, W. C., Davis, C. A., Dudhia, J., Gill, D. O., Coen, J. L. and Gochis, D. J.:  
617 The Weather Research and Forecasting Model: Overview, system efforts, and future directions. *Bull. Amer.*  
618 *Meteor. Soc.*, 98, 1717–1737, <https://doi.org/10.1175/BAMS-D-15-00308.1>, 2017.

619 Quinn, N., Bates, P. D., Neal, J., Smith, A., Wing, O., Sampson, C., Smith, J. and Heffernan, J.: The Spatial  
620 Dependence of Flood Hazard and Risk in the United States, *Water Resour. Res.*, 55(3), 1890–1911,  
621 doi:10.1029/2018WR024205, 2019.

622 Schumann, G., Hostache, R., Puech, C., Hoffmann, L., Matgen, P., Pappenberger, F., & Pfister, L.: High-Resolution  
623 3-D Flood Information From Radar Imagery for Flood Hazard Management. *IEEE Transactions on Geoscience and*  
624 *Remote Sensing*, 45(6), 1715–1725. <https://doi.org/10.1109/TGRS.2006.888103>, 2007.

625 Schumann, G., Matgen, P., Cutler, M. E. J., Black, A., Hoffmann, L., & Pfister, L.: Comparison of remotely sensed  
626 water stages from LiDAR, topographic contours and SRTM. *ISPRS Journal of Photogrammetry and Remote Sensing*,  
627 63(3), 283–296. <https://doi.org/10.1016/J.ISPRSJPRS.2007.09.004>, 2008.

628 Schumann, G., Matgen, P., Hoffmann, L., Hostache, R., Pappenberger, F., & Pfister, L.: Deriving distributed  
629 roughness values from satellite radar data for flood inundation modelling. *Journal of Hydrology*, 344(1–2), 96–111.  
630 <https://doi.org/10.1016/J.JHYDROL.2007.06.024>, 2007.

631 Shen, X., & Anagnostou, E. N.: A framework to improve hyper-resolution hydrological simulation in snow-affected  
632 regions. *Journal of Hydrology*, 552, 1–12. <https://doi.org/10.1016/j.jhydrol.2017.05.048>, 2017.

633 Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D. M., Duda, M. G., Huang, X., Wang, W. and  
634 Powers, J. G.: A description of the Advanced Research WRF version 3. NCAR Tech. Note NCAR/TN-475+STR,  
635 113 pp., <https://doi.org/10.5065/D68S4MVH>, 2008.

636 Song–You, H., Noh, Y. and Dudhia, J.: A new vertical diffusion package with an explicit treatment of  
637 entrainment processes. *Mon. Wea. Rev.*, 134, 2318–2341. doi:10.1175/MWR3199.1, 2006.

638 Székely, G. J., Rizzo, M. L. and Bakirov, N. K.: MEASURING AND TESTING DEPENDENCE BY  
639 CORRELATION OF DISTANCES, *Ann. Stat.*, 35(6), 2769–2794, doi:10.1214/009053607000000505, 2007.

640 Tewari, M.F., Chen, W., Wang, J., Dudhia, M.A., LeMone, K., Mitchell, M.E., Gayno, G., Wegiel, J. and Cuenca,  
641 R.H.: Implementation and verification of the unified NOAA land surface model in the WRF model. 20th  
642 conference on weather analysis and forecasting/16th conference on numerical weather prediction, pp. 11–15, 2004.

643 Thompson, G., Paul, R. F., Roy, M. R. & William, D. H.: Explicit Forecasts of Winter Precipitation Using an  
644 Improved Bulk Microphysics Scheme. Part II: Implementation of a New Snow Parameterization. *Mon. Wea.*  
645 *Rev.*, 136, 5095–5115. doi:10.1175/2008MWR2387.1, 2008.

646 U.S.S Geological Survey.: 1/9th Arc-second Digital Elevation Models (DEMs) - USGS National Map 3DEP  
647 Downloadable Data Collection: U.S.S Geological Survey., 2017.

648 Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Jevrejeva, S., Jackson, L. P. and Feyen, L.: Global  
649 probabilistic projections of extreme sea levels show intensification of coastal flood hazard, *Nat. Commun.*, 9(1), 1–  
650 12, doi:10.1038/s41467-018-04692-w, 2018.

651 Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Jevrejeva, S., Jackson, L. P. and Feyen, L.: Global  
652 probabilistic projections of extreme sea levels show intensification of coastal flood hazard, *Nat. Commun.*, 9(1), 1–  
653 12, doi:10.1038/s41467-018-04692-w, 2018.

654 Wahl, T., Jain, S., Bender, J., Meyers, S. D., & Luther, M. E.: Increasing risk of compound flooding from storm surge  
655 and rainfall for major US cities. *Nature Climate Change*, 5(12), 1093–1097. <https://doi.org/10.1038/nclimate2736>,  
656 2015.

657 Wahl, T., Ward, P., Winsemius, H., AghaKouchak, A., Bender, J., Haigh, I., ... Westra, S.: When Environmental  
658 Forces Collide. *Eos*, 99. <https://doi.org/10.1029/2018EO099745>, 2018.

659 Wang, H., Loftis, J., Liu, Z., Forrest, D. and Zhang, J.: The Storm Surge and Sub-Grid Inundation Modeling in New  
660 York City during Hurricane Sandy, *J. Mar. Sci. Eng.*, 2(1), 226–246, doi:10.3390/jmse2010226, 2014.

661 Warner, N. N., & Tissot, P. E.: Storm flooding sensitivity to sea level rise for Galveston Bay, Texas. *Ocean*  
662 *Engineering*, 44, 23–32. <https://doi.org/10.1016/J.OCEANENG.2012.01.011>, 2012.

663 Winsemius, H. C., Van Beek, L. P. H., Jongman, B., Ward, P. J. and Bouwman, A.: A framework for global river  
664 flood risk assessments, *Hydrol. Earth Syst. Sci*, 17, 1871–1892, doi:10.5194/hess-17-1871-2013, 2013.

665 Xia, Y., Mitchell, K., Ek, M., Sheffield, J., Cosgrove, B., Wood, E., ... Mocko, D. : Continental-scale water and  
666 energy flux analysis and validation for the North American Land Data Assimilation System project phase 2 (NLDAS-  
667 2): 1. Intercomparison and application of model products. *Journal of Geophysical Research: Atmospheres*, 117(D3),  
668 n/a-n/a. <https://doi.org/10.1029/2011JD016048>, 2012.

669 Xian, S., Lin, N. and Hatzikyriakou, A.: Storm surge damage to residential areas: a quantitative analysis for Hurricane  
670 Sandy in comparison with FEMA flood map, *Nat. Hazards*, 79(3), 1867–1888, doi:10.1007/s11069-015-1937-x, 2015.

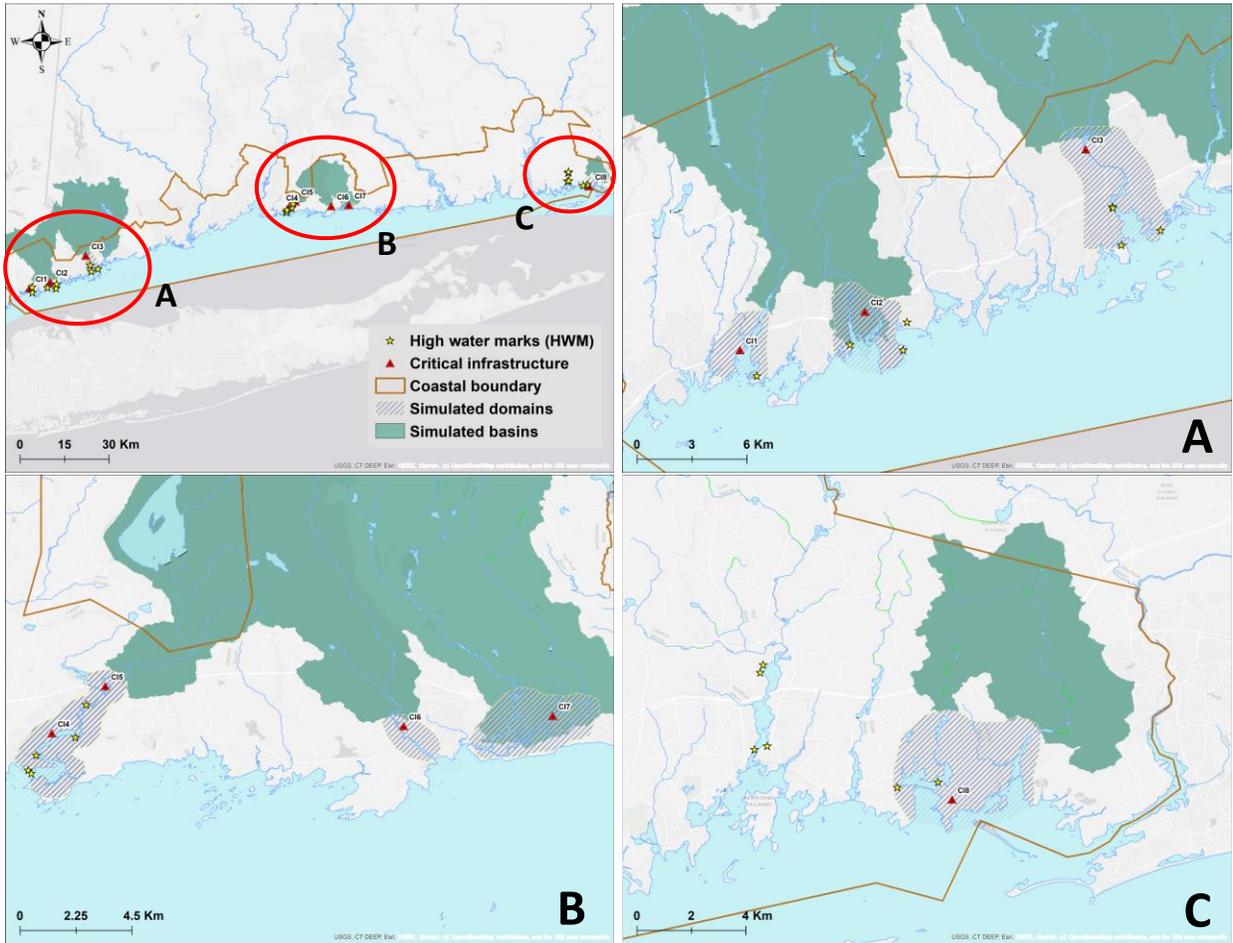
671 Ziervogel, G., New, M., Archer van Garderen, E., Midgley, G., Taylor, A., Hamann, R., Stuart-Hill, S., Myers, J. and  
672 Warburton, M.: Climate change impacts and adaptation in South Africa. *Wiley Interdiscip Rev Clim Chang* 5:605–  
673 620. doi: 10.1002/wcc.295, 2014.

674 Ziervogel, G., New, M., Archer van Garderen, E., Midgley, G., Taylor, A., Hamann, R., ... Warburton, M.: Climate  
675 change impacts and adaptation in South Africa. *Wiley Interdisciplinary Reviews: Climate Change*, 5(5), 605–620.  
676 <https://doi.org/10.1002/wcc.295>, 2014.

677 Zscheischler, J., Westra, S., van den Hurk, B. J. J. M., Seneviratne, S. I., Ward, P. J., Pitman, A., ... Zhang, X.: Future  
678 climate risk from compound events. *Nature Climate Change*, 8(6), 469–477. [https://doi.org/10.1038/s41558-018-](https://doi.org/10.1038/s41558-018-0156-3)  
679 0156-3, 2018.

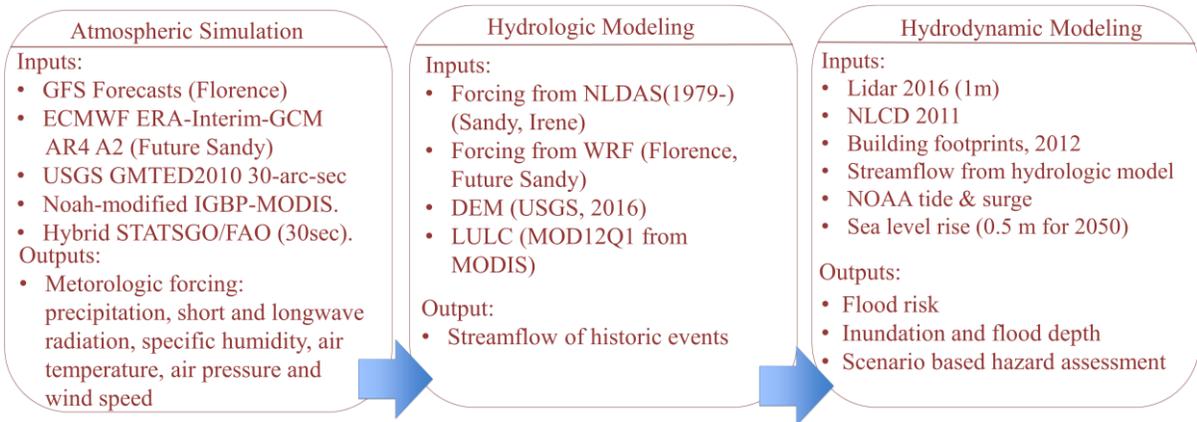
680

681



682

683 **Figure 1: Study area with associated watersheds and simulation domains. Locations of substations and USGS high water**  
 684 **marks are also shown. Red circles in the top left-hand panel, and marked with A, B, and C are highlighted in the panels A**  
 685 **to C respectively. Background map by ESRI web-services, provided by UConn/CTDEEP, Esri, Garmin, USGS, NGA,**  
 686 **EPA, USDA, NPS**



687

688 **Figure 2: Considered framework including atmospheric simulations, hydrologic, and hydrodynamic modeling. Hurricane**  
689 **events (actual and simulated), and inputs and outputs of each component are shown. Readers should refer to chapter 2.2**  
690 **for specifications**

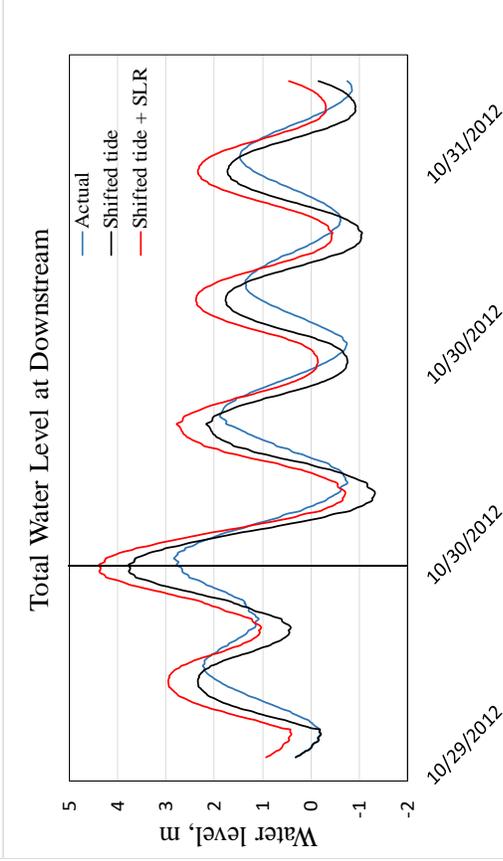
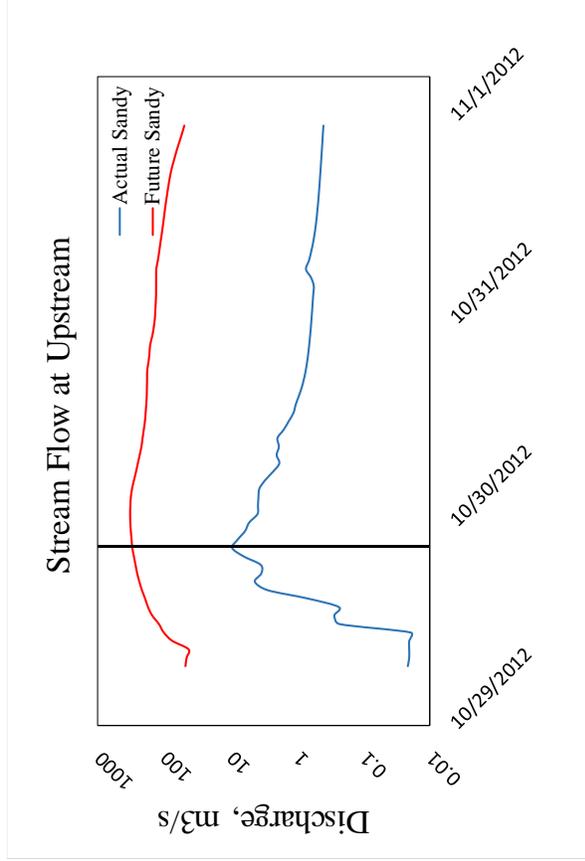
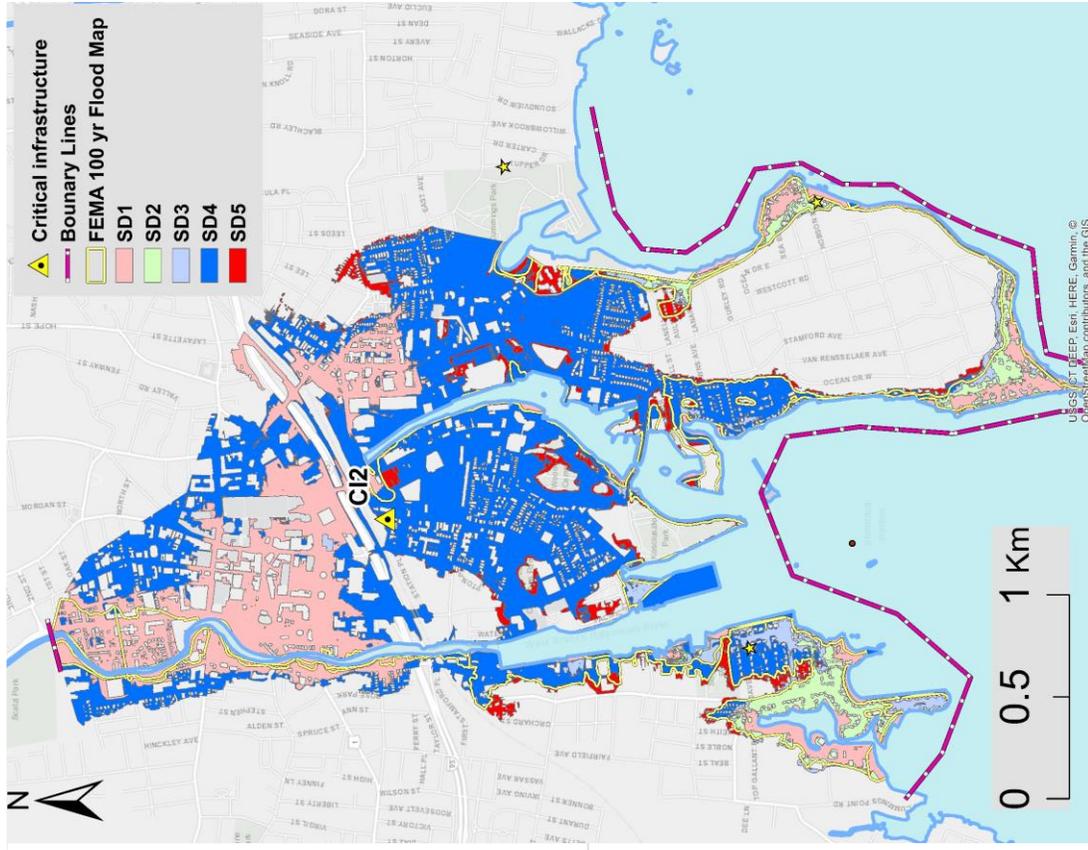
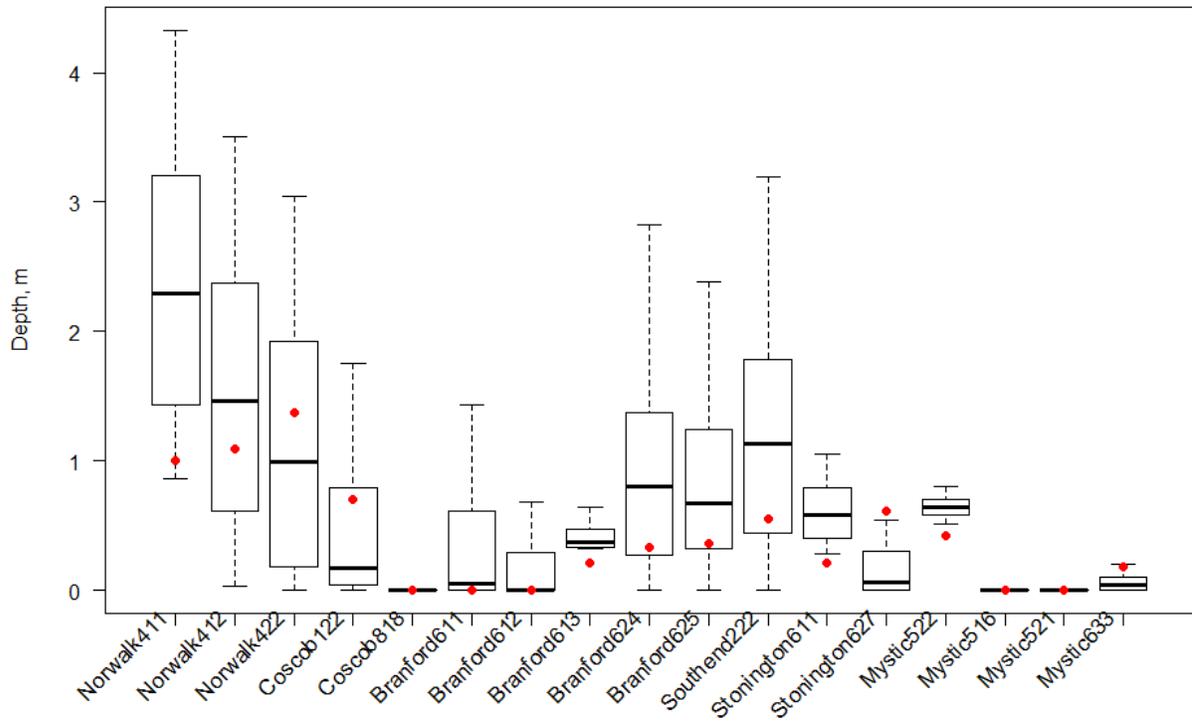
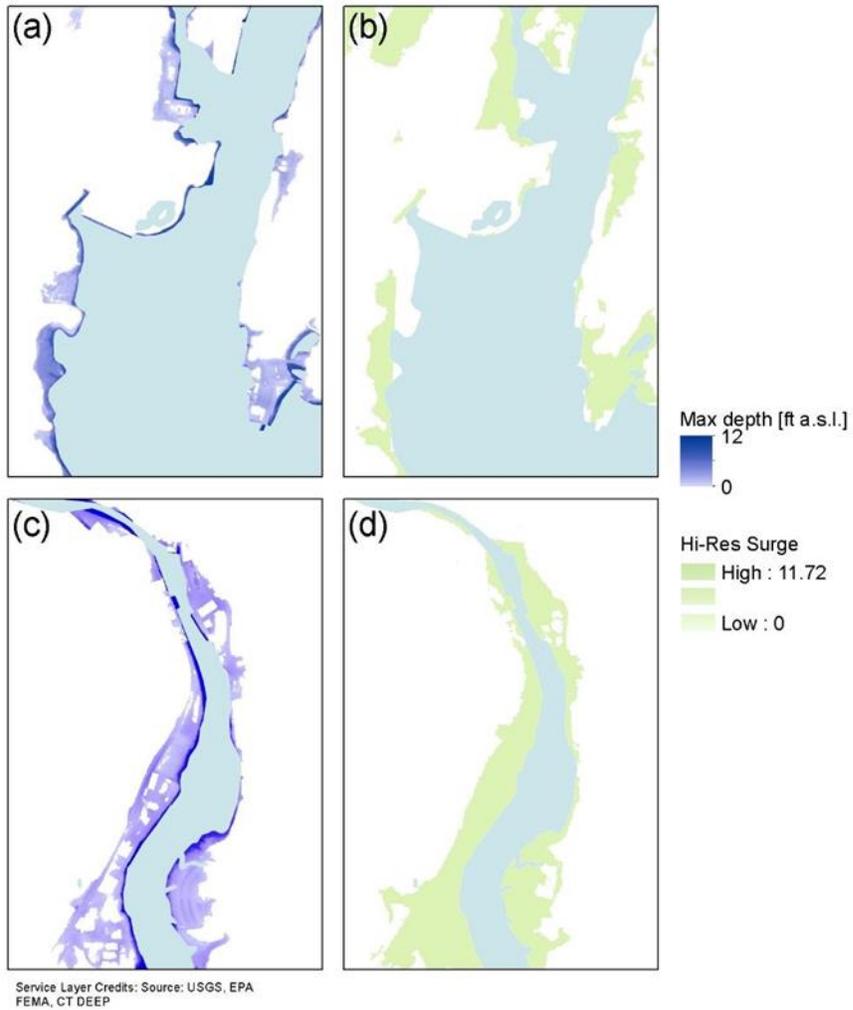


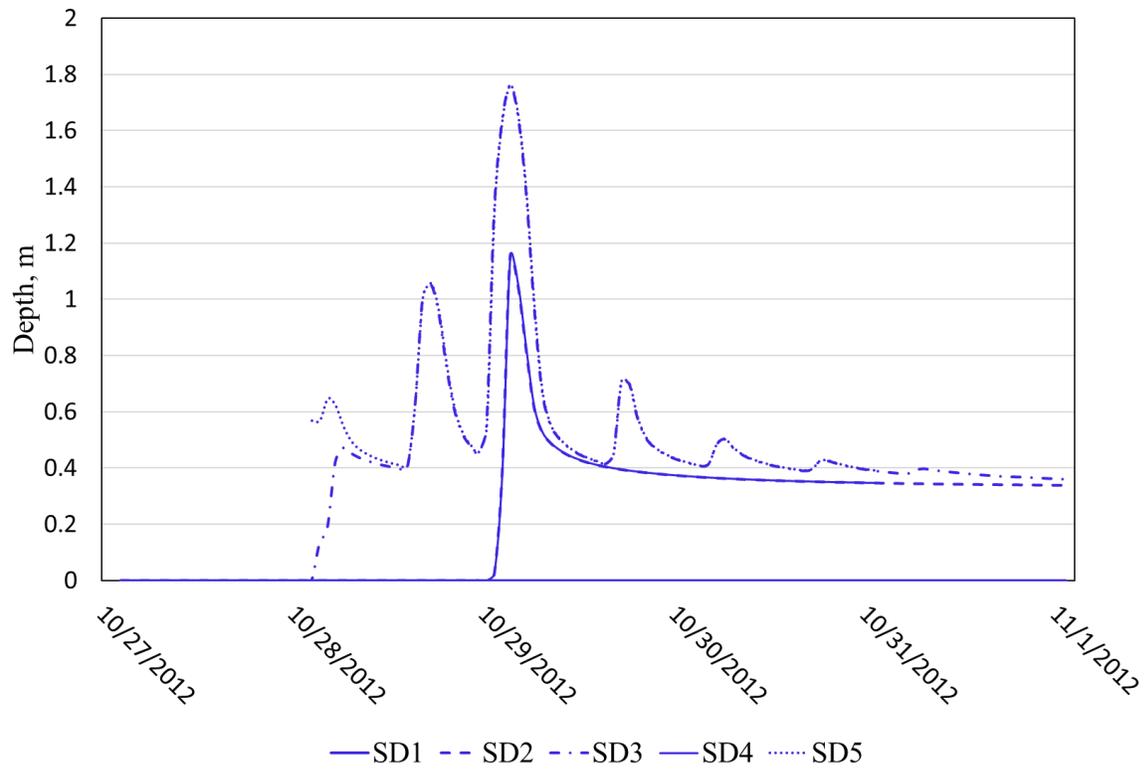
Figure 3: Example of different scenarios showing the upstream boundary condition (top left-hand panel, including the discharge for actual Sandy and future Sandy), and downstream boundary (bottom left-hand panel, including tide, shifted tide, and shifted tide with SLR). Output flood extend is also shown (right-hand panel), including results for SD1 to SD5 [reader should refer to Tab. 3 and chapter 2.2 for specification on the scenarios]. Background map on the right-hand panel by ESRI web-services, provided by UConn/CTDEEP, Esri, Garmin, USGS, NGA, EPA, USDA, NPS



**Figure 4: Validation results (boxplot of water depth within 10x10m around the high-water mark -HWM- location) compared to selected HWM (red dots) by USGS**



**Figure 5: Comparison between the results of the proposed model for two selected locations (a,c, CI1 and CI2 respectively) and the maximum surge extent as proposed by CtEco (c,d respectively).**



**Figure 6: Example of time series of depth values for the different scenarios of Sandy event at CI3 [SD1 to SD5, readers should refer to Table 3 and chapter 2.4 for specification on the scenarios]**

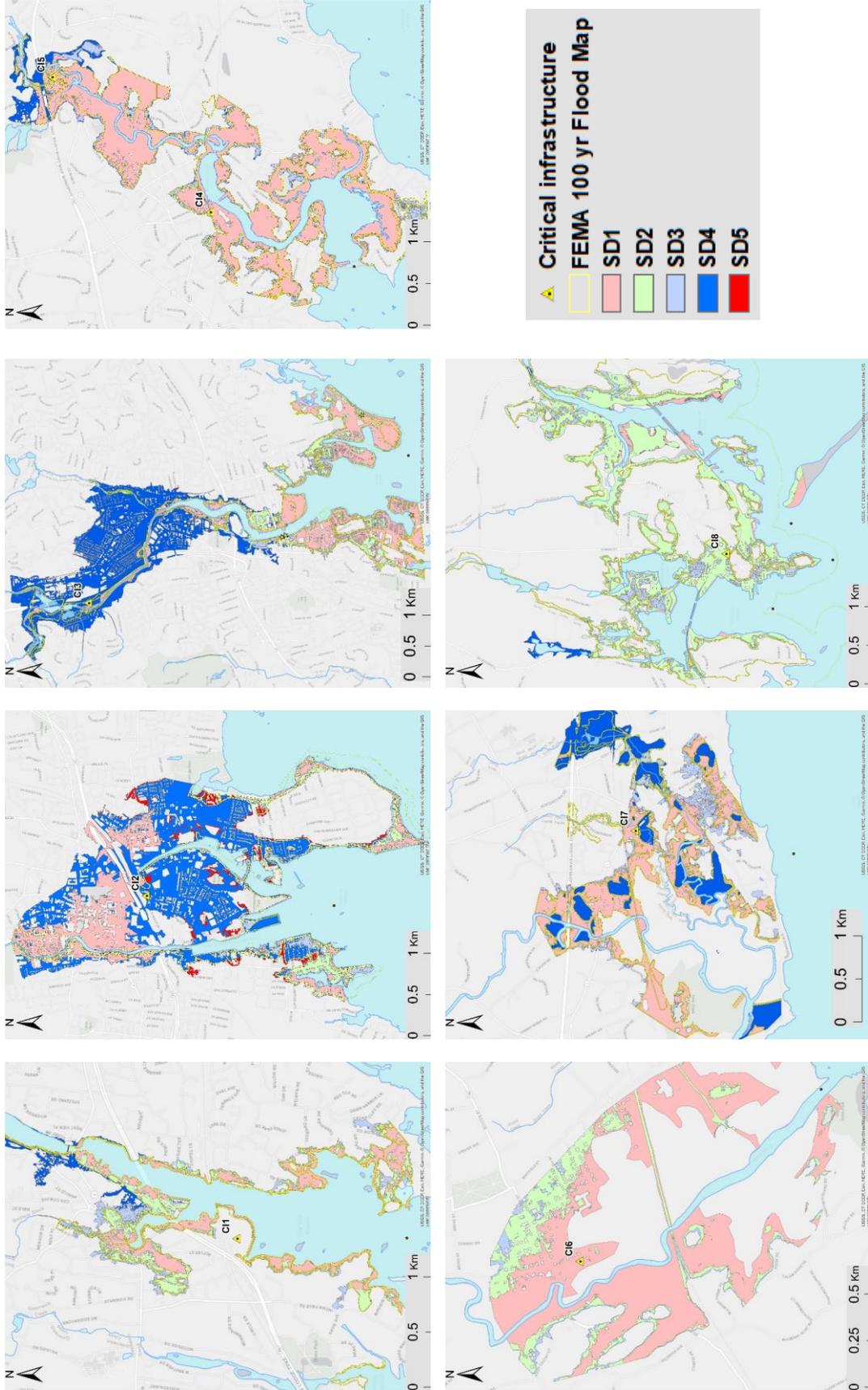


Figure 7a: Map overlay of maximum inundation for all the study domains containing CI1 through CI8 for the scenarios of Sandy [SD1 to SD5, readers should refer to Table 3 and chapter 2.2 for specification on the scenarios]

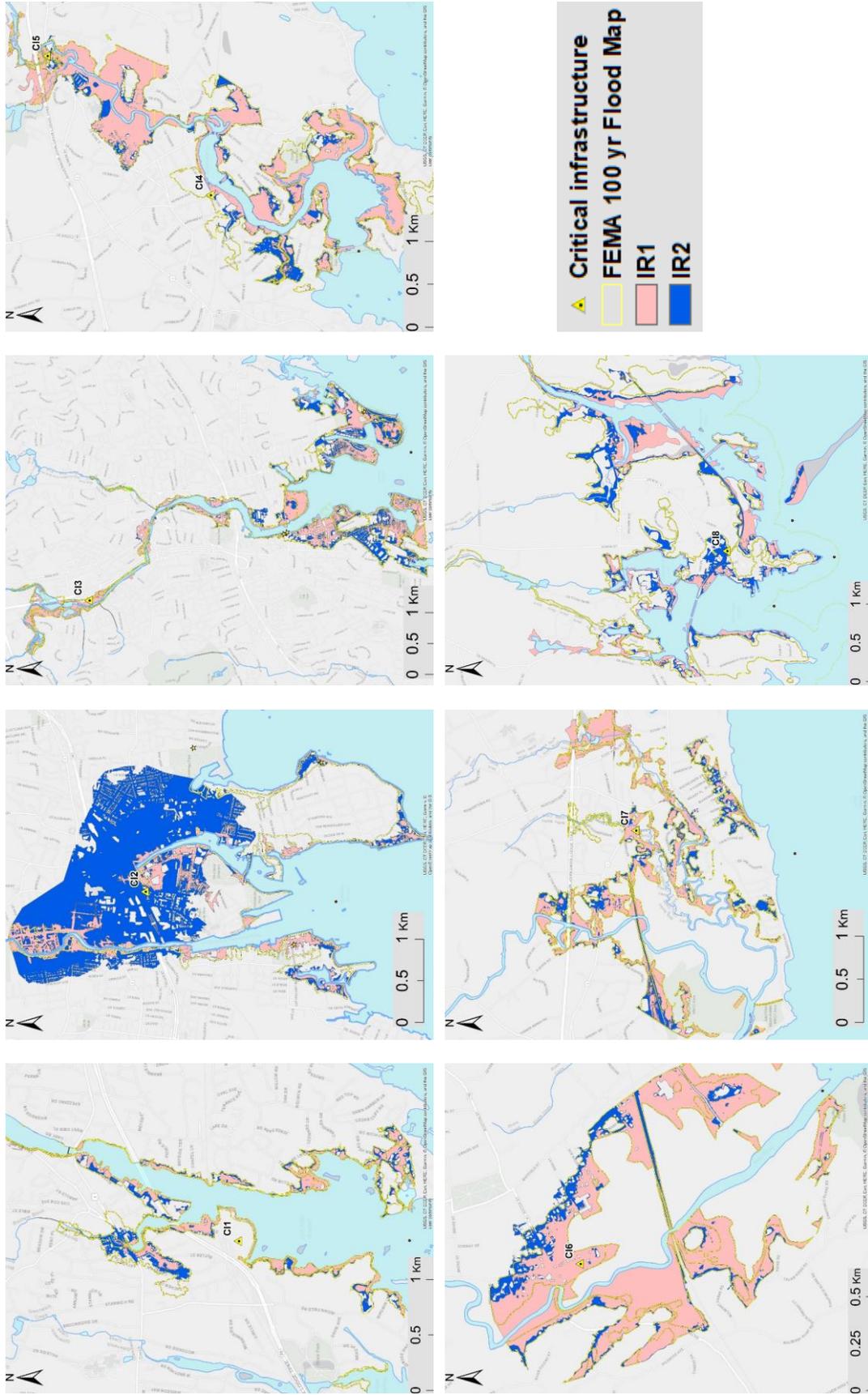


Figure 7b: Map overlay of maximum inundation for all the study domains containing CI1 through CI8 for the scenarios of Irene [IR1 and IR2, readers should refer to Tab. 3 and chapter 2.2 for specification on the scenarios]. Background map by ESRI web-services, provided by UConn/CTDEEP, Esri, Garmin, USGS, NGA, EPA, USDA, NPS

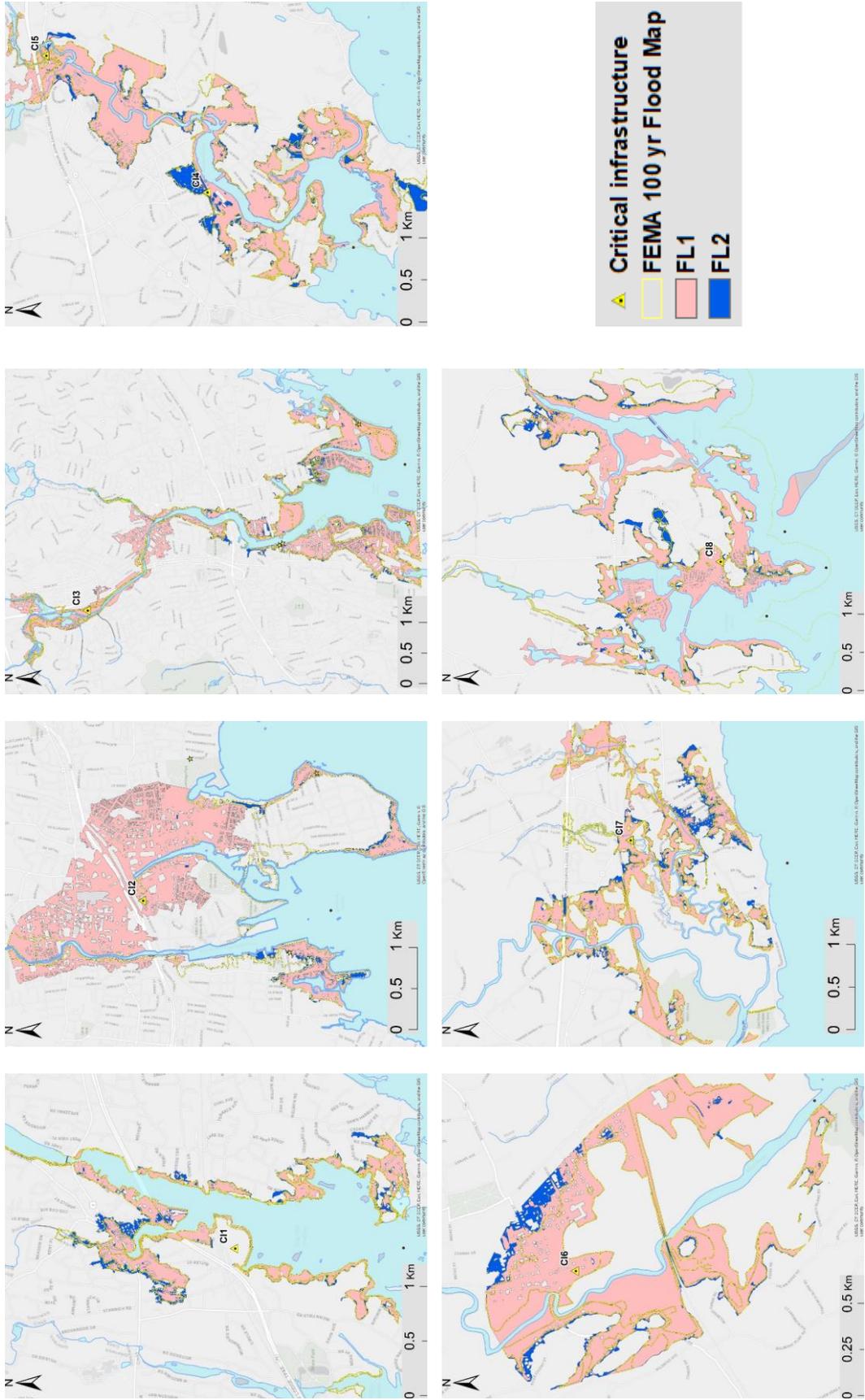


Figure 7c: Map overlay of maximum inundation for all the study domains containing CI1 through CI8 for the scenarios of Florence [FL1 and FL2, readers should refer to Table 3 and chapter 2.2 for specification on the scenarios]. Background map by ESRI web-services, provided by UConn/CTDEEP, Esri, Garmin, USGS, NGA, EPA, USDA, NPS

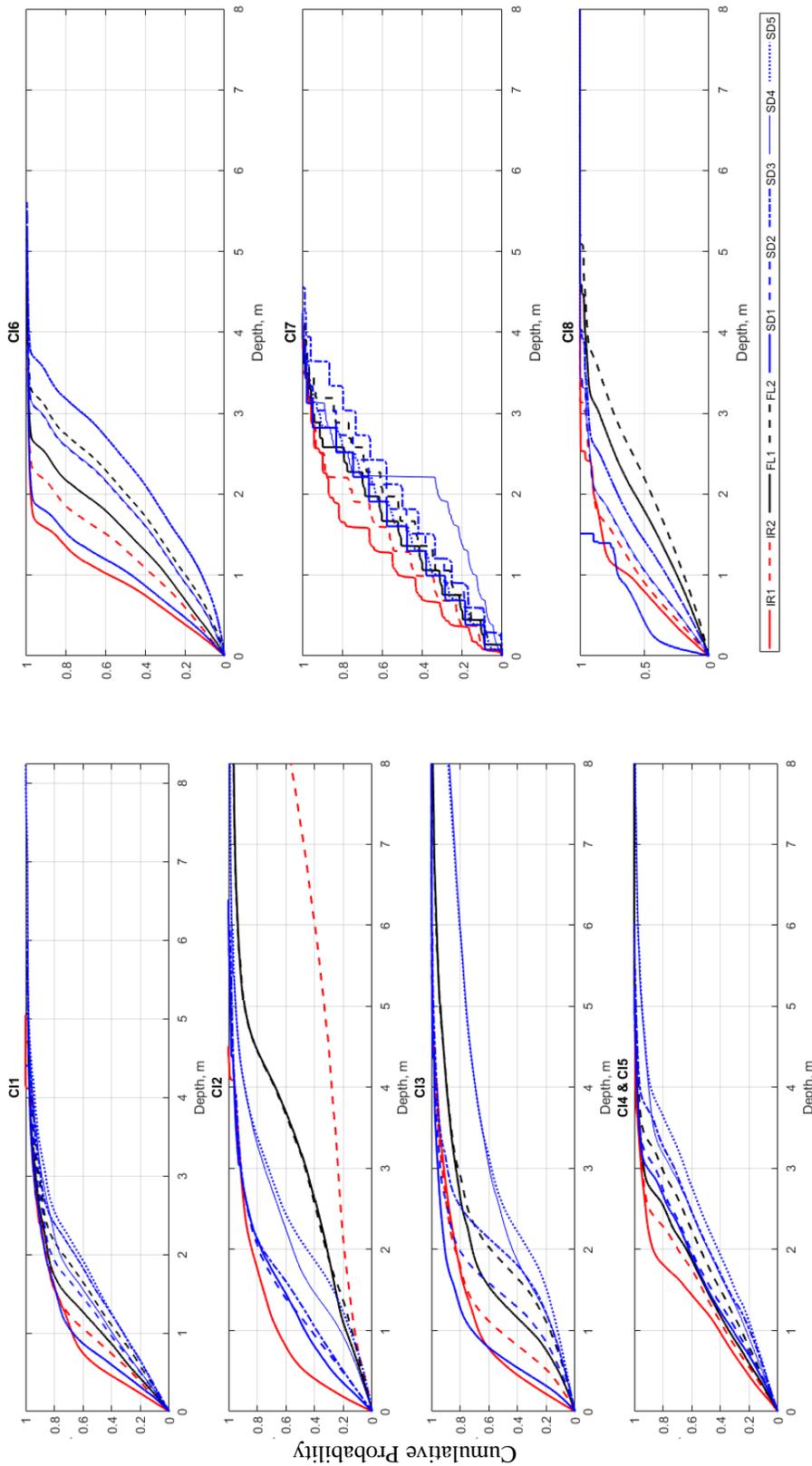


Figure 8: Cumulative density plot of the depth of all the flooded cells during maximum inundation. Hurricanes scenarios are labelled according to Table 3 and explained in chapter 2.2. Critical infrastructures are labelled CI1 to CI8, as described in Table 1.

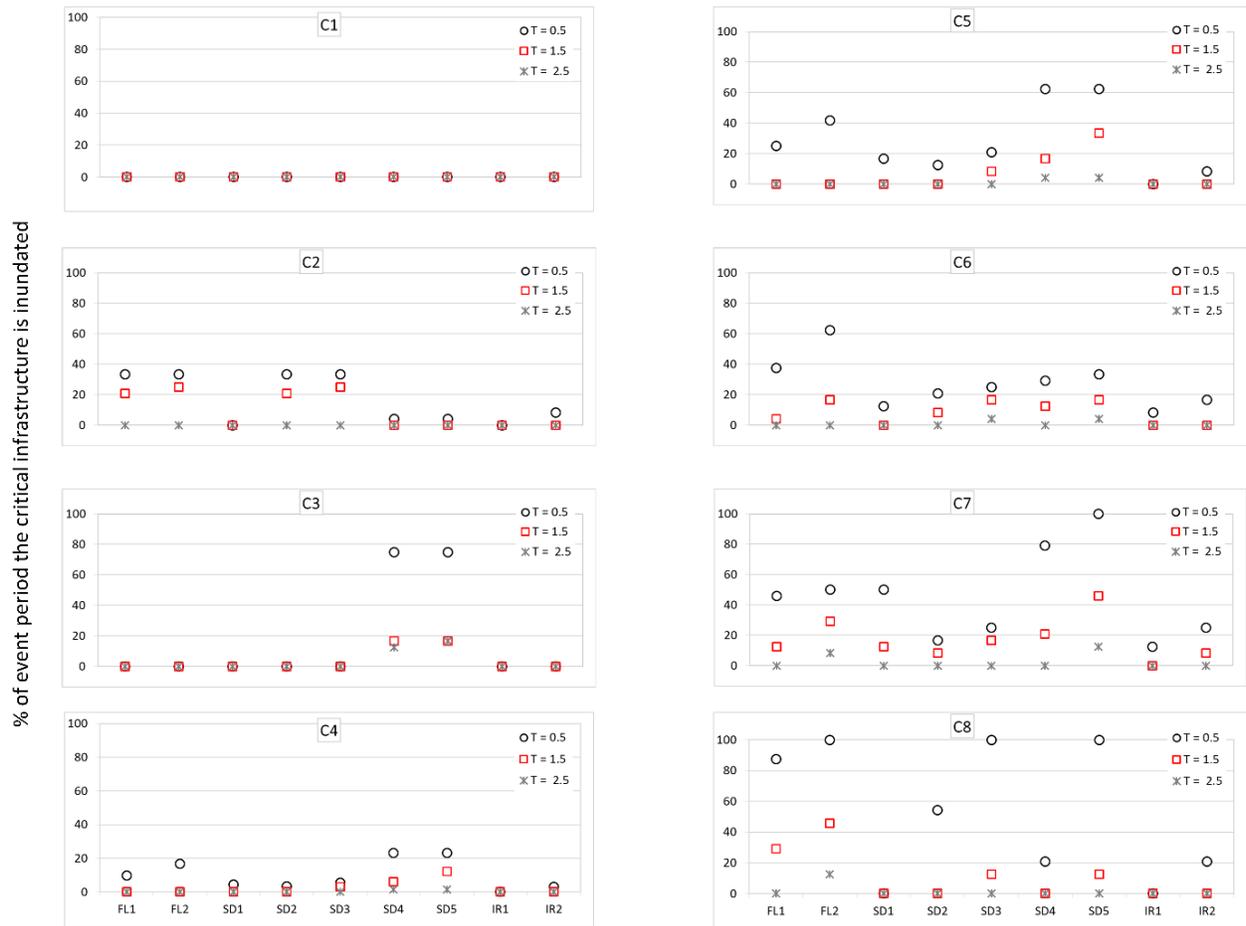


Figure 9: Peak over threshold (T=0.5, 1.5 and 2.5m) at selected critical infrastructures. Hurricanes scenarios, along the x-axis, are labeled according to Table 3 and explained in chapter 2.2. Critical infrastructures are labeled CI1 to CI8, as described in Table 1.

**Table 1: Study area- Characteristics of the considered CIs, with river and model domain information. Basin area represents the area of the underlining watershed; domain area is the extent of the simulation domain; reach length represents the length of the stream within the domain; hydrologic distance represents the distance from each CI to the coastline.**

Critical Infrastructure (CI)	Town	Rivers	Basin area, km <sup>2</sup>	Domain area, km <sup>2</sup>	Reach length, km	Hydrologic distance, km
CI1	Coscob	Mianus River	216.6	7.5	7.8	4.5
CI2	Southend	Rippowam River	308.4	12.1	4.9	5.3
CI3	Norwalk	Norwalk River	268.7	20.7	8.3	7.8
CI4/ CI5	Branford	Branford River	84.5	7.9	6.7	8.8/5.3
CI6	Guilford	West River	126.4	2.2	3.7	5.1
CI7	Madison	East & Neck Rivers	173.0	8	5.3	6.8
CI8	Stonington	Stonington harbor	10.0	14.9	5.2	2.9

**Table 2: Model domain information for Florence**

Horizontal Resolution	18, 6, and 2 km
Vertical levels	28
Horizontal Grid Scheme	Arakawa C grid
Nesting	Two-way nesting
Convective parameterization	Grell 3D ensemble scheme (18 and 6 km grids only)
Microphysics option	Thompson graupel scheme (Thompson et al., 2008)
Longwave Radiation option	RRTM scheme (Mlawer et al., 1997)
Shortwave Radiation option	Goddard Shortwave scheme (Chou and Suarez 1994)
Surface-Layer option	Monin-Obukhov Similarity scheme
Land-Surface option	Noah Land-Surface Model (Tewari et al., 2004)
Planetary Boundary Layer	Yonsei scheme (Song–You et al., 2006)

**Table 3: Peak Tide, Surge at the maximum total water level instance, Accumulated precipitation & peak flows (with return period reported within brackets) for the simulated scenarios. Reader should refer to Chapter 2.2 for a detailed description of each hurricane scenario (IR for Irene, SD for Sandy, FL for Florence). The “\*” denotes the scenarios having sea level rise (SLR) added to the surge. Critical infrastructures are labelled CI1 to CI8 according to Table 1.**

Scenarios		CI1	CI2	CI3	CI4/ CI5	CI6	CI7	CI8
FL1	Tide (m)	0.99	0.99	0.99	0.94	0.94	0.94	0.17
	Surge (m)	2.51	2.51	2.51	2.56	2.46	2.56	3.33
	Accumulated precipitation (mm)	128.5	147.5	165.1	192	203.9	200.7	289.2
	Peak flow, m3/s	51.3	87.4	74.9	106.1	113.3	143.2	93.1
	(return period)	(<2)	(5)	(<2)	(13)	(8)	(51)	(6)
FL2*	Tide (m)	0.99	0.99	0.99	0.94	0.94	0.94	0.17
	Surge (m)	3.12	3.12	3.12	3.17	3.07	3.17	3.93
	Accumulated precipitation (mm)	128.5	147.5	165.1	192	203.9	200.7	289.2
	Peak flow, m3/s	51.3	87.4	74.9	106.1	113.	143.2	93.1
	(return period)	(<2)	(5)	(<2)	(13)	3(8)	(51)	(6)
SD1	Tide (m)	0.82	0.82	0.82	0.4	0.4	0.4	0.01
	Surge (m)	2.37	2.37	2.37	2.3	2.3	2.3	1.87
	Accumulated precipitation (mm)	24.8	24.7	21.5	17	17.7	15.1	8.9
	Peak flow, m3/s	3.4	9.3	3.3	4.7	1.3	0.9	0.03
	(return period)	(<2)	(<2)	(<2)	(<2)	(<2)	(<2)	(<2)
SD2	Tide (m)	1.01	1.01	1.01	1.13	1.13	1.13	-0.15
	Surge (m)	2.56	2.56	2.56	2.8	2.8	2.8	1.95
	Accumulated precipitation (mm)	24.8	24.7	21.5	17	17.7	15.1	8.9
	Peak flow, m3/s	3.4	9.3	3.3	4.7	1.3	0.9	0.03
	(return period)	(<2)	(<2)	(<2)	(<2)	(<2)	(<2)	(<2)
SD3*	Tide (m)	1.01	1.01	1.01	1.13	1.13	1.13	-0.15
	Surge (m)	3.12	3.12	3.12	3.4	3.4	3.4	2.5640 16
	Accumulated precipitation (mm)	24.8	24.7	21.5	17	17.7	15.1	8.9
	Peak flow, m3/s	3.4	9.3	3.3	4.7	1.3	0.9	0.03
	(return period)	(<2)	(<2)	(<2)	(<2)	(<2)	(<2)	(<2)
SD4	Tide (m)	1.01	1.01	1.01	1.13	1.13	1.13	-0.15
	Surge (m)	2.56	2.56	2.56	2.8	2.8	2.8	1.95
	Accumulated precipitation (mm)	555.3	546.9	526.8	338.2	330.2	316.6	323.7
	Peak flow, m3/s	242.4	319.1	201.7	178.3	168.4	197.0	94.7
	(return period)	(316)	(326)	(28)	(98)	(48)	(301)	(6)
SD5*	Tide (m)	1.01	1.01	1.01	1.13	1.13	1.13	-0.15
	Surge (m)	3.12	3.12	3.12	3.4	3.4	3.4	2.5640 16
	Accumulated precipitation (mm)	555.3	546.9	526.8	338.2	330.2	316.6	323.7
	Peak flow, m3/s	242.4	319.1	201.7	178.3	168.4	197.0	94.7
	(return period)	(316)	(326)	(28)	(98)	(48)	(301)	(6)
IR1	Tide (m)	1.16	1.16	1.16	1.1	1.1	1.1	0.93

	Surge (m)	1.94	1.94	1.35	1.42	1.42	1.42	1.1
	Accumulated precipitation (mm)	187.8	177.8	173.5	98.1	91.6	86.1	58.5
	Peak flow, m <sup>3</sup> /s (return period)	158.5 (56)	201.1 (58)	126.7 (26)	93.9 (5)	85.7 (5)	93.5 (5)	30.8 (3)
	Tide (m)	1.16	1.16	1.16	1.1	1.1	1.1	2
	Surge (m)	2.54	2.54	1.94	2.03	2.03	2.03	1.7
IR2*	Accumulated precipitation (mm)	187.8	177.8	173.5	98.1	91.6	86.1	58.5
	Peak flow, m <sup>3</sup> /s (return period)	158.5 (56)	201.1 (58)	126.7 (26)	93.9 (5)	85.7 (5)	93.5 (5)	30.8 (3)

**Table 4: Overall extent of the inundated area (in km<sup>2</sup>), the relative difference (% change in parenthesis) compared to the FEMA 100yr Flood Zone and dCorr (correlation between differences in flood extent as compared by FEMA, and flow and surge peak)**

CI <sub>s</sub>	FL1	FL2	SD1	SD2	SD3	SD4	SD5	IR1	IR2	dCorr surge	dCorr flow
CI1	1.6	1.8	0.9	1.4	1.9	1.7	2.0	1.3	1.5	0.86	0.40
	(-8.5)	(2.9)	(-48.1)	(-21.7)	(8.3)	(-2.8)	(13.9)	(-27.5)	(-15.9)		
CI2	3.9	4.0	1.9	2.1	2.3	3.7	4.8	1.6	4.9	0.53	0.55
	(134.2)	(139.4)	(-12.7)	(25.6)	(36.3)	(123.7)	(185.2)	(-1.9)	(192.2)		
CI3	4.7	4.9	3.5	4.0	4.3	5.4	7.1	3.2	4.0	0.67	0.70
	(2.6)	(7.5)	(-24.5)	(-10.5)	(-6.2)	(17.5)	(56.2)	(-29.3)	(-12.1)		
CI4/CI5	2.7	3.2	2.4	2.6	3.4	2.9	3.6	2.0	2.4	0.98	0.43
	(-8.3)	(8.4)	(-18.5)	(0.3)	(13.8)	(2.5)	(22.2)	(-32.3)	(-17.3)		
CI6	0.9	0.9	0.7	0.8	1.0	0.9	1.0	0.7	0.8	0.84	0.56
	(3.7)	(13.1)	(-14.9)	(-10.3)	(16.6)	(11.4)	(16.5)	(-20.4)	(-4.8)		
CI7	2.5	2.7	1.6	2.0	2.6	2.1	2.6	1.9	2.3	0.81	0.46
	(1.0)	(12.5)	(-33.9)	(-12.8)	(8.5)	(-10.7)	(7.3)	(-23.5)	(-7.5)		
CI8	3.1	3.5	0.4	2.1	2.6	2.2	2.7	1.1	1.8	0.88	0.67
	(4.5)	(18.4)	(-87.8)	(-28.8)	(-11.1)	(-22.3)	(-8.9)	(-63.1)	(-37.9)		

Note: (-) Area inundated less than FEMA's 100yr zone