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ORIGINAL PAPER

Vulnerability of population and transportation infrastructure at the east bank of Delaware Bay due to coastal flooding in sea-level rise conditions

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Abstract Catastrophic flooding associated with sea-level rise and change of hurricane patterns has put the northeastern coastal regions of the United States at a greater risk. In this paper, we predict coastal flooding at the east bank of Delaware Bay and analyze the resulting impact on residents and transportation infrastructure. The three-dimensional coastal ocean model FVCOM coupled with a two-dimensional shallow water model is used to simulate hydrodynamic flooding from coastal ocean water with fine-resolution meshes, and a topography-based hydrologic method is applied to estimate inland flooding due to precipitation. The entire flooded areas with a range of storm intensity (i.e., no storm, 10-, and 50-year storm) and sea-level rise (i.e., current, 10-, and 50-year sea level) are thus determined. The populations in the study region in 10 and 50 years are predicted using an economic-demographic model. With the aid of ArcGIS, detailed analysis of affected population and transportation systems including highway networks, railroads, and bridges is presented for all of the flood scenarios. It is concluded that sea-level rise will lead to a substantial increase in vulnerability of residents and transportation infrastructure to storm floods, and such a flood tends to affect more population in Cape May County but more transportation facilities in Cumberland County, New Jersey.

Keywords Sea-level rise · Coastal flooding · Prediction · Vulnerability · Population · Transportation infrastructure

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1 Introduction

Global warming and climate change are reshaping our environment in numerous ways, and one of their most significant consequences is a rise in sea level. The median range of global sea-level rise over the next 100 years is projected to be within a range from 0.2 to 0.6 m, and from 0.8 to 2 m under unfavorable glaciological conditions (Pfeffer et al. 2008). According to a recent study, global warming is expected to cause sea level to rise twice as fast along the northeastern US coastlines as compared to the average global rate (Yin et al. 2009). Another important change with regard to our environment is the pattern of hurricanes, although the contribution of global warming and climate change is still a subject of research. Recorded data indicate that hurricanes have become stronger and more frequent, with the number of categories IV and V storms greatly increased over past 35 years along with values of the ocean temperature (Gabriel et al. 2008). While we still remembered the effects from Hurricane Irene that passed over New York City (NYC) in August of 2011, the landfall of Hurricane Sandy directly impacted the New York metropolitan region in October of 2012, further manifesting the change of hurricane pattern in strength and frequency.

The rise in sea level and the change in hurricane patterns present a greater potential for catastrophic flooding along the northeastern coastlines in the United States. What is now considered a once-in-a-century coastal flood in NYC is projected to occur at least twice as often by mid-century and 10 times as often by late-century (NECIA 2007). The increasing potential for coastal flooding puts many residence communities and infrastructure systems along coastlines of the Tri-State region (i.e., New York, New Jersey, and Connecticut) at risk for loss of life and malfunction of facilities. Especially, the areas with relatively low elevations in the region are more vulnerable to coastal flooding. For instance, a large fraction of NYC and its surrounding region lies less than 3 m above mean sea level, and even the seawall that protects lower Manhattan is only about 1.5 m above mean sea level (NYC PCC 2009).

Coastal flooding has attracted considerable attention, and a number of flood maps as a result of many years of study have been available from public sources such as Web sites of the Federal Emergency Management Agency (FEMA). Nevertheless, most of them are obtained with simplified approaches and presented with regional scales, coarse resolution, and low accuracy, and thus updates are necessary (Landers 2009). In addition, these maps consider no effects of sea-level rise and hydrodynamic processes of floods. In recent years, prediction of coastal flooding and its risk assessment in conditions of our changing environment has become a main concern of governmental agencies, academic institutions, and private sectors (NYC PCC 2009; TRB 2008; IPET 2009). In particular, since Hurricane Katrina that caused massive flooding, devastating loss of life, and widespread damage throughout metro New Orleans and the Mississippi Gulf coast, more efforts have been made to improve our understanding of the hydrodynamic processes in flood-prone coastal regions. For example, Ebersole et al. (2010) simulated the flood at Louisiana coastlines during Hurricane Katrina. Lin et al. (2010) studied storm surges along metro NYC coastlines. Condon and Sheng (2012) investigated the flood hazards at southwest Florida in current and future sea-level conditions. In order to assess societal impact of a coastal flooding, a first step is to estimate the affected population. Toward this end, Crowell et al. (2010) estimated US coastal population affected by 100-year flood. Shepard et al. (2012) predicted affected populations of Long Island Sound in metro NYC. Nevertheless, as indicated by Mondal and Tatem (2012), a prediction of affected population could contain a good amount of uncertainty that comes from various sources including data with inadequate resolution for population.

In this paper, we conduct a study on coastal flooding and the resulting vulnerability of the residents and transportation infrastructure at the east bank of Delaware Bay, about 100 miles south of NYC. This region, including Cape May City in particular, is one of the country's oldest vacation resorts, which has a dense population but is frequently flooded during storms (Johnson 1930; Savadore and Bucholz 1993; Watson 2001; Wu et al. 2002). For example, in 2010, the city had a year-round population of 3,607, but in summer, the population of the city community expanded by as many as 40,000–50,000 visitors (Mulvihill 2009; USCB 2010). To compound the situation, this region does not have many roadways, so that any flooding is expected to cause major traffic jams, especially during the peak population season in summers (Chien and Opie 2006). In the past, investigations have been made on flooding in this region and the corresponding risk management. Chien et al. (2000) evaluated the effectiveness of the existing New Jersey State Police Lane Reversal Plan for Routes 47/347 in Cape May County. The evacuation times under varying population, behavioral responses, hurricane levels, and reversal lane operation scenarios were assessed. A detailed discussion on future flooding at conditions of sea-level rise and its impact on population in this region was made by Wu et al. (2002) using a GIS approach and data obtained from a simplified coastal model, SLOSH. Nevertheless, in view of the climate change conditions, this region is now even more vulnerable to coastal flooding, and therefore, it is imperative to better evaluate the flooding risk to its residents and infrastructure to develop plans for evacuation and risk mitigation.

This study is novel in making a prediction of coastal flooding and its impact on residents and transportation facilities (roads, railroads, and bridges) in the region. Different from previous efforts that deal with much larger spatial scales (e.g., Lin et al. 2010), this research focuses on flooding at local regions with small spatial scales and predicts it with high-resolution at residence zones and transportation facilities using a newly developed modeling technique by Tang et al. (2013). In contrast to most previous investigations that essentially use static approaches such as GIS (e.g., Chien et al. 2000; Shepard et al. 2012), this work predicts flooding with a simulation of its dynamic processes. Distinct to most past predictions that merely include coastal waters (Ebersole et al. 2010; Lin et al. 2010), this paper considers floods not only from coastal waters but also from inland runoff, both of which frequently occur during storms. The approach is multidisciplinary, combining efforts from hydrodynamics, hydrology, and transportation areas for a more reasonable assessment of the vulnerability of the study region. In addition, for a more realistic estimate of affected residents, population growth is considered, which is usually not taken into account in previous studies (e.g., Wu et al. 2002). The remainder of the paper is organized as follows. In Sect. 2, a review is presented for the area of study and scenarios to be investigated. Section 3 discusses the methodology of this study. The results of the coastal flooding and its impact are presented in Sect. 4. Section 5 concludes the paper.

2 Area of study and relevant data

As indicated in Fig. 1, this study focuses on the northeast bank of Delaware Bay, covering the west side of Cape May County and the southeastern region of Cumberland County in New Jersey. Cape May County is bordered by the Atlantic Ocean on the east and Delaware Bay on the west, its elevation is at most a few meters above sea level, and its landscape is rather flat and expansive (Polistina Associates 2009). Cumberland County lies at the northwestern border of Cape May County. The Delaware Bay is a shallow water body with mean depth of 7 m and maximum depth of approximately 30 m near its mouth (Muscarella et al. 2011).

It is estimated that the global rate for sea-level rise has been 0.18 cm/year during 1961–2003, but it has escalated to an alarming rate of 0.38 cm/year near the Atlantic City, New Jersey area for the same period (Psuty and Collins 1986; Solomon et al. 2007). IPCC (2007) predicts that the global sea-level rise will be 0.04 m in 10 years (2020) and 0.19 m in 50 years (2060). Considering the global sea-level prediction and using the ratio of the current rate for Atlantic City versus the global rate, that is, 0.38/0.18, and the projection by IPCC, we estimate future sea levels at Cape May as shown in Table 1. Data for 40 years of water surface elevation variation are available at Lewes station, located at the mouth of the Delaware Bay (NGDC 2013). Assuming the histogram of the elevation data follows a log-normal distribution and using statistical analysis (Abramowitz and Stegun 1965), the peak values for water elevation at different return periods are also computed and presented in Table 1.

In the past, this region has experienced a number of storms, which are frequently extra-tropical coastal storms, or so-called nor'easters. Nor'easters occur once per year on average in recent years, and they are very destructive and have created tremendous damage along New Jersey coastlines (Wu et al. 2002). For instance, the Category V nor'easter that stalled off the New Jersey coast for 3 days in March 1962 led to 10 deaths and hundreds of millions of dollars in damage (Savadore and Bucholz 1993; Watson 2001). In this study, a synthetic storm will be used to drive the flood; the time history of the surface elevation at the mouth of the Bay and upstream of the Bay will be that recorded at the Lewes and Reedy Point stations, respectively, during the 1998 nor'easter. Peak values are adjusted as presented in Table 1. Due to the lack of appropriate data, wind effects are not included in this study. For the details of setup for the flood modeling, see Tang et al. (2013). We identify three situations for sea-level rise: current, 10, and 50 year. We also specify three

Fig. 1 Delaware Bay and area of study

Table 1 Projected sea-level rise and storm scenarios (NAVD88)

Scenario		Frequency, projected sea-level rise		
		Current, 0 m	10 year, 0.09 m	50 year, 0.42 m
Storm returning period, peak elevation value	No storm, 0 m	0	1	2
	10-year, 1.63 m	3	4	5
	50-year, 1.79 m	6	7	8

meteorological conditions: no storm, a 10-year storm, and a 50-year storm. The situation with the current sea level and no storm results, or Scenario 0, will not be studied since it has no flooding. Thus, there are 8 scenarios in total to be studied, as shown in Table 1. For example, Scenario 5 represents a 10-year storm and with sea levels 50 years from now, which corresponds to a peak water surface elevation of 1.63 m at Lewes station and the sea-level condition in 2060.

Bathymetric data are obtained from NGDC, and a VDATUM conversion tool is applied to adjust the datum of the bathymetric data to NAVD88 (NGDC 2013; VDATUM 2013). Both LIDAR and USGS DEM data are used to map topographic elevations of the region; the LIDAR data are used only for anticipated flooding zones, and the USGS DEM data are used over the rest of the region (USGS CLIDAR 2013; USGS TD 2013).

The 2010 Census data indicate that there is a total population of 97,200 in Cape May County and 156,900 in Cumberland County as summarized in Table 2. As shown in Fig. 2, the east coast of Delaware Bay is densely populated, especially in the west and north regions of Cape May County where year-round residents and business centers are located, and the seasonal residents tend to live on the east region (Wu et al. 2002). In addition, investigations conducted by Cape May County Department of Tourism and Official Tourism Web site of New Jersey identify 42 campgrounds and 738 hotels in Cape May County, see Fig. 3.

The 2010 Census data are applied to locate transportation infrastructure, including roadway, bridge, and railroad systems, as listed in Table 3. There are 1,618 miles and 2,329 miles of roads in Cape May County and Cumberland County, respectively, which include primary, secondary, local neighborhood, rural roads, and city streets. A total of 172 bridges are located in the two counties as shown in Fig. 4.

3 Methodology

3.1 Hydrodynamic and hydrologic modeling of coastal flooding

Since this study targets a relatively small region and its associated transportation facilities, a high-resolution modeling approach at an affordable expense is desirable. We employ a recently developed modeling system, which couples in a two-way fashion a circulation model to a shallow water model (SWM) and is capable to model a coastal flooding with high-resolution as well as affordable expensive (Tang et al. 2013). In particular, the system consists of the three-dimensional FVCOM and a two-dimensional SWM that is based on a Godunov-type scheme. The two models exchange depth average velocity and surface elevation with each other and advance in time simultaneously as an integrated system, and the two-way coupling is realized by the Schwarz alternative iteration. Both FVCOM and

Table 2 Population 2010 in municipals for Cape May and Cumberland counties (US Census Bureau 2013)

ID	Name	Population	ID	Name	Population
1	Avalon Borough	1,334	17	Bridgeton City	25,349
2	Cape May City	3,607	18	Commercial Township	5,178
3	Cape May Point Borough	291	19	Deerfield Township	3,119
4	Dennis Township	6,467	20	Downe Township	1,585
5	Lower Township	22,866	21	Fairfield Township	6,295
6	Middle Township	18,911	22	Greenwich Township	804
7	North Wildwood City	4,041	23	Hopewell Township	4,571
8	Ocean City city	11,701	24	Lawrence Township	3,290
9	Sea Isle City city	2,114	25	Maurice River Township	7,976
10	Stone Harbor Borough	866	26	Millville City	28,400
11	Upper Township	12,373	27	Shiloh Borough	516
12	West Cape May Borough	1,024	28	Stow Creek Township	1,431
13	West Wildwood Borough	603	29	Upper Deerfield Township	7,660
14	Wildwood City	5,325	30	Vineland City	60,724
15	Wildwood Crest Borough	3,270			
16	Woodbine Borough	2,472			
Cape May County		*97,265*	*Cumberland County*		*156,898*

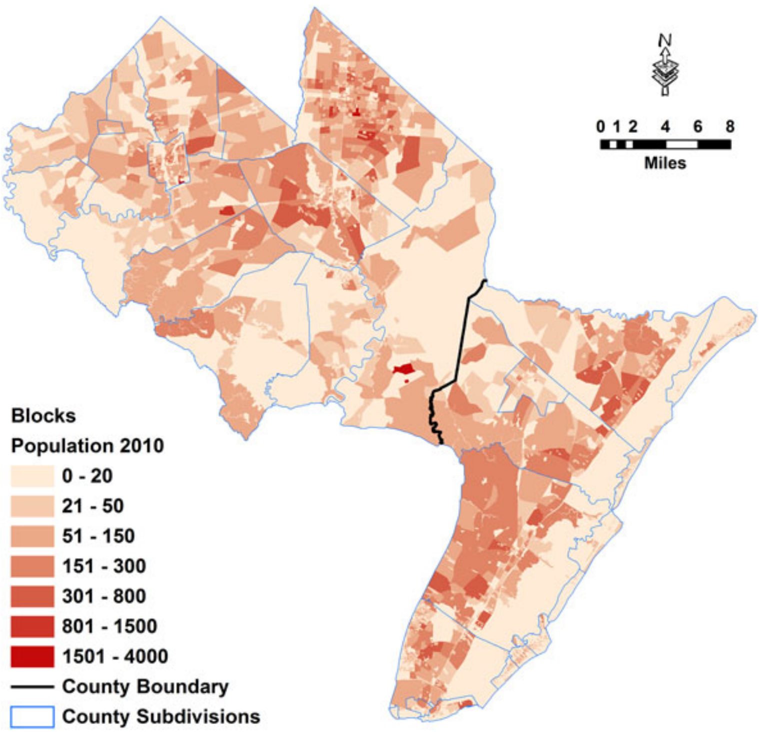


Fig. 2 Population 2010 in Cape May and Cumberland Counties (US Census Bureau 2013)

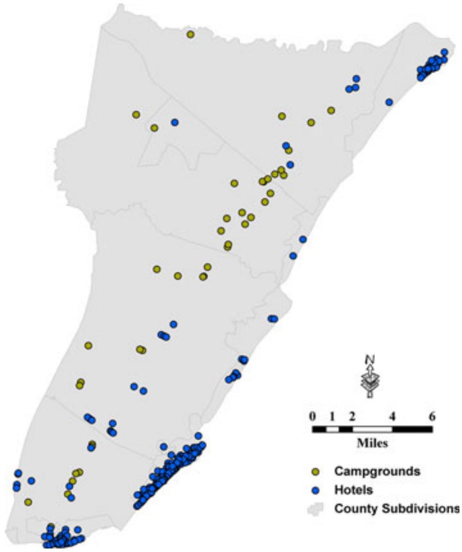


Fig. 3 Campgrounds and hotels in Cape May County (Cape May County Dept Tourism 2013; New Jersey DEP 2013)

Table 3 Roads, railroads, and bridges in Cape May County and Cumberland County (RITA 2013)

County	Roads (mile)	Railroads (mile)	Bridges
Cape May	1,618	51	69
Cumberland	2,329	72	103

the SWM use triangle meshes, and thus they are able to accurately as well as efficiently handle complex flow boundaries of floods. This approach has been tested in a number of example flows, which illustrate that it is able to save a substantial amount of CPU time while achieving a solution accuracy similar to that obtained with FVCOM only. For details of the modeling system, readers may refer to Tang et al. (2013).

FVCOM is used to simulate flow in the main channel of Delaware Bay, while the SWM is employed to model flow in the surrounding shallow water zone as well as the flooding region along the coastlines of Cape May County and Cumberland County (Fig. 5). The overall mesh has 39,976 elements, the SWM uses 37,353 elements, FVCOM employs 3,325 elements, and the two models have some overlapping elements. Spatial resolution of the mesh in the potential flooding region is 50 m or smaller. Calibration of the SWM/FVCOM coupling approach is achieved through application to regular tidal flows in Delaware Bay, or Scenario 0 in Table 1. The observational data of NGDC (2013) at Lewes and Cape May stations during the time period between April 10 and 14, 2010 are used as the southern boundary condition, and that at Reedy Point station for the northern boundary condition (Fig. 5). The observation data provide water surface elevation every 6 min at the three stations. Comparisons between the computed solution and the measurement at Brandywine Shoal, Brown Shoal, and Ship John Shoal stations in the Bay indicate that the coupling approach is able to satisfactorily reproduce the observation data. More details on the calibration of the modeling system can be found in Tang et al. (2013).

In order to account for the inland flooding due to precipitation, a flood potential model is considered. The flood potential is used to estimate the relative likelihood of flooding on a

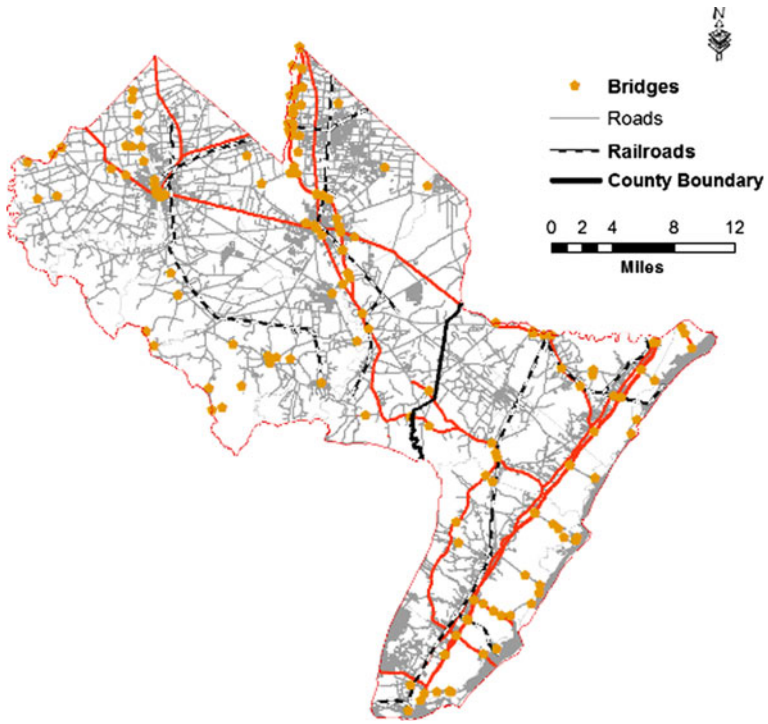


Fig. 4 Roads, railroads, and bridges in Cape May County and Cumberland County (RITA 2013)

per pixel basis. The concept of the flood potential was introduced and successfully tested to accurately reflect the likelihood of flooding of pixels located in different watersheds due to precipitation as well as overflows from rivers and water bodies (Galantowicz 2002; Temimi et al. 2007). It depends on the point's altitude and its proximity to a water body. In this study, we propose the following formula to evaluate flood potential:

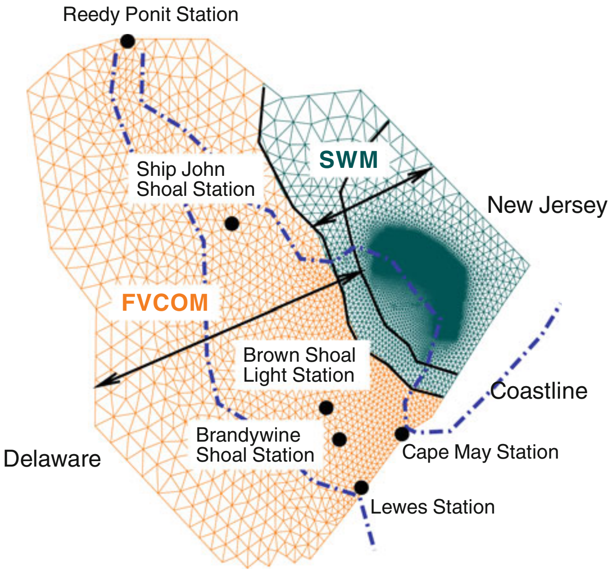
$$f_p = \frac{1}{\left[\frac{\alpha - \Delta_{\mathrm{alt}}}{\alpha} + \frac{d}{d_{\max}}\right]}, \quad (1)$$

where Δ_{alt} is the altitude of the pixel, d is its distance to the nearest water body, and $d_{\max}$ is the maximum value of the distance to the water among all pixels with same Δ_{alt}. α is a parameter, and it is determined as $\alpha = \min\,(-\Delta_{\mathrm{alt}})$, where the minimal is determined over the whole region. Eq. (1) results from a modification of the formula presented in Galantowicz (2002) and Temimi et al. (2007) in which the parameter α is introduced, thus the flood potential becomes a dimensionless number. Consider the effect of Δ_{alt} and ignore the term $d/d_{\max}$ in Eq. (1), one is left with

$$\begin{cases} f_p < 1, & \Delta_{\mathrm{alt}} > 0, \\ f_p = 1, & \Delta_{\mathrm{alt}} = 0, \\ f_p > 1, & \Delta_{\mathrm{alt}} < 0. \end{cases} \quad (2)$$

Therefore, f_p is a decreasing function of Δ_{alt}. Obviously, f_p is also a decreasing function of d. From the hydrologic approach, a point on land is considered to be flooded due to runoff if flooding potential is larger than a critical value:

Fig. 5 Setup and meshes of the hydrodynamic model system



$$f_p \geq f_{p_{\min}}, \tag{3}$$

where

$$f_{p_{\min}} = (1-\beta)\bar{f}_{p_{\min}}, \ \beta \geq 0, \tag{4}$$

and

$$\bar{f}_{p_{\min}} = \min_{D>0}\{f_p\}, \tag{5}$$

where D is the water depth predicted by the hydrodynamics models, and β is a parameter with a small positive value reflecting the degree of inland flooding due to precipitation and drainage failure. The higher the value of β is, the larger the region containing runoff flooding will be. The value of β depends on the rainfall intensity and topography of the study region. In this research, on the basis of sensitivity tests, $\beta = 0.03$ is used, which is a conservative estimate and reflects conditions of a major event like those considered in this study. Actual observation of inland flood extent could allow for more accurate determination of the empirical parameter. It is seen in Eqs. (4) and (5) that the critical value of flood potential is determined as the minimum of f_p in the flooding region predicted by hydrodynamics modeling minus another small portion that accounts for inland flooding due to rainfall. In this sense, the hydrologic model is coupled with the hydrodynamic model.

A location on land is considered to be flooded if it is predicted to be flooded by the FVCOM/SWM system, or by the hydrology approach (3), or by the both. As such, a flooding function is defined as follows:

$$F = \begin{cases} 0, & D = 0, \ f_p \leq f_{p_{\min}}, \\ 1, & D = 0, \ f_p > f_{p_{\min}}, \\ 2, & D > 0, \ f_p \leq f_{p_{\min}}, \\ 3, & D > 0, \ f_p > f_{p_{\min}}. \end{cases} \tag{6}$$

Therefore, flooding happens at a point where

$$F \geq 1. \tag{7}$$

3.2 Estimation of affected population and facilities

Population data from US Census 2010 are used to estimate population in 10 and 50 years for cases under current sea-level conditions. In this study, effects of sea-level rise on future population are not considered because they involve a range of factors such as mortality and fertility rate, migration rate, and labor force migration that are difficult to estimate. Generally, four models are applied in population projections: economic-demographic models, historical migration models, zero migration models, and linear regression models (New Jersey DLWD 2013a).

In this study, the projected population data (2010–2030) were collected from New Jersey Department of Labor and Workforce Development (New Jersey DLWD 2013b) and are applied to determine the population in 10 years. Their projection was based on an economic-demographic model. This model links economic and demographic inputs for the population projection, which has been widely applied in population and labor force projection (Hertsgaard et al. 1978; Anderson 1982; Glavac et al. 2003). The model was developed based on the assumptions of future trends on mortality, fertility, and migration in the projected area, which were adopted from a study conducted by Glavac et al. (2003), and the projected results are shown in Table 4. It was found that the plausibility of a projection declines with increasing departure from the base year, and thus the projection in a 50-year period has not been provided. In order to estimate population in 50 years, or in 2060, the following formula is used:

$$P_{60} = P_{30} \times (1 + \rho)^3 \tag{8}$$

where P_{60} represents the projected population in 2060, P_{30} is the population in 2030, and ρ is the growth rate between 2020 and 2030 predicted by New Jersey DLWD (2013b). The population projected with formula (8) and data of RITA (2013) in each municipality of these two counties are summarized in Table 5.

In view that the campgrounds in Cape May County also have a significant contribution to its population, their information is collected from Cape May County Department of Tourism (2013). Since it is not easy to accurately estimate the trend of campgrounds in 50 years, the current numbers of campsites are used for all of the 8 scenarios.

With the aid of ArcGIS (2013), the predicted population data will be overlaid with the maps of the flooded areas predicted by above hydrodynamic and hydrologic approaches, and the overlapping areas will represent regions where the population is affected by flooding.

Table 4 Projected population in Cape May and Cumberland counties (New Jersey DLWD 2013b)

County	Actual pop		Projected pop		Growth rate		
	2000	2010	2020	2030	00–10	10–20	20–30
Cape May	102,326	97,265	98,600	99,600	−4.9 %	1.4 %	1.0 %
Cumberland	146,438	156,898	165,200	173,200	7.1 %	5.3 %	4.8 %

Table 5 Projected population in municipals on the basis of RITA (2013)

Municipalities	2010	2020	2060
Avalon borough	1,334	1,352	1,408
Cape May city	3,607	3,657	3,807
Cape May Point borough	291	295	307
Dennis Township	6,467	6,556	6,826
Lower Township	22,866	23,180	24,135
Middle Township	18,911	19,171	19,960
North Wildwood city	4,041	4,096	4,265
Ocean City city	11,701	11,862	12,350
Sea Isle City city	2,114	2,143	2,231
Stone Harbor borough	866	878	914
Upper Township	12,373	12,543	13,059
West Cape May borough	1,024	1,038	1,081
West Wildwood borough	603	611	636
Wildwood city	5,325	5,398	5,620
Wildwood Crest borough	3,270	3,315	3,451
Woodbine borough	2,472	2,506	2,609
Cape May County total	*97,265*	*98,600*	*102,661*
Bridgeton city	25,349	26,690	32,248
Commercial Township	5,178	5,452	6,587
Deerfield Township	3,119	3,284	3,968
Downe Township	1,585	1,669	2,016
Fairfield Township	6,295	6,628	8,008
Greenwich Township	804	847	1,023
Hopewell Township	4,571	4,813	5,815
Lawrence Township	3,290	3,464	4,185
Maurice River Township	7,976	8,398	10,147
Millville city	28,400	29,903	36,130
Shiloh borough	516	543	656
Stow Creek Township	1,431	1,507	1,820
Upper Deerfield Township	7,660	8,065	9,745
Vineland city	60,724	63,937	77,251
Cumberland County total	*156,898*	*165,200*	*199,600*

4 Coastal flooding and estimate of impact

4.1 Modeling of flooding

The hybrid hydrodynamic and hydrologic approaches are employed to predict floods under varying sea-level rise and storm conditions detailed in Table 1. The modeling results show that both Cape May County and Cumberland County are flooded over a large area along the coast of Delaware Bay. The hydrodynamic modeling of the flood in Scenario 4 is shown in Fig. 6a, and that resulting from the hydrology approach is depicted in Fig. 6b.

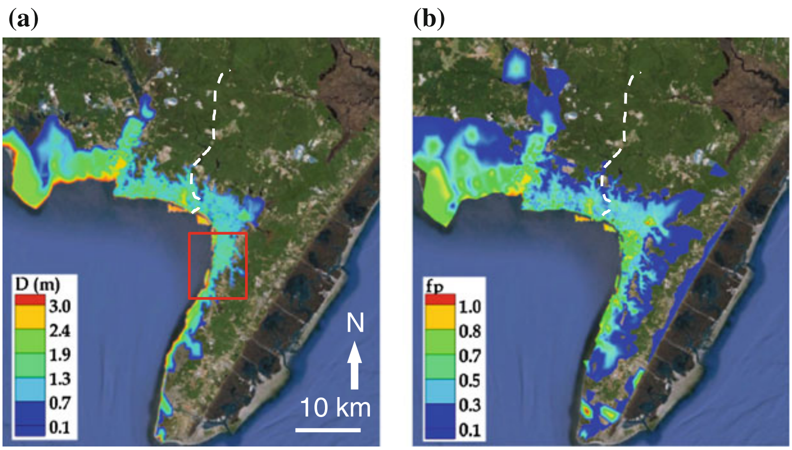


Fig. 6 Prediction of maximum of flood depth by the hydrodynamic approach and flood potential by the hydrologic method considering Scenario 4, or, sea level in 10 years and a 10-year storm. The *dash line* indicates the border between Cape May and Cumberland. **a** Maximum flood depth, **b** flood potential

Interestingly, as seen in Fig. 6, the hydrologic approach predicts a flooded region with a shape larger but similar to that predicted by the hydrodynamic method, and this is considered as a validation for the former. The flooded zone predicted by the former approach is a little larger than that estimated by the latter, and this is because of the fact that the former considers inland flooding resulting from runoff that the latter does not includes.

As indicated in Eq. (7), a point on land is considered to be flooded when either or both of the two approaches predict flooding at this point. According to Eq. (7), the flood map in Scenario 4 is plotted in Fig. 7a. This figure is an overlay of Fig. 6a, b, and its flooding area should cover every location that is flooded in the latter two figures (due to visualization difficulty, the overlay may not be exactly shown in Fig. 7a). For comparison, flooded maps in another few scenarios are also given in Fig. 7. The contrast of Fig. 7a–c indicates the effect of storm strength on flooding, and it shows that the flooded area increases dramatically as a storm occurs. Moreover, the difference among Fig. 7a, d, and e explicitly tells the effects of sea-level rise on flood in this region. A zoom of Fig. 7a, d, and e actually shows that the water tends to flood more places at a higher sea level.

Figure 8a shows quantitative predictions for flooded areas under the 8 scenarios listed in Table 1. In the study region, the flooded area changes considerably with sea level and storm strength. For instance, in the case of a 50-year storm, the flooded area is about 60 km^2 under current sea-level condition, while the area becomes 90 km^2 under sea-level conditions in 50 years. Interestingly enough, Fig. 8a shows that as sea level increases from its current value to that in 10 years, the slopes of the three curves are not the same, meaning that flooded area increases nonlinearly with the sea level at these storm scenarios. Furthermore, from 10 to 50 years, the slopes of the three curves seem to be the same, indicating that the estimated flooded area increases linearly with sea level, regardless of the strength of storms. It is expected that the relationship between the flooded region and sea level is attributed to the geometric features of local topography. Figure 8b presents the temporal variation of the flooded area in case of a 50-year storm, and it shows that the flooded area reaches its peak value in about 35 h after the storm arrives and then declines, changing with time in an oscillating pattern, which clearly indicates the dynamic process of the inundation of the flooding.

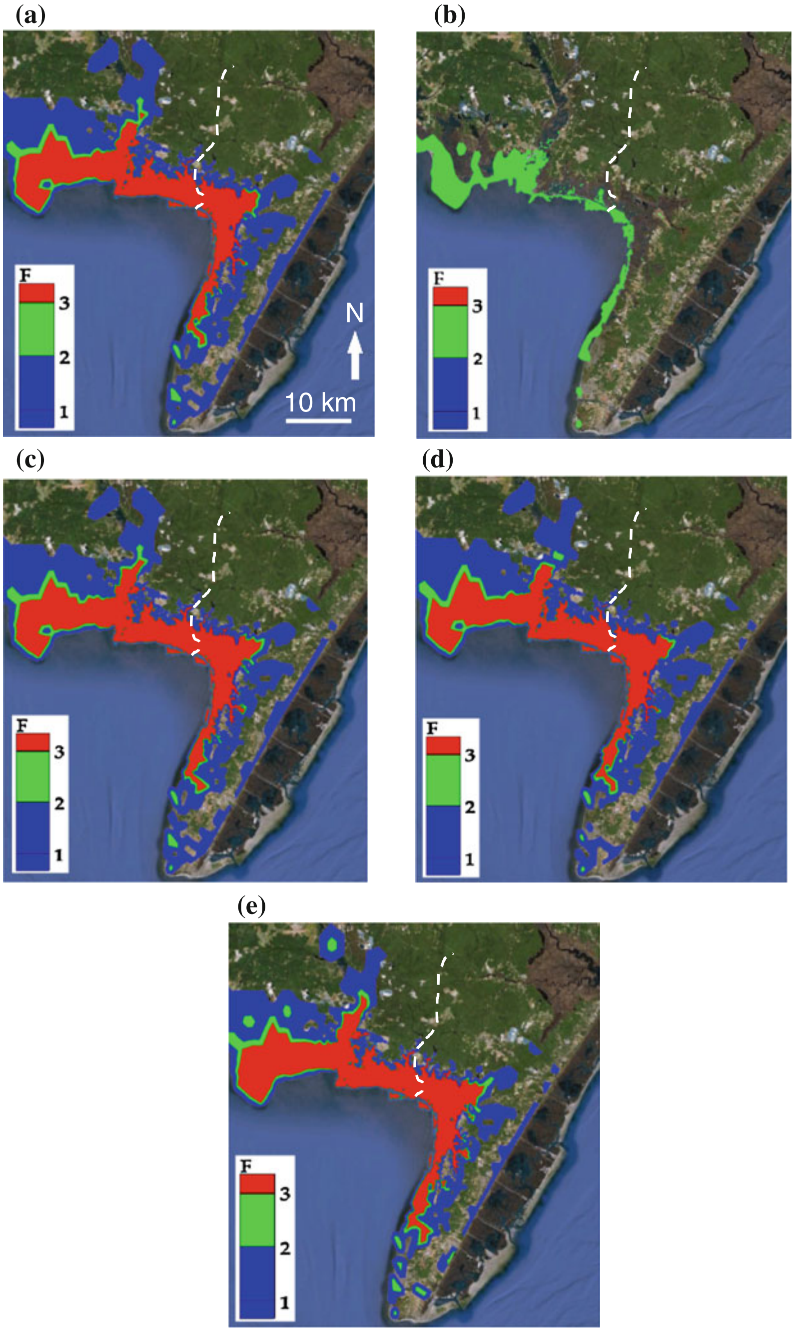


Fig. 7 Prediction of zones flooded by both coastal water and inland runoff ($F \geq 1$).The *dash line* indicates the border between Cape May and Cumberland. **a** Scenario 4, **b** Scenario 1, **c** Scenario 7, **d** Scenario 3, **e** Scenario 5

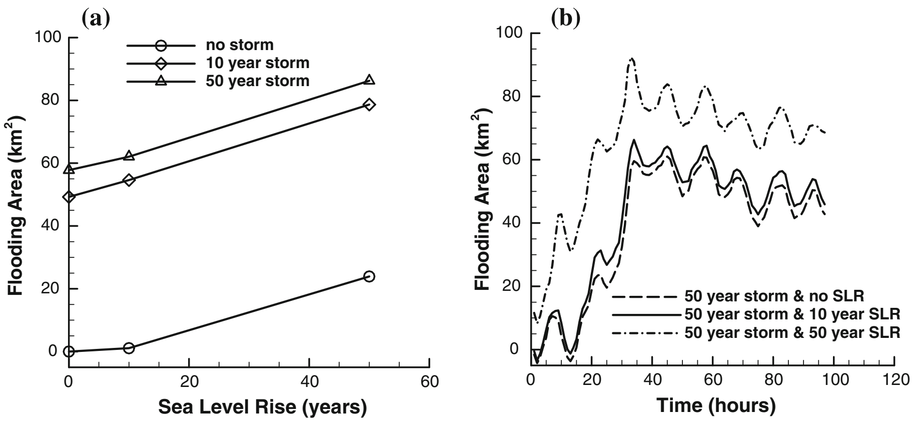


Fig. 8 Hydrodynamic prediction of flood area in Cape May County and its change with time. **a** Flooded area, **b** evolution of flood area

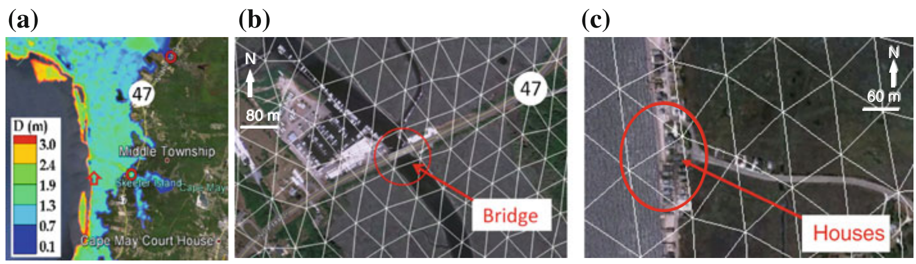


Fig. 9 A zoom view of the hydrodynamic prediction of flooding in Scenario 4 at residence zones and transportation systems within the region marked by the *red rectangle* in Fig. 6a. Houses are marked as *red arrows*, bridges are marked as *red circles*, and these in **b** and **c** are located near Middle Township in **a**. **a** Local flooded region, **b** mesh at a bridge, **c** mesh at houses

The hydrodynamic approach contains the resolution to coarsely resolve residence zones and transportation systems. Figure 9 shows a zoom of the local flooding prediction in Scenario 4 and the corresponding mesh. It is seen from the figure that the mesh is fine enough to bracket residential zones, traffic roads, and bridges, allowing flood predictions to be identified with the mesh points over these regions, thus demonstrating the advantages of the hydrodynamic approach applied in this paper. It should be pointed out that the modeling system is capable of simulating floods with higher resolution as long as the relevant data and finer grids are available. The simulation clearly shows the transportation systems are disrupted; highway 47 within Cape May is cut off by the flood waters; and several bridges along this highway are also in flood zones. More detailed discussions on affected transportation systems will be given in Sect. 4.2.

4.2 Affected population and facilities

On the basis of prediction for flooding in the 8 scenarios considering different sea level and hurricane strength, it is known that floods cover various zones, including urban areas, forests, wetlands, and water bodies, as shown in Fig. 10. In this figure, Scenarios 1, 4, and 7 present flooded zones at different storm strength associated with the projected sea level in 10 years, and Scenarios 3, 4, and 5 show flooded zones at a 10-year storm but different sea

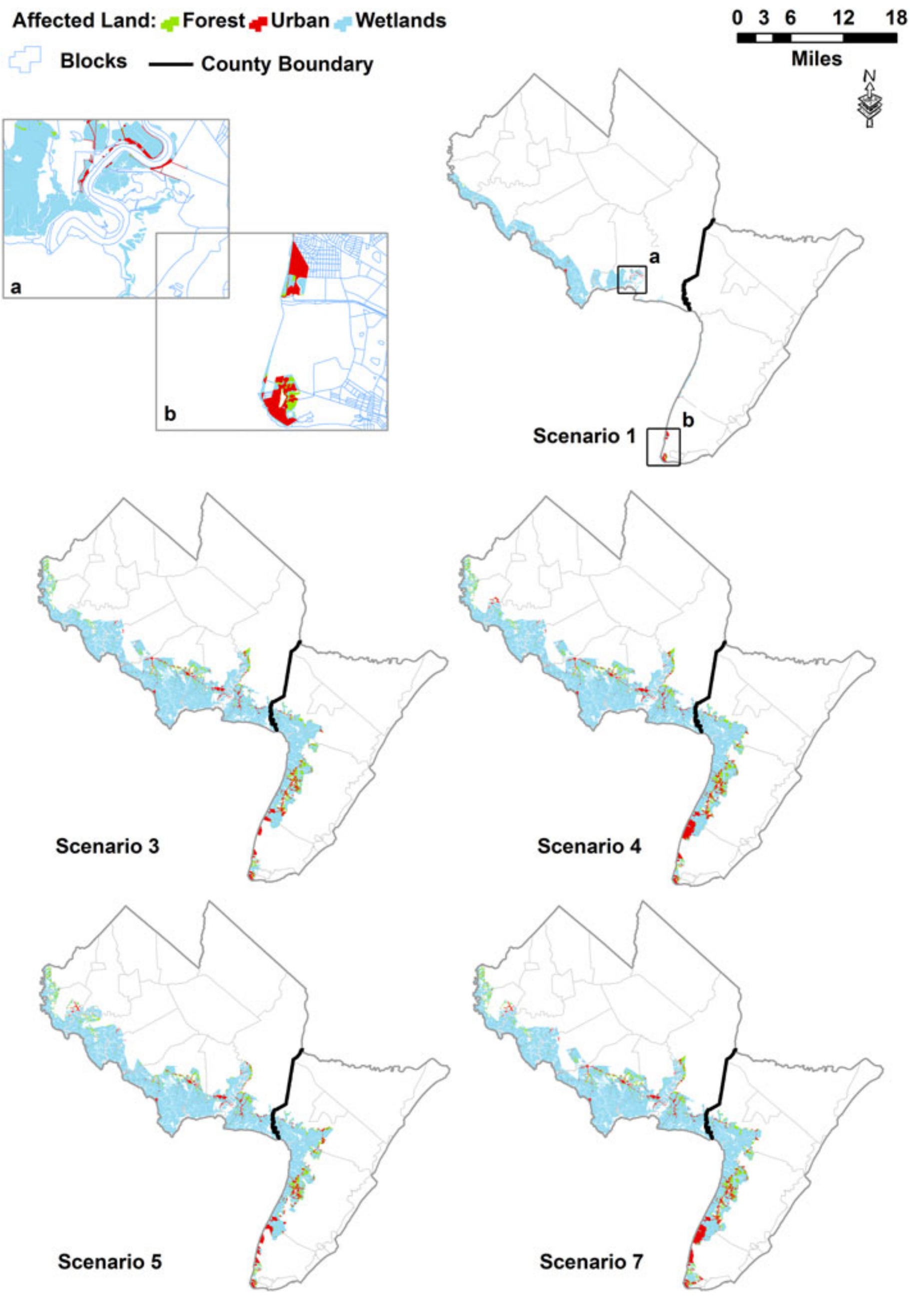


Fig. 10 Prediction of various flooded zones corresponding to Fig. 7

levels. In the following, detailed discussions will be made on the influence of floods on population and transportation facilities.

According to the predicted flooded areas in the 8 scenarios, 4 municipals in Cape May County and 8 ones in Cumberland County are underwater, and the distribution of affected people among the municipals is summarized in Table 6. Figure 11 illustrates the spatial distributions of the affected population in scenarios presented in Fig. 7. It is seen that a stronger storm associated with a higher sea level tends to cause a larger area of flood and thus influence more population. An exception happens in Scenario 2, which has a higher sea level than Scenario 1 but presents a less influenced population in Cape May. This is interesting and may be attributed to the complexity of the flow patterns that are related to coastlines, bathymetry, and land topography. Further analysis on the influenced population as well as transportation facilities is made as follows.

Let us consider the influence of flooding on population at the current sea-level conditions. Numerical values under Scenario 3 in Table 6 show the affected population along the Delaware Bay side when a 10-year hurricane occurs, that is, 2,707 people in the Cape May County and 1,154 people in Cumberland County. For the case of a 50-year storm, or Scenario 6, the number of affected people increases to 3,341 and 1,390 in the two counties, respectively. In both scenarios, the affected population in Cape May County is more than two times of that in Cumberland County, indicating that the population of the former is more vulnerable than that of the latter to coastal flooding as a result of storms. Actually, this is because of the fact that most population in Cumberland lives inland while most of Cape May is located close to the Delaware Bay.

In 10 years, according to the predicted results shown in Table 5, the population increases to 98,600 and 165,200 in Cape May and Cumberland, respectively. As indicated in Table 6, even when there is no hurricane, or under Scenario 1, the total affected population is, respectively, 1,043 and 534 in the two counties because of astronomic tides

Table 6 Affected population under different scenarios

Municipals	Scenario							
	1	2	3	4	5	6	7	8
Cape May Point Borough	254	187	253	255	284	257	259	293
Dennis Township	0	0	116	171	718	193	241	756
Lower Township	596	106	1,246	1,702	5,704	1,637	1,994	6,928
Middle Township	193	122	1,092	1,208	3,118	1,254	1,378	3,571
West Cape May Borough	0	0	0	0	0	0	0	10
Cape May County Total	*1,043*	*415*	*2,707*	*3,336*	*9,824*	*3,341*	*3,872*	*11,558*
Commercial Township	109	281	326	354	481	346	386	522
Downe Township	352	418	367	404	533	403	438	586
Fairfield Township	6	9	15	19	37	23	25	81
Greenwich Township	6	7	21	23	343	147	241	363
Hopewell Township	0	0	0	0	0	0	0	11
Lawrence Township	37	55	59	66	86	66	73	89
Maurice River Township	24	67	337	377	557	371	412	624
Stow Creek Township	0	0	29	34	48	34	40	51
Cumberland County total	*534*	*837*	*1,154*	*1,277*	*2,085*	*1,390*	*1,615*	*2,327*

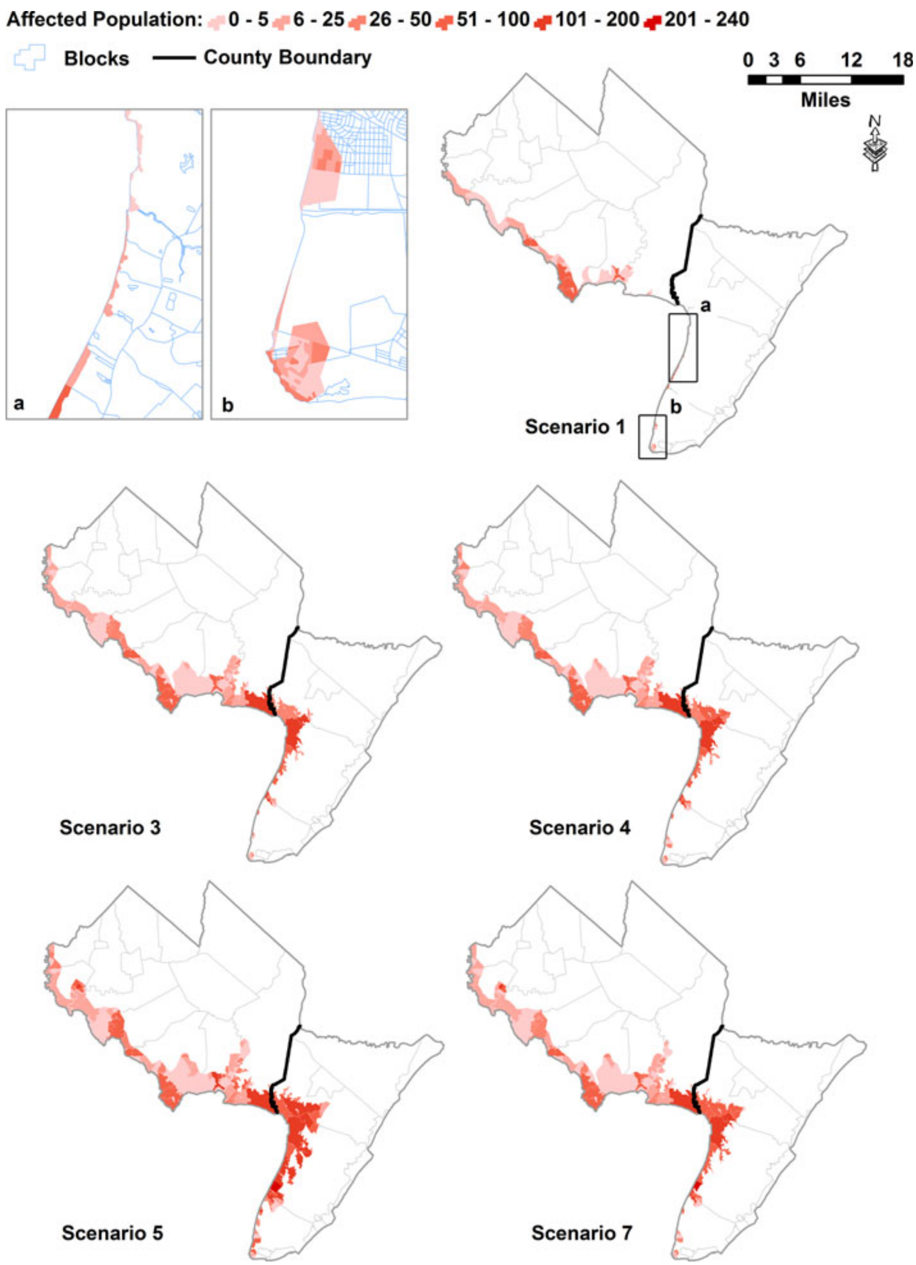


Fig. 11 Affected population distributions in scenarios corresponding to Fig. 7

associated with a higher sea level, clearly indicating the effects of sea-level rise. In this scenario, Table 6 indicates that the people most affected by floods are in Lower Township in Cape May County and Downe Township in Cumberland County. As a storm occurs, by a comparison of Scenarios 3 and 4 or 6 and 7, it is seen in Table 6 that the numbers of affected people increase slightly in both Cape May and Cumberland as a result of sea-level rise. In addition, in all of the cases at this sea level, that is, Scenarios 1, 4, and 7, more people are in flood zones in Cape May County than in Cumberland County. Particularly, from Scenarios 1 to 4, it is seen that the affected population in Cape May has increased by 2 times while that in Cumberland does by only about 1.4 times, confirming that the former is more vulnerable to flooding due to a storm than the latter.

In scenarios subject to 50-year sea-level conditions, according to estimations in Table 5, the population continues to increase. In case of no storm, contradictory to what happens at sea level in 10 years, more people are affected by inundation of tides in Cumberland than in Cape May. However, if a storm occurs, that is, in Scenario 5 or 8, the affected population in Cape May is much larger than that in Cumberland. In addition, the number of influenced people in the former increases faster with rising sea level than in the latter; comparing Scenarios 4 and 5, and 7 and 8, it is seen in Table 6 that the affected population is almost tripled for Cape May County and is doubled in Cumberland. Therefore, during a storm at this sea level, Cape May has significantly more people in flood zones than Cumberland, which is a confirmation of the conclusion obtained in previous two sea-level conditions, and population in Cape May will be more vulnerable than that in Cumberland to coastal flooding due to sea-level rise. However, it should be pointed out that locally Cumberland could be more vulnerable. For instance, in scenario 2, Downe Township in Cumberland has about 418 people that will be affected by sea-level rise and inundation, more than that of any other town in Cape May (Tables 5, 6).

Now, let us analyze the influence of floods on transportation infrastructure. The analysis is mainly based on the locations of transportation facilities rather their elevation because of

Table 7 Affected length (miles) of railroads

Name	Scenario							
	1	2	3	4	5	6	7	8
Conrail RR	0.15	0.04	0.34	0.38	2.66	0.40	0.89	3.22
Old railroad grade	0	0	0.17	0.30	0.55	0.35	0.40	0.60
Railroad spur	0	0	0	0	1.44	0	0.58	1.45

Table 8 Affected length (centerline miles) of roadways

County	Scenario							
	1		2		3		4	
	Total	Highway	Total	Highway	Total	Highway	Total	Highway
Cape May	21.00	0.73	10.15	0.37	39.78	3.02	47.06	3.97
Cumberland	36.90	0	48.75	0	88.86	0.21	94.73	0.23
County	Scenario							
	5		6		7		8	
	Total	Highway	Total	Highway	Total	Highway	Total	Highway
Cape May	130.36	19.85	48.80	4.22	53.97	5.88	150.89	23.34
Cumberland	130.08	0.67	104.19	0.31	115.17	0.35	148.17	1.14

Table 9 Affected bridges

Bridge Name	Scenario							
	1	2	3	4	5	6	7	8
Bidwells Creek	–	–	x	x	x	x	x	x
Branch Of Dennis Creek	–	–	–	–	x	–	–	x
Cape May Branch	–	–	–	–	n	–	–	n
Cedar Ditch	x	x	x	x	x	x	x	x
Cohansey River	x	x	x	x	x	x	x	x
Dennis Creek	–	–	–	–	x	–	x	x
Division Gut	x	x	x	x	x	x	x	x
East Creek	–	–	–	x	x	x	x	x
Fortescue Creek	f	f	f	f	f	f	f	f
Maurice River	–	–	–	–	n	–	–	n
Oyster Creek	x	x	x	x	x	x	x	x
Raccoon Ditch	–	–	–	–	x	–	–	x
Riggins Ditch	–	–	x	x	x	x	x	x
Skeeter Island Creek	–	–	–	–	x	–	–	x
Sluice Creek	–	–	–	–	x	–	x	x
Weir Creek	–	–	x	x	x	x	x	x
West Creek	–	–	x	x	x	x	x	x

Bridge information comes from RITA (2013)

"–" represents a bridge is not located in a flooded area under that scenario

"x" represents a bridge is possibly flooded because it is located in a flooded area

"f" represents a bridge located in a flooded area will be flooded

"n" represents a bridge located in a flooded area will not be flooded

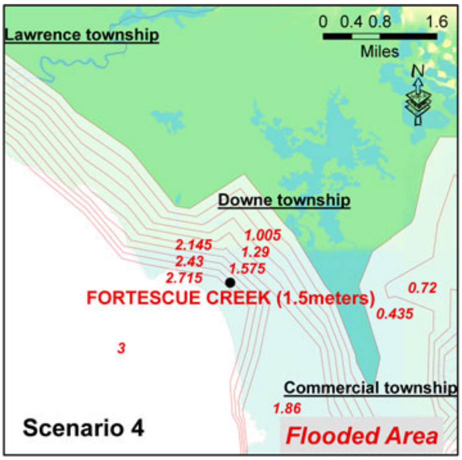


Fig. 12 Example of a flooded bridge, represented by a black dot, near Downe Township in Scenario 4. Contours of flood depth and bridge height are shown in the figure. The bridge has elevation 1.5 m, flood depth is at 2.7 m, and it is therefore underwater and flooded

lack of information for the latter. Table 7 presents the total length of affected segments of two railroads in these two counties in all scenarios, Table 8 shows total length of affected roads (i.e., interstate highway, state highway, US highway, or county highway), and affected bridges are listed in Table 9. It is seen that in general, Cumberland has a longer length of flooded roads than Cape May but a shorter length of flooded highways.

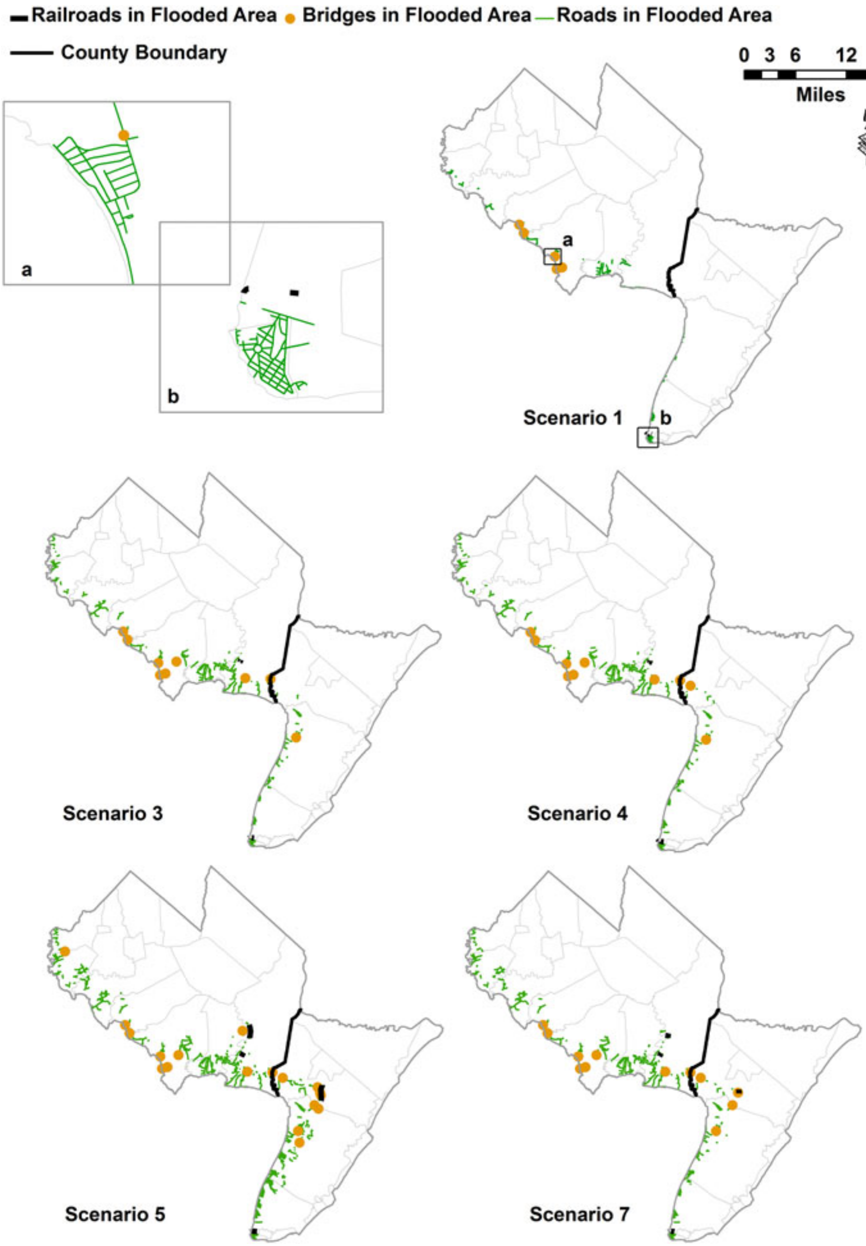


Fig. 13 Transportation facilities located in flood areas

Comparing Tables 7 and 8, we see that roads have a much greater length to become flooded than railroads. Based on National Bridge Inventory (NBI), the heights of several bridges are applied to analyze the affected bridges. For a bridge in the flooded area, its height is compared with the flooding depth surrounding that bridge. If the height of the bridge is higher than the flooding depth, it will not be flooded or underwater. Otherwise, the bridge will be underwater (Fig. 12). For bridges without height information, detailed information on height is necessary to conduct accurate analysis on whether they are underwater.

All flooded facilities (roads, railroads, and bridges) are summarized and marked in Fig. 13. A comparison among Scenarios 1, 4, and 7 in the figure shows that stronger a storm is, more bridges, roads, railroads will be flooded, and a comparison among Scenarios 3, 4, and 5 indicates that higher a sea level is, more bridges, roads, railroads will be influenced by water. The figure also clearly tells that generally speaking flooded infrastructures are mainly located at north bank of Delaware Bay, which is primarily within Cumberland County. Among all of the situations shown in the figure, Scenario 5 has the largest numbers of infrastructure facilities in flood plain.

5 Concluding remarks

We propose a multidisciplinary approach to predict coastal flooding and its impact on residents and transportation systems. A newly developed FVCOM/SWM coupling system is employed to simulate hydrodynamic processes of flooding from coastal water, a hydrologic model is modified to estimate inland flooding due to precipitation, and an economic-demographic model and ArcGIS are used to predict affected population and transportation infrastructure. This approach is applied to study flooding at New Jersey coastlines along Delaware Bay, and its capabilities and performance have been demonstrated in this application. It is shown that the hydrologic model, although very simple, presents a flooded region larger but with a shape similar to that predicted by the hydrodynamic models. The numbers of population and flooded railroads, traffic ways, and bridges are predicted under 8 scenarios of storms and sea levels, indicating this region is at a serious risk for coastal flooding. In the worst situation, which is Scenario 8 or in conditions of a 50-year storm and the predicted sea level in 50 years, about 11,000 and 2,000 residents are affected by the flood in Cape May County and Cumberland County, respectively. In general, a storm flood incorporated with sea-level rise affects more residents in Cape May than in Cumberland, but it tends to influence more transportation facilities in the latter than in the former. Interestingly, the results also show that the flooded area may increase nonlinearly with sea level. It is anticipated that the approach and modeling tools proposed in this paper, together with the predictions for the Cape May and Cumberland counties, will be useful for future plans of evacuation and flood risk mitigation.

It should be pointed out that a flood and its impact on population and transportation systems in the east bank of Delaware Bay involve various uncertainties such as those in strengths and paths of the storms, and their accurate prediction is a challenging task. In order to achieve a more accurate and higher resolution prediction, which the hydrodynamic and hydrologic approaches proposed in this paper are capable of, more detailed data such as those for land topography, population distribution, and bridge heights and more factors such as wind fields are necessary, and a lot of more amount of work will be involved. In addition, actual measurement data such as those for floods in this region can further calibrate and tune the hydrodynamic, hydrologic, and transportation models. Given the performance of our approach demonstrated in this paper, we shall consider these issues as future work.

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