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Flood Vulnerability Assessment and Data Visualization for Lifeline Transportation Network

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16. Abstract

Developing an effective real-time evacuation strategy during extreme storm events such as hurricanes has been a topic of critical significance to the emergency planning and response community. The spatial and temporal variabilities of inland flooding during hurricanes present significant challenges for robust evacuation planning. In this study, a framework for real-time evacuation planning was developed that combines the results obtained from hydrodynamic modeling and traffic microsimulation. First, a fine-scale hydrodynamic model was developed based on depth-averaged 2D shallow-water equations (SWE) to obtain information pertaining to flood depth and velocity for planning evacuation routes during a storm event. Next, a traffic microsimulation was conducted using time-dependent information from the hydrodynamic model regarding the traffic velocities along evacuation routes during an event. An optimization technique was also implemented to reduce the overall travel time by about 6% from that of the base model. The last component of the framework involves combining the results from both models to generate a time-lapse animation of emergency evacuation based on a geographic information system (GIS). The results obtained using this framework could be easily accessed by the general public and decision-makers to enable efficient evacuation planning during extreme storm events.

17. Key Words Evacuation, Flood modeling, Framework, Hurricanes, Traffic simulation, TUFLOW, VISSIM	18. Distribution Statement		
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DESCRIPTION OF THE PROBLEM

In recent years, extreme natural events have challenged and revealed weaknesses in our transportation systems, making design and assessment of the future performance of our civil structures a priority. These structures are often the only means of survival, access, and evacuation for communities during extreme events. Traffic evacuation plans and routes must be decided and analyzed, and transportation infrastructure must be optimized during evacuation to achieve an efficient emergency management response. The United States (U.S.) Nuclear Regulatory Commission (NRC) claimed that approximately every three weeks, there were large-scale evacuations involving at least 1000 people evacuating the danger regions. These evacuations were ordered for many reasons, including natural disasters, wildfire, hazardous materials release, and terrorist attacks, where natural disaster was the leading issue with 58% of total evacuation. However, a successful evacuation requires organizing the necessary manpower, equipment resources and technological support available at the right time, place, and quantity. Communication, coordination, and knowledge to make the process work also play an important role in the success of traffic evacuation. Every three years, there are approximately five hurricanes strike the eastern coastline, resulting in 50-100 casualties. These hurricanes impact our society in numerous ways. Meanwhile, in 2012 there was a very catastrophic natural disaster along the east coast of the United States of America. This disaster was known as Superstorm Sandy, and it took over 100 lives and caused billions of dollars in structural and property damage. It was one of the largest and costliest recorded storms to impact the U.S. Northeast. The majority of this damage was associated with infrastructure, including buildings, transportation links and facilities, water retaining structures, and water/wastewater treatment systems. New Jersey’s aging and degraded stormwater infrastructures threaten daily life, commerce and industry and stunt future economic prosperity (Van et al. 2014). The damage revealed the importance of appropriate preparation and response strategies in the face of extreme weather events. The heterogeneous disasters challenge transportation planners, engineers and emergency managers to estimate the time needed to evacuate people from a threatened area to a safe place efficiently and smoothly during hurricanes. Prior estimation of the evacuation time also could be used to identify the evacuation strategies and optimize the existing roadway capacity. The federal government mandates that each state agency have to develop its own evacuation strategies and guidelines before any major hurricanes, cyclones or storms hit the land surface. These strategies should be evaluated and practiced before identifying their efficiency of these strategies. Moreover, government agencies are responsible for updating strategies timely based on recent experiences. However, there were still huge delays and long congestions on our roads and highways while evacuating people as they failed to optimize the existing transportation structure during evacuation. In particular, bridges and other transportation networks are often subject to extreme events (e.g. earthquakes, hurricanes, riverine floods and even vicious attacks) throughout their lifetime. Furthermore, the capacity of structural systems to resist hazards is reduced in time due to aging and deterioration. Understanding the adverse impact of natural hazards on the life-cycle performance of transportation networks and their system interconnectivity on the communities they serve can lead to improved pre and/or post-hazard vulnerability mitigation strategies. Such work can ultimately have a tremendous long-lasting impact on community resilience and mitigation efforts. As a result, there is a need for providing a robust methodology to quantify the metrics of vulnerability and resilience for vital transportation networks with respect to their location, size of the population they serve, and availability of other means of access and evacuation. This proposal aims to establish a framework for time-variant loss and resilience assessment of major roads and transportation networks and the impact of their functionality reduction on the surrounding communities for extreme storm surge events. Additionally, the probabilistic changes in the hazard intensity and frequency resulting from climate change on the total life-cycle hazard loss will be considered.

APPROACH

The objective of this project was to develop a 2D hydrodynamic model to assess the extent of flooding due to extreme weather events like Hurricane Sandy and use this hydrodynamic model to evaluate the efficiency of existing transportation infrastructure. Therefore, we needed to incorporate a network representation of the transportation systems, the generation of flood event scenarios, and a method to estimate transportation link vulnerability. The transportation link vulnerability was evaluated in terms of its service disruption related to the number of interrupted vehicles and the durations of interruption. Frequency analysis of annual peak flow data was collected at a stream gauge to estimate the flood magnitude and frequency and generate the flood scenarios. Furthermore, this evaluation can be used to develop a decision-support framework for extreme evacuation planning to prepare the communities living in critical regions.

METHODOLOGY

To evaluate the proposed approach, in this study, we selected Brick Township in northeastern Ocean County in the U.S. state of New Jersey (NJ) (Fig. 1). According to the U.S. Census, Brick Township is one of the largest municipalities and ranks third in terms of population in Ocean County, NJ (U.S. Census Bureau, 2010). Brick Township consists of 25.71 square miles of land and 6.60 square miles of water, for a total area of 32.31 square miles. Although most of this township is situated on the mainland, three ocean beaches are located on the Barnegat Peninsula that separates Barnegat Bay from the Atlantic Ocean. The township consists of five major watershed areas (i.e., Manasquan and Metedeconk Rivers, Beaver Dam, and Kettle and Reedy Creek Watersheds). Brick Township has a relatively high density of New Jersey waterfront property, with access to several major state highways traveling northeast to southwest through the central portion of the township. This township was severely affected by Hurricane Sandy in 2012, and all residents were under mandatory evacuation orders during the event. Severe flooding on evacuation routes such as Routes 70 and 35 caused the complete washing away of roads and delayed emergency evacuation efforts (SRPR, 2012). In this section, we discuss the hydrodynamic and traffic modeling tools utilized in this study, our data collection and pre- processing, and the integration technique employed in the hydrodynamic and traffic microsimulations. Table 2 highlights key modeling tools, necessary inputs and outputs, and the runtime for each model used in this study.

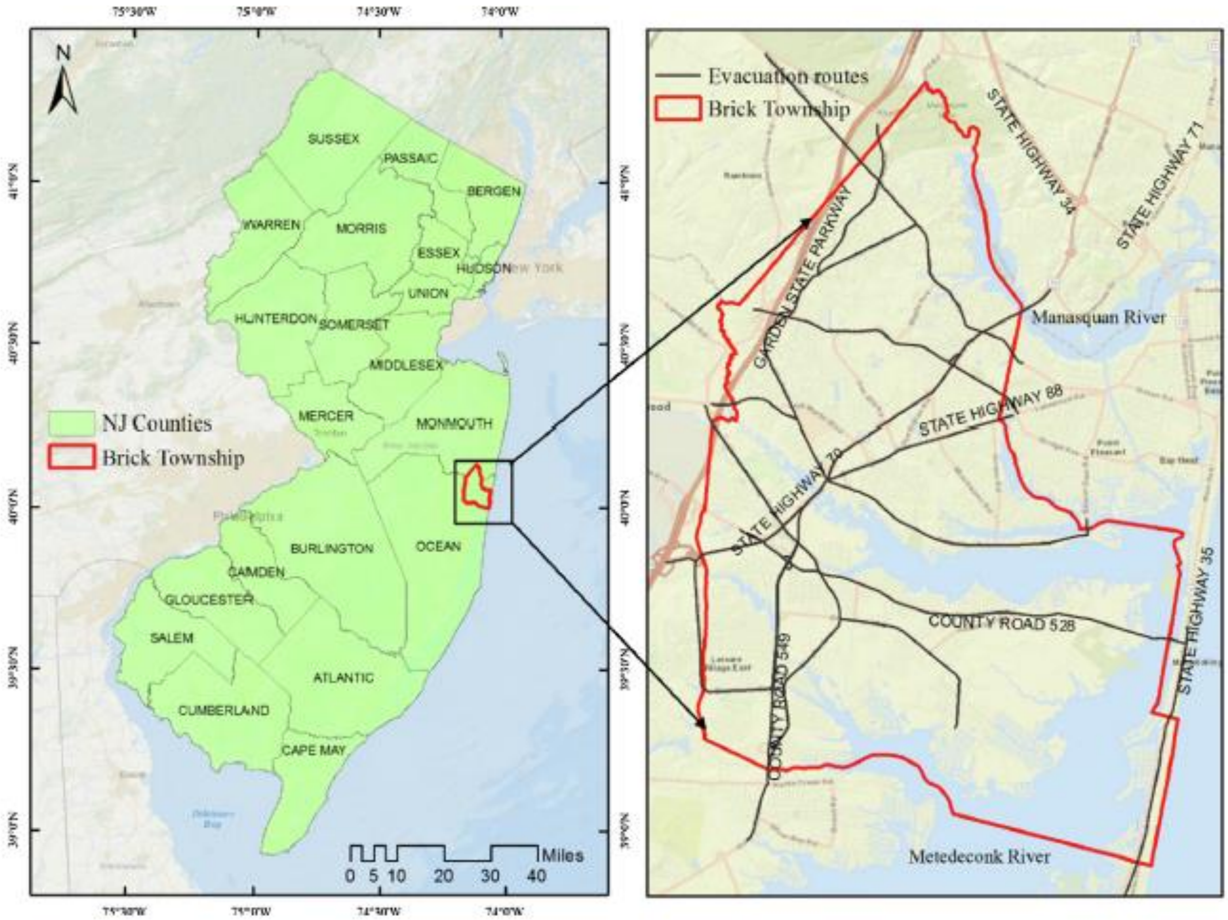

Fig. 1. Map of study area, main river channels and evacuation routes for Brick Township

Table 1
Key modeling tools, necessary inputs/outputs, and runtime for each model

Models/Tools	Inputs	Outputs	Processing time (minutes)*
Hydrodynamic model: TUFLOW	Topographic information, landuse/landcover, water level vs. time, discharge vs. time, rainfall, friction factor	Flood depth, flow direction flow velocity	~50
Traffic microsimulation: VISSIM	Vehicle types, classes, speeds, compositions, routes	Travel time, delay	~40
Data visualization and processing: R, ArcGIS & XML	Road network in ESRI shapefile (.shp) format, temporal flood depth and flow velocity maps from TUFLOW, spreadsheet containing road segments exported from VISSIM, spreadsheet containing road closure information	Traffic velocity maps, dynamic evacuation scenarios, .kmz, .kml, export to ArcGIS online	~30

* Processing times in this table are based on the study area and available computational resources.

Model developments

Evacuation traffic network modelling

In this study, the PTV VISSIM traffic microsimulation package was utilized to evaluate different evacuation scenarios under different extreme weather events. The main reason for this selection was the ability of this package to simulate detailed vehicle interactions at specific locations in the transportation network. This software was also used for the dynamic rerouting/detouring of evacuation vehicles because it can support the modeling of dynamic interactions between vehicles and transportation infrastructure systems in the Component Object Model (COM). Any desired functionality provided by the COM interface within VISSIM must also be modeled in the COM object model (Fellendorf and Vortisch, 2010). The objects and their respective attributes within VISSIM are structured in a hierarchy. To accurately model an extreme storm event during which some roadways will be subject to closure, dynamic routing must be used. Dynamic assignment is useful for modeling the decisions made by drivers in choosing a route based on a set of available alternatives. This type of decision making is a specific example of the discrete choice modelling technique used in modern traffic assignment methods (Fellendorf and Vortisch, 2010). Within VISSIM, an iterated simulation approach is employed tobmodel the dynamic routing. A network is modeled through multiple iterations, and drivers choose routes based on the travel costs obtained in the previous simulation (Fellendorf and Vortisch, 2010). When addressing assignment-based problems, a more abstract view is adopted by the network. VISSIM considers intersections as nodes and the roads between intersections as edges of a conceptual framework. The dynamic assignment calculations are based on a node–edge topology (Fellendorf and Vortisch, 2010). The travel time for individual networks is determined by the following equation:

$$T_e^{p,q} = \lambda . TM_e^{p,q} + (1-\lambda) . T_e^{f-1,q} \quad \text{Eq. (1)}$$

Where $T_e^{p,q}$ are the anticipated and measured travel times for a certain edge e during period p for iteration q, p and q are indexes for the iteration and evaluation intervals, respectively, e is the index for the edges, and λ is a smoothing factor. The optimum route choice for VISSIM is based on a general cost function comprising a linear combination of parameters such as travel time, distance travelled, and cost of travel. Users can assign different weights to each of these components based on their preferences. Travel demands are specified by the utilization of an origin–destination matrix. The model utilizes an iterative approach to search for the best route for the origin–destination pairs. Because of the dynamic characteristics, travel times will also change within iterations, which thus enables the determination of an optimal route via the simulations. The collection of optimal routes then serves as a reference for future iterations. The first iteration will have no travel time history for reference, so the cost is initially evaluated by distance rather than travel time. The travel demand distribution of an origin–destination pair is defined by Kirchhoff's formula (Fellendorf and Vortisch, 2010), as shown in Eq. (2):

$$p(R_m) = \frac{U_m^l}{\sum_n U_n^l} \quad \text{Eq. (2)}$$

Where Um represents the utility of route m, p (Rm) is the probability of selecting route m, and l is defined as the sensitivity of the model. A comprehensive literature review was conducted to identify the current practices and strategies used for extreme weather events in the selected study region, Brick Township. Furthermore, the critical regions and location of shelters, hence the origins and destinations, were established based on the literature review. The next step was to develop a detailed microsimulation model of the existing evacuation transportation infrastructure in the VISSIM environment, which served as the base model for the entire study, and then to release the evacuation traffic onto the road networks based on the flooding scenarios (Fig. 2). The base model was calibrated using the data collected from a field survey conducted by the research team including travel times, speed, and turning percentages. Fig. 3 shows the road segments for which field surveys were conducted in the study area. The collected data was later compared to model simulated travel times for the calibration performed during the simulation iterations along the same road segments. We note that travel time was used to calibrate the simulation model because it is a common performance measure used in traffic studies. Model accuracy was determined by comparing the observed travel times with the VISSIM-simulated travel times along the calibration segments illustrated in Fig. 3. Due to the lack of actual traffic data during hurricane evacuations, similar to other previous studies (Wolshon and Dixit, 2012; Ballard, 2007), we calibrated the model using normal daily traffic with different assumptions that approximated the emergency traffic conditions.

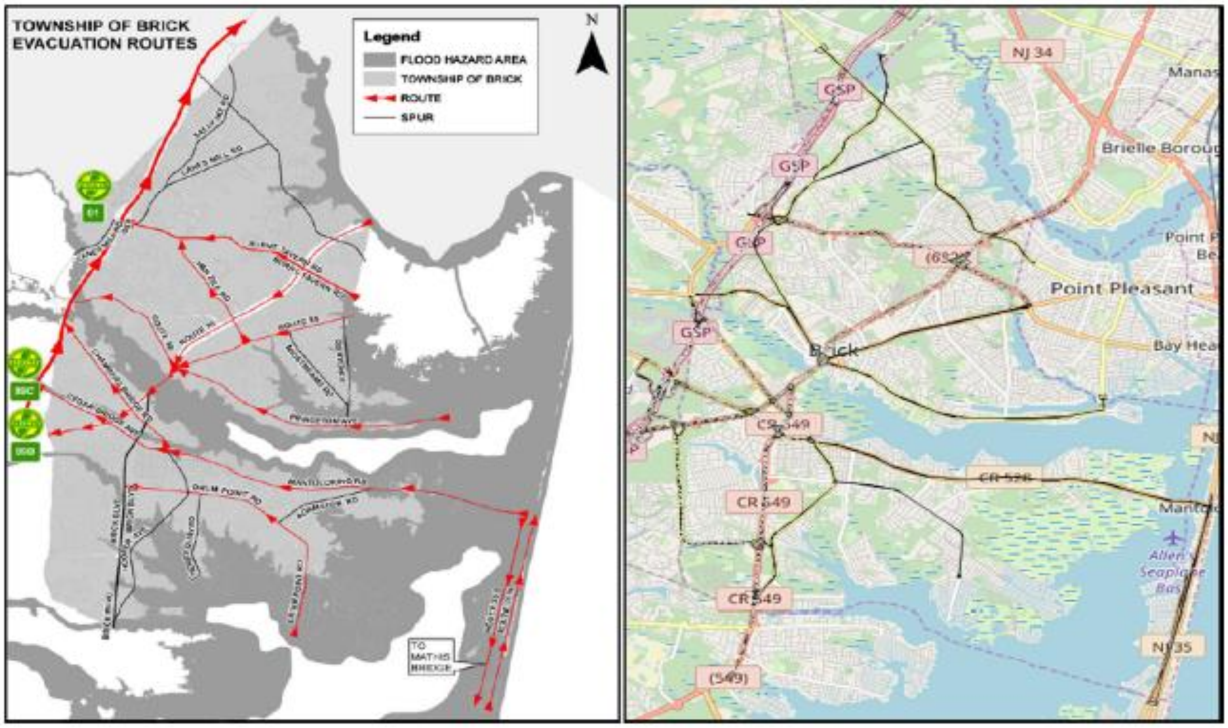

Fig. 2. Traffic evacuation network of Brick Township; collected evacuation route (left) and microsimulation model (right).

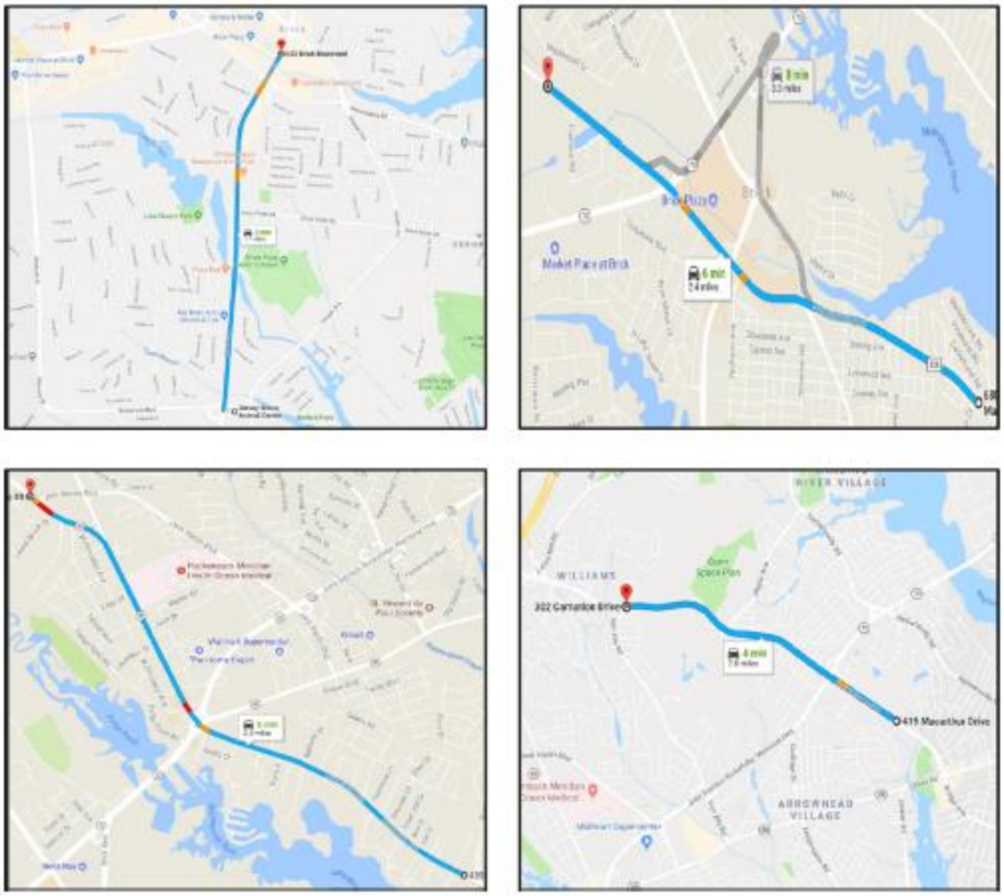

Fig. 3. Calibration segments used in traffic microsimulations

Specifically, the model was calibrated using the normal daily traffic flow, based on annual average daily traffic (AADT) values in 2012–13, obtained from the New Jersey Department of Transportation (NJDOT, 2018). By comparing the NJDOT evacuation traffic volume with the historical daily traffic count volume, similarities and dissimilarities in the vehicle patterns were explored. Specifically, we compared the traffic volumes in the studied routes before and during the Hurricane Sandy evacuation plan and identified the similarities in the vehicle volume patterns (there was only a 15 percent difference in traffic volumes). With respect to driver behaviors during mass evacuation, Tu et al. (2010) found that increases in the acceleration rate and in the maximum speed have no significant impact on the evacuation clearance time.

Hydrodynamic model development

Fine-scale hydrodynamic modeling of a floodplain requires a numerical tool with the capability for large-scale flood modeling to ensure enough detail in terms of the depth and extent of a flood event. For this study, the SMS-TUFLOW model was utilized due to its capacity for large-scale flood modeling at very high resolution, ability to perform flood hazard analysis at a two-dimensional level, and its support of spatial data processing and viewing capabilities. SMS is primarily a GIS-based system for developing, running, and processing water surface models using a wide variety of river and coastal hydraulics models. The two-dimensional solution algorithm for TUFLOW was based on the work of Stelling (1983). Shallow-water equation (SWE) algorithms are based on Navier–Stokes equations for the motion of fluid in a two-dimensional horizontal medium, while conserving the laws of mass and linear momentum in a Cartesian coordinate system

(TUFLOW, 2008). An SWE solution algorithm can adequately model different hydrodynamic phenomena such as gravitational wave propagation, momentum transportation during advection, the effect of bottom friction and the Coriolis effect due to the Earth's rotation, changes in atmospheric pressure, etc. The three main data components in hydrodynamic modelling include topography, land use/land cover (LU/LC), and water level vs. time. Topographic information about the study area was collected as high-resolution LIDAR point clouds and then converted into a digital elevation model (DEM) at 0.5-m spatial resolution. As LIDAR cannot produce accurate information underwater, the LIDAR-derived DEM includes only the topography over land.

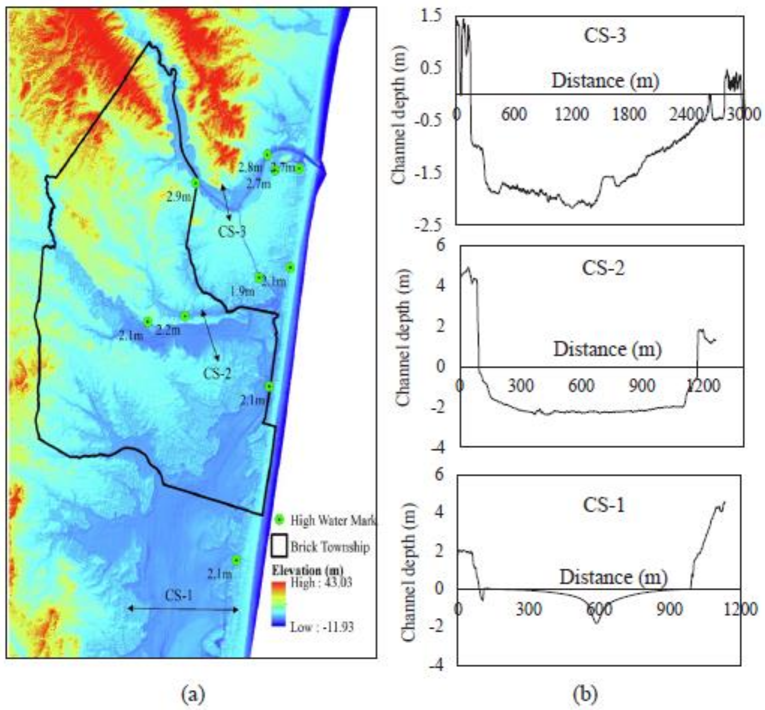

Fig. 4. (a) Elevation and observed high water marks (HWMs) during Hurricane Sandy (b) channel cross section (CS) at three different locations in the study area.

We know that physical processes in coastal environments are dominated by the geomorphology of both the land topography and underwater bathymetry, so it was necessary to merge the DEM file with bathymetry data to produce seamless topobathymetry data. The bathymetry data corresponding to our study area was obtained from the Coastal National Elevation Database (CoNED) Project. This bathymetry data was first resampled to match the spatial resolution and then merged with the LIDAR-derived DEM data in ArcGIS via a mosaic operation. Both the LIDAR-derived DEM and bathymetric data were vertically referenced to North American Vertical Datum (NAVD, 1988), so no vertical datum transformation was performed. Fig. 4 shows the seamless topobathymetric data generated for hydrodynamic modelling. Overall, being adjacent to the ocean to the east, Brick Township has a low-lying topography. The western and northwestern areas of Brick Township have higher elevations than its eastern region (Fig. 4a). The topobathymetry used in the study also indicates the accurate channel delineation within the study area, as shown in Fig. 4b for three different cross sections (CSs). There were 10 HWMs within the model domain, as collected and verified by the U.S. Geological Survey (USGS), which were used to calibrate and validate the model-simulated flooding during Hurricane Sandy. The land use data was obtained from the New Jersey Department of Environmental Protection (NJDEP) in 2012 by the Bureau of Geographical Information Science (GIS) with the following categories: Agriculture, Barren Land, Forest, Urban Land, Water, and Wetlands. The required water-level data as an upstream and downstream boundary condition (BC) was obtained from the USGS current water data (source: https://maps. waterdata.usgs.gov/). An important step in hydrodynamic modelling is defining the mesh size of the 2D domain. The mesh size must fulfill two important criteria: (i) it must be fine enough to reproduce the physical processes during flooding and thus ensure a stable model and (ii) the runtime must be minimized to ensure computational efficiency. It is also recommended that a fine mesh be provided across the channel where complex flow condition might occur during flooding. Considering all these criteria, a mesh size of 7.5 m was implemented to ensure model stability and computational efficiency for the model domain. The model was also discretized using a 3-second time step to ensure numerical stability. An appropriate Manning's friction factor was implemented so that the flood flow reflected the real-world scenario in the channel as well as in the floodplain. Model calibration was performed by changing Manning's friction factor and the initial water level in the channel. To achieve faster computation, we utilized a graphics processing unit (GPU) for parallel computing. The GPU has 2560 CUDA cores and runs well over one hundred times faster than when utilizing only a central processing unit (CPU) for hydrodynamic modelling.

Integration of hydrodynamic and traffic evacuation models

The evacuation network for the traffic microsimulation was divided into road segments for which we computed the velocity distributions over time. Whether these road segments would be available or closed for evacuation was determined based on the flood depth or inundation level. According to FEMA (2010), 0.15 m of water can reach the bottom of a passenger car and cause loss of control, 0.3 m of flooding can cause cars to float, and as low as 0.61 m of flood flow at a velocity of 0.89 m/s can carry away the majority of vehicles. Most of the departments of transportation (DOTs) around the U.S have adopted similar types of thresholds for road closures. The framework in this study adopted a threshold of 0.3 m of flood depth with 0.6 m/s of flow velocity for determining whether to close the road segments of evacuation routes. This determination was made by extracting the flooding characteristics from the hydrodynamic modeling along the evacuation routes. The threshold can be changed as needed based on the requirements of the government or other decision-making agencies responsible for emergency evacuation planning. The accuracy of dynamic flood prediction at street level plays a crucial role in the overall evacuation. Over or under predictions of flood depth or misrepresentation of flood extent can potentially lead to a failed evacuation effort. To ensure an accurate representation of flood characteristics, the hydrodynamic modeling results were exported at a very high resolution (3 m) to capture street-level flooding. Several geospatial techniques, as well as statistical parameters, were used to assess the accuracy of the hydrodynamic modeling by comparing it to various sources of observed data for Hurricane Sandy (Section 3.1). The level of precision obtained from dynamic traffic assignment models depends heavily on data availability. We note that compared to conventional travel demand models, dynamic traffic assignment requires a significantly larger volume of data, which may not be readily available in most scenarios. In this study, we used the default values for dynamic traffic assignment. Decision-makers must evaluate the anticipated level of precision and the available resources and select and use the appropriate model from the range of dynamic traffic assignment and conventional travel demand models. The results of the 2D hydrodynamic models were integrated into the traffic evacuation models using a code controlled by Visual Studio (Halvorson, 2010). Based on the predicted flooding depth, the future availability of a road segment was computed by the hydrodynamic model, and this information was passed to the VISSIM model. Next, this information was utilized to detour the evacuating traffic in advance. The detour routing was coded based on the suggestions provided in the Interactive Detour Route Mapping (IDRuM) application (Arva, 2015), a web-based application developed in the joint venture of the Delaware Valley Regional Planning Commission (DVRPC) and the Pennsylvania Department of

Transportation (PennDOT).
Making updates in the evacuation traffic flow can serve to optimize the usage of existing transportation infrastructures and, hence, reduce the overall network evacuation travel time. The network travel time was recorded at fifteen-minute intervals. Fig. 5 shows the integration algorithms used in this framework. At first, the evacuation was initiated without considering the effect of flooding, since the evacuation routes were not flooded, or the inundation depth had not met the threshold for a road closure. During this step, rerouting decisions were made to prevent traffic congestion and facilitate the exit of vehicles from vulnerable regions since the effect of flooding was not prominent. Once roads were flooded, certain routes were closed, as evacuation could not proceed along those specific routes. During this step, traffic congestion or the formation of bottlenecks was anticipated, so rerouting decisions were made with consideration of optimum travel time and to ensure the free flow of traffic.

FINDINGS

The results of the hydrodynamic and traffic simulation models could be divided into two sub-sections. However, the results of the evacuation traffic velocity distribution were sketched in Google Earth format.

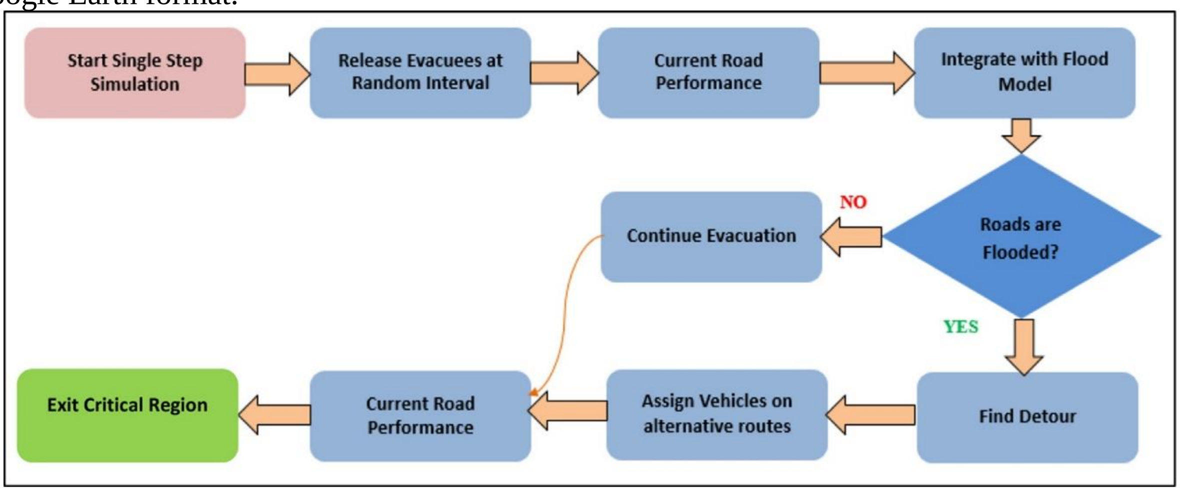

Fig. 5. Integration algorithms used in traffic and hydrodynamic modeling.

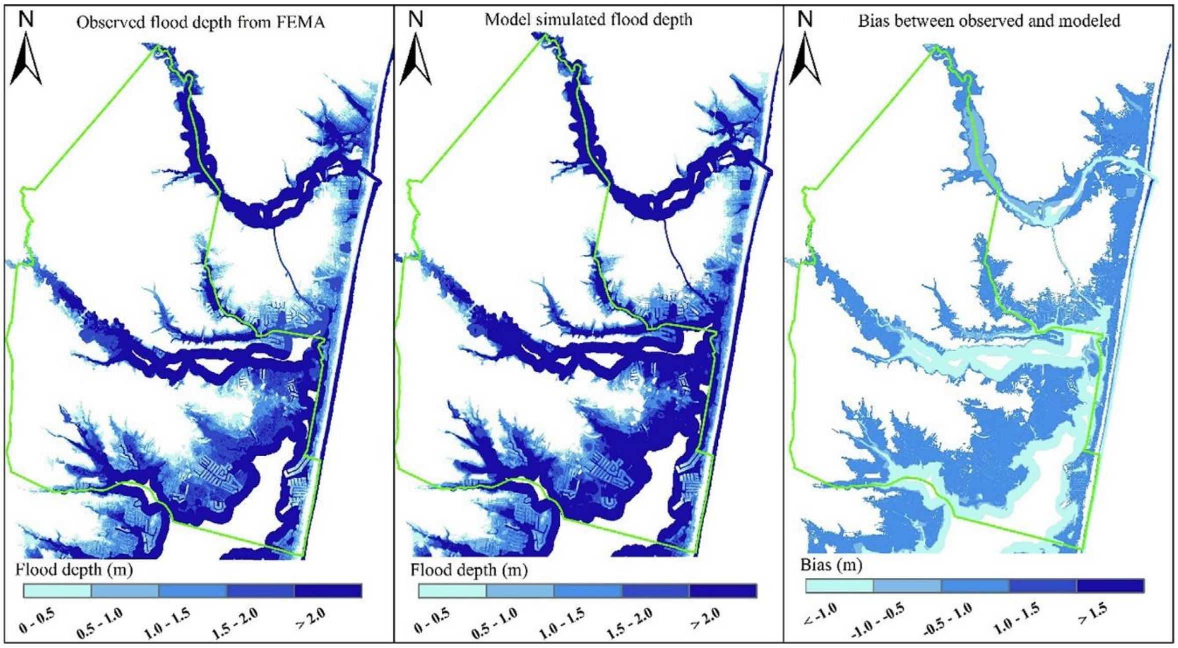

Fig. 6. Comparison of observed and model-simulated inundation depths for Hurricane Sandy. The solid line outlines administrative boundary of Brick Township, NJ.

Results from hydrodynamic modeling

In this study, we considered the Hurricane Sandy event. The dynamic flood simulation contains information about flood depth at fifteen-minute intervals. From all these time intervals, the maximum flooding was extracted in terms of maximum flood depth and extent. This maximum flooding information from the hydrodynamic modelling of Hurricane Sandy was then compared with the observed Hurricane Sandy impact analysis from the official FEMA Modelling Task Force, also known as FEMA-MOTF (FEMA, 2014). This high-resolution (3 m) product was created from a fine-scale DEM, field-verified HWM data collected during Hurricane Sandy, as well as surge sensor data from the USGS. The results indicate that the model predicted the spatial variation of inland flooding very well (Fig. 6) with a small degree of overestimation (~0.61 m) near the river channel. The overall difference in the observed and model-simulated flooding information was calculated by subtraction, and the differences were plotted to show the bias between the observed and simulated data (Fig. 6).

The inland flooding or inundation level has a more crucial role in our framework as it determines whether a certain road segment will be closed or remain open during an emergency evacuation. The friction factor for surface runoff has been adjusted carefully to ensure that our hydrodynamic model reflects the actual flooding during Hurricane Sandy. The model results generated reasonable predictions of inland flooding with a bias range of −0.5 m to 1.0 m (Fig. 6). Point-based comparisons of flood depth were made by utilizing 10 USGS HWMs that had been collected and verified for the Hurricane Sandy event. The correlation coefficient, RMSE, and ratio of the standard deviations were 0.79, 0.71, and 1.41, respectively, between the observed and model-simulated flood depths for those locations. From the hydrodynamic modeling, we estimated the depth of flooding with respect to time for the evacuation routes in the study area. The highest water level inland ranged from 0.27 m to 1.5 m (Fig. 6). Moreover, the southern part of Brick Township was affected most by flooding. Several predictive skill tests were also conducted to quantify the similarity or agreement between the observed and model-simulated flood inundation extents (Saleh et al., 2017; Sampson et al., 2015; Schubert and Sanders, 2012; Bates and de Roo, 2000) through a pixel-by-pixel analysis. Similarities between the two datasets were determined by the critical coefficient of similarity (Fa), as defined by Eq. (3):

$$F_a = \frac{E_p \cap E_m}{E_p \cup E_m} \quad \text{Eq. (3)}$$

where Ep indicates the model-simulated or predicted flood extent and Em indicates the observed flood inundation extent. Dividing the intersection (∩) and union (∪) between the two datasets shows the similarity of flooding in terms of inundation extent. A value of Fa = 1 indicates perfect similarity between the predicted and observed inundation extents. Likewise, the metric for over-predicted (Fop) and under-predicted (Fup) flood extents were quantified as follows (Eqs. (4) and (5)):

$$F_{op} = \frac{E_p - E_p \cap E_m}{E_p \cup E_m} \quad \text{Eq. (4)}$$

Table 2
Summary of performance metrics based on a comparison of model-simulated results with the observed FEMA MOTF inundation product.

Metrics	*Fa*	*Fup*	*Fop*	*POD*	*FAR*	*CSI*
Value	96.49%	2.61%	0.89%	97.38%	0.91%	96.5%

$$F_{up} = \frac{E_m - E_p \cap E_m}{E_p \cup E_m} \quad \text{Eq. (5)}$$

$F_{op} = F_{up} = 0$ indicates a perfect model validation with no over or under prediction for the observed inundation extent. Furthermore, three other metrics derived from the aforementioned metrics for over and underprediction, probability of detection
(POD), false-alarm ratio (FAR), and critical success index (CSI) were used to further assess the model's ability to accurately replicate flooding during the Hurricane Sandy event (Saleh et al., 2017; Bhatt et al., 2017), as follows:

$$POD = \frac{hits}{hits + misses} \quad \text{Eq. (6)}$$

$$FAR = \frac{falsealarms}{hits + \ flasealarms} \quad \text{Eq. (7)}$$

$$CSI = \frac{hits}{hits + misses + \ flasealarms} \quad \text{Eq. (8)}$$

The POD (Eq. (6)) value was obtained by a pixel-by-pixel analysis in which the simulated inundation map was overlaid on and compared with the FEMA MOTF reanalysis product at 3-m spatial resolution. FAR (Eq. (7)) indicates the fraction of the simulated flood extent that was over predicted by the model. CSI (Eq. (8)), which is like the similarity metric, indicates the model performance as compared to the FEMA MOTF product. Table 3 summarizes results of these metrics used in our study to validate the model performance. We also performed a random sampling analysis to analyze the spatial variation of flood depth. Using ArcGIS, a total of 60 random samples of flood depth were taken from the FEMA MOTF inundation map and the model-simulated map and their values compared with the corresponding model-simulated flood depths at these randomly sampled points. The results indicated satisfactory agreement (R2 = 0.9308) between the two datasets in terms of flood depth (Fig. 7a). Fig. 7b shows the pixel-by-pixel spatial distribution of the performance metric in terms of false alarms, hits and misses. The analysis yielded good agreement with the predicted flood extent, as supported byPOD = 97.38%, FAR = 0.91%, and CSI = 96.5%. Using the simulated flooding information, we identified which roads would be affected by flooding. We also identified when the roads would be affected and the predicted water levels at certain locations along the evacuation routes. A separate database was created for the road segments modeled in VISSIM, which includes the depth of flooding and corresponding time at fifteen-minute intervals.

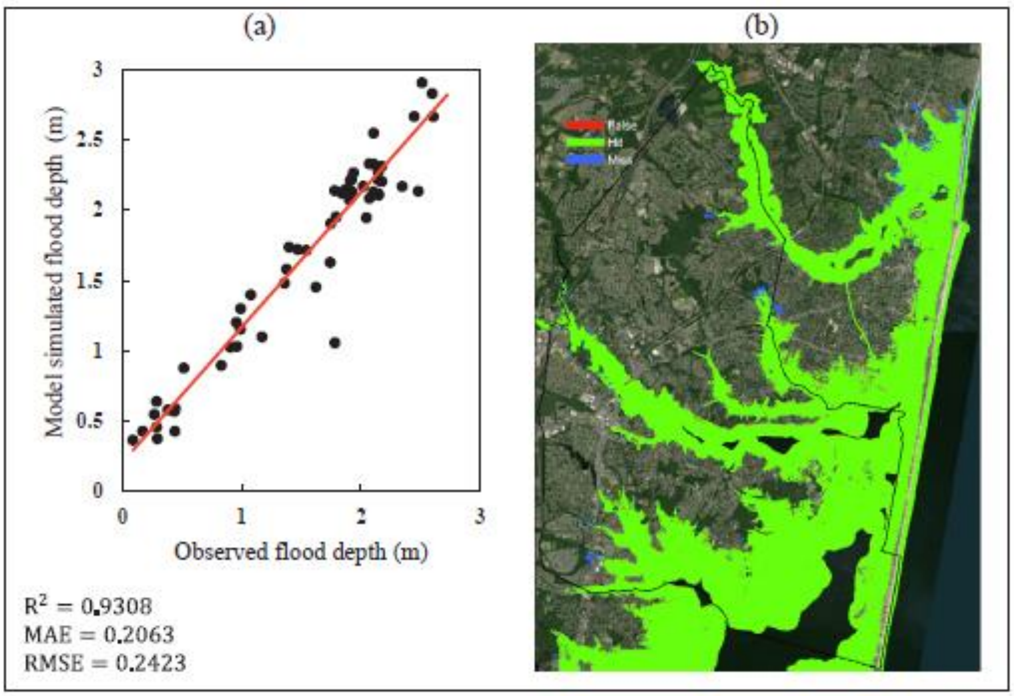

Fig. 7. (a) Scatter plot showing observed vs. model-simulated flood depth for 60 random points sampled within the boundary of the study area. (b) Spatial distribution of performance metrics compared with FEMA MOTF reanalysis product.

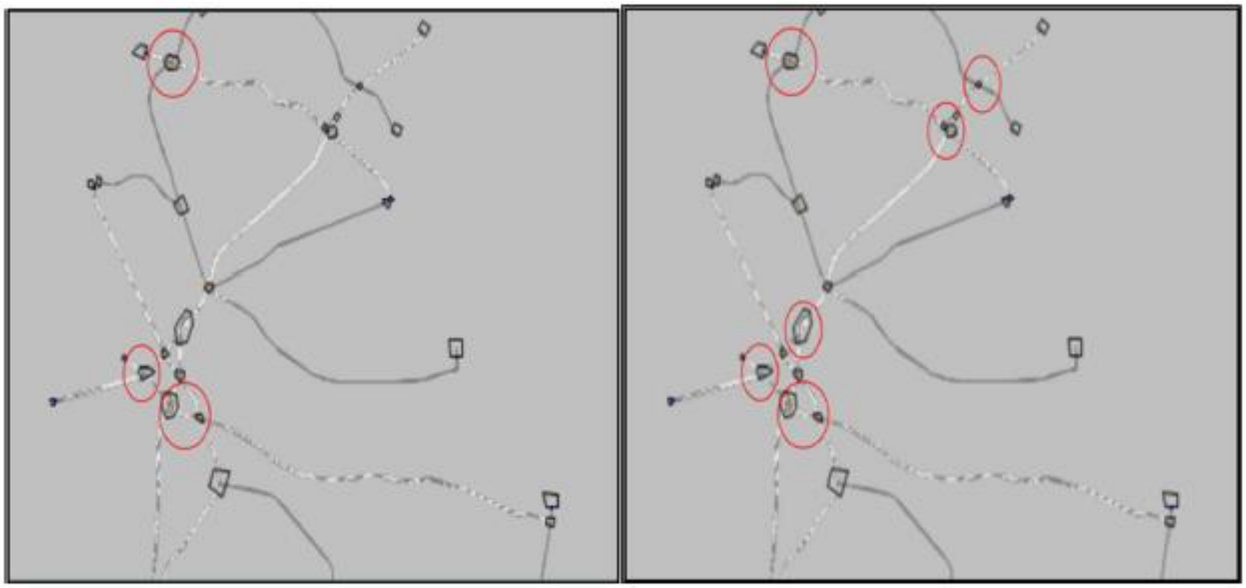

Fig. 8. Bottleneck formation following the announcement of a mandatory evacuation; (a) 2 h of simulation (left) and (b) 6 h of simulation (right).

All this information was fed into the traffic simulation models for the individual road segments. This database thus provides information about which road segments must be closed and at what time, based on the traffic simulation. On this basis, what-if scenarios were created for the evacuation routes at multiple time intervals.

Results from evacuation modeling

Using evacuation traffic models, the performances of the existing transportation infrastructures were explored. To do so, the times required to evacuate from critical regions to a safe zone were estimated while running the microsimulation. During this simulation, the roads that would be closed due to flooding were determined based on the hydrodynamic modeling results at fifteen-minute intervals. This was determined by calculating the flooding depths along the evacuation routes. Using flood-prediction algorithms, hydrodynamic models were able to generate information on the future status of any specific roadway segment.

This information was passed to the VISSIM traffic evacuation model using the Visual Basic (Halvorson, 2010) code developed specifically for this study area. First, we performed model simulations without re-routing vehicles to alternative routes. After 6 h of simulation, three additional bottlenecks or temporary capacity-decrease zones had formed, as compared after 2 h of simulation. Fig. 8 shows the locations of these bottlenecks, which formed in specific regions due to the physical condition of the roads, sharp curves, or narrow road sections. We also found these bottlenecks to be stationary. Therefore, appropriate rerouting decisions would be ne- cessary to facilitate the free flow of traffic and prevent any bottlenecks, and thereby ensure safe evacuation scenarios. Finally, the alternative routing provided in the IDRuM web application was modeled in traffic simulations. Later, outputs from previous flood modeling results for a hurricane of the same category were integrated into the traffic simulation models. The alternative routing information was then utilized to optimize the capacity of the existing road structure and distribute the evacuating traffic among less congested road segments. This optimization led to a roughly 6% reduction in the overall travel time compared to the base model, as shown in Fig. 9.

Final visualization

The velocity distributions of the road segments generated by the traffic simulation models were coupled with the evacuation road network in the study area. Each road segment contained velocity information at fifteen-minute intervals during the two-hour emergency evacuation scenario. The traffic velocities along the evacuation routes were reclassified into three categories, i.e., 0–5 mph, 6–25 mph, and 26–50 mph. The road segments were also color coded, respectively, in red, yellow, and green to indicate the traffic velocities along the evacuation routes. Thus, for each fifteen-minute time interval, a map was created that combined inundation maps and corresponding color-coded traffic velocities along the evacuation routes. Using the Extensible Markup Language (XML) library (Bray et al., 2008), these time-dependent static snapshots of the road network at fifteen-minute intervals were later converted into a seamless dynamic application. Fig. 10 shows the results of the integration of the flooding and traffic modelling. As shown in this figure, before the flood approached, all evacuation routes were open after two hours of simulation and the traffic velocities varied between 5 and 25 mph (yellow line) and 25–50 mph (green line).

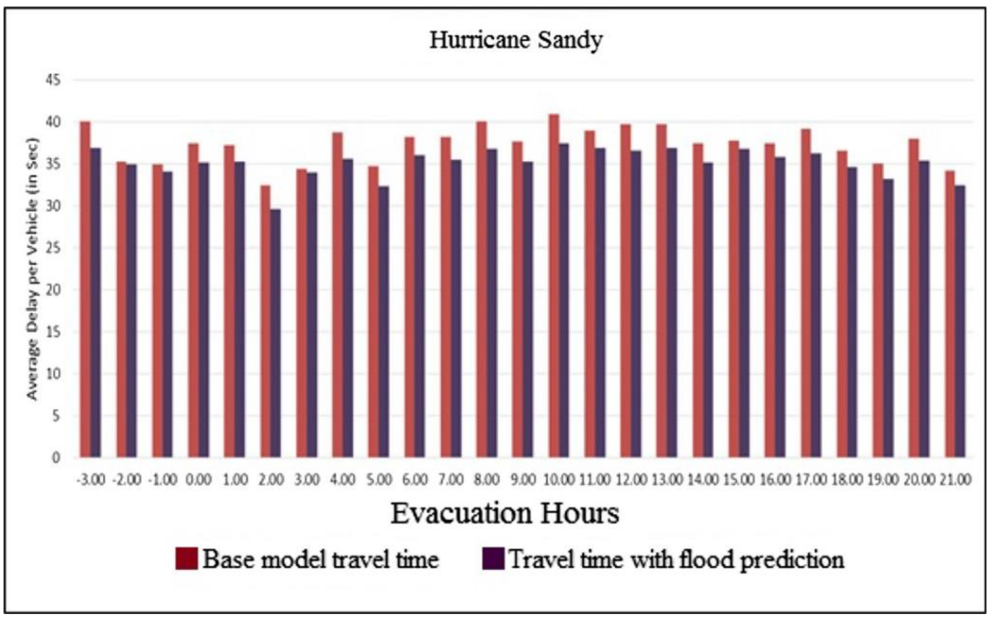

Fig. 9. Comparison of travel times between base model and the model with flood prediction information.

Practical implementation

Developing a real-time and robust evacuation framework for extreme storm events is a challenging task that is constrained by the complex integration required among several steps, including storm forecast, flood prediction, street-level inundation, road closure information, traffic microsimulation, GIS integration for final visualization, and finally public dissemination. The inherently erratic nature of storm paths and traffic behavior make emergency evacuation even more challenging. The runtime for the two-fundamental modeling efforts involving emergency evacuation during extreme storm events (i.e., hydrodynamic and traffic microsimulation) rely heavily on the available computational resources. Integration, data transaction, and dissemination require less computational effort but depend on painstaking data-quality control.

An emergency evacuation system in which forecasts are made at the time of hurricane landfall or, even worse, after a major flooding event has occurred makes the framework totally impractical and leads to inefficient utilization of time and valuable re- sources. To overcome these problems, several technological challenges must be overcome by the adoption of innovative engineering approaches that ensure a near real-time, robust, and easy-to-implement emergency evacuation framework. In this research, a set of tools and scripts was developed to help automate data processing, simulation runs, and the integration of models. The proposed evacuation framework provides two types of evacuation scenarios: (i) a 'no flood scenario' where mandatory evacuation begins at least 48 h before a hurricane makes landfall, so the effect of flooding is not considered and (ii) a 'flooding scenario' where a sudden change in the storm pattern mandates emergency evacuation from vulnerable regions or during an ongoing evacuation effort when roads become flooded and the dynamic nature of flooding plays important role in guiding efficient evacuation management.

Table 1 provides a general summary of the time required for a successful evacuation prior to hurricane landfall. Based on previous evacuation efforts during major hurricanes in the U.S, about 48 h (2 days) has been required for a state-level evacuation. The 'no flood scenario' in our framework adopted a similar timeline for evacuation scenarios prior to hurricane landfall. The 'no-flood scenario' simulation is conducted entirely by traffic microsimulation with no road closure information passed to VISSIM. This evacuation scenario is planned to run only once every 48 h at least as a boundary condition for a traffic simulation assumed to be constant with no flooding effect. Currently the 'no flood scenario' provides two-day forecasts for traffic patterns at hourly intervals, which could be shortened to fifteen-minute intervals if required. Traffic microsimulations are computationally intensive depending on the complexity of the network and the number and extent of evacuation routes to be modeled in the VISSIM environment. During the implementation phase, the proposed framework utilizes a prebuilt calibrated traffic model in which traffic volume and road closure information are two key boundary conditions. The computational infrastructure for the evacuation framework is based on advanced computers that utilize parallel processing, as well as two CUDA-enabled NVIDIA GTX 1080Ti GPU units that greatly reduce the runtime. During the test phase, both the hydrodynamic and traffic simulation models ran within 3 h, with the machine solely dedicated to running the simulations. We note that by using high-performance computers, it is possible to significantly reduce the simulation time from 3 h to ~30 min. This approach can save great amounts of time in executing the evacuation framework and thus ensure an efficient evacuation to get people 'out of harm's way' prior to hurricane landfall. On the other hand, the 'flooding scenario' considers the hydrodynamic effect of hurricane-induced flooding. The framework for this second scenario utilizes a 6-hour forecast product from the National Hurricane Center (NHC) (Chen et al., 2019), which starts ~124 h (7 days) prior to hurricane landfall as a boundary condition for the 2D hydrodynamic model (i.e., discharge vs. time, water level vs. time). The storm surge products are generated

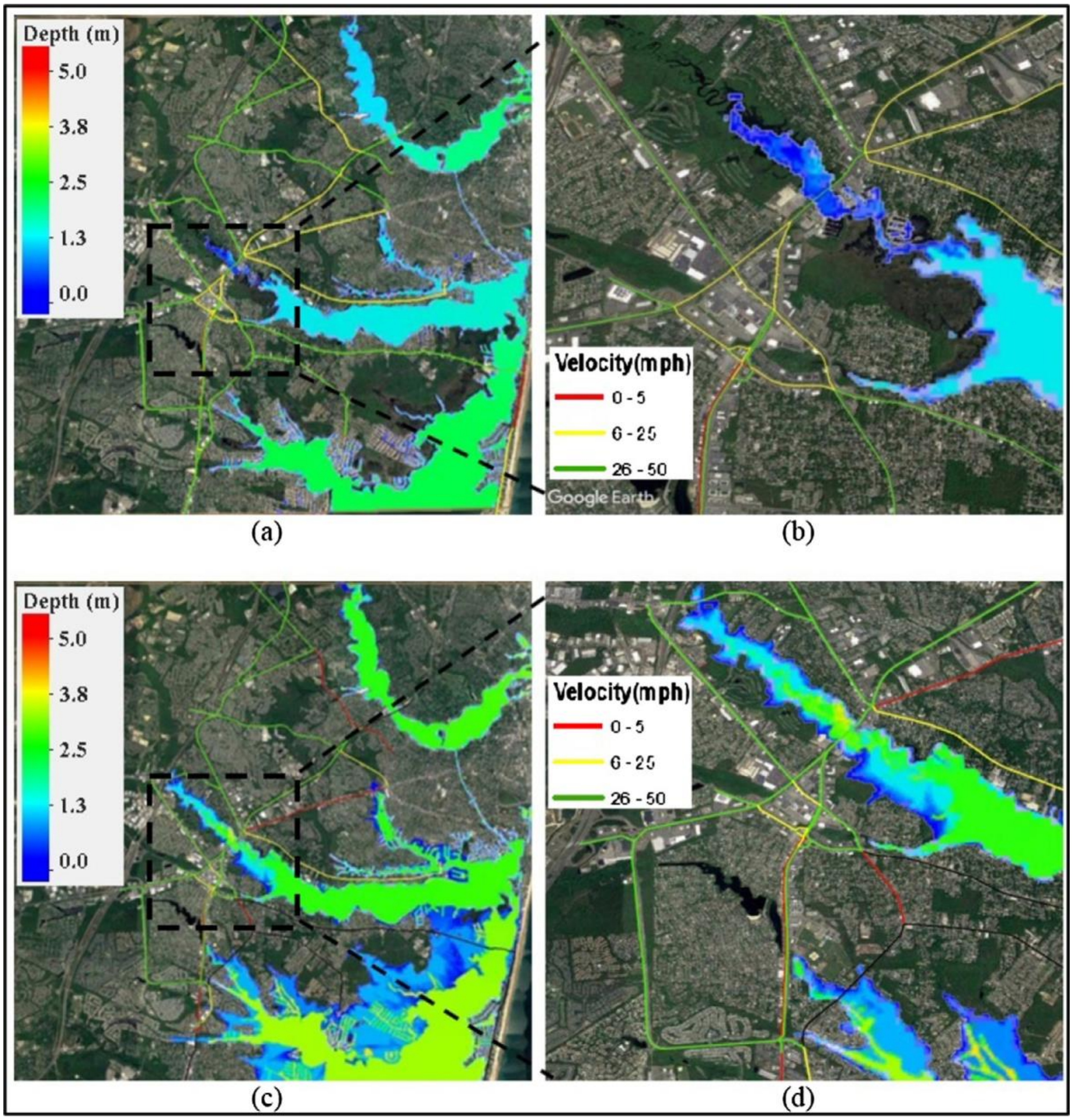

Fig. 10. Final evacuation planning based on integrated traffic and hydrodynamic modeling. Figures on the left (a and c) show the effect of flooding before and after Hurricane Sandy made landfall. Figures on the right (b and d) show a zoomed-in version of the highlighted region where bottlenecks had formed during the evacuation traffic simulation.

through a seamless integration of hurricane and storm surge forecasts from the Storm Surge Unit at the NHC (Rappaport et al., 2009). In this study, the research team utilized the OPeNDAP (Cornillon et al., 2003) framework within an R environment (R, 2013) to enable automatic download and processing of data for the hydrodynamic model. To avoid a continuous flooding simulation, the proposed framework adopts a threshold approach, whereby flood simulations are conducted only when the water levels of the major rivers in the study area exceed a predefined flood stage (Linsley, 1942). An 'if–else' statement within R checks if the water level of the river exceeds the assigned flood-stage threshold and if 'True', a water level or discharge time series as a boundary condition for hydrodynamic modeling is generated and stored in a location where a pre-built and calibrated hydrodynamic model has been installed for hydrodynamic modeling. The random nature and intensity of flooding necessitates a higher frequency of flood fore- casting so that any changes in flooding patterns due to sudden changes in storm behavior can be captured by the hydrodynamic model to ensure a robust evacuation framework. The framework adopts a fifteen-minute interval for dynamic flooding, which shows flood depth, flow velocity, time required for flooding to reach the evacuation routes, and duration of flooding. The hydrodynamic model results are extracted for the evacuation routes in a GIS framework to generate road closure information based on the elevations of the routes and the inundation depths of every road segment to be modeled in the traffic microsimulation. A database in a

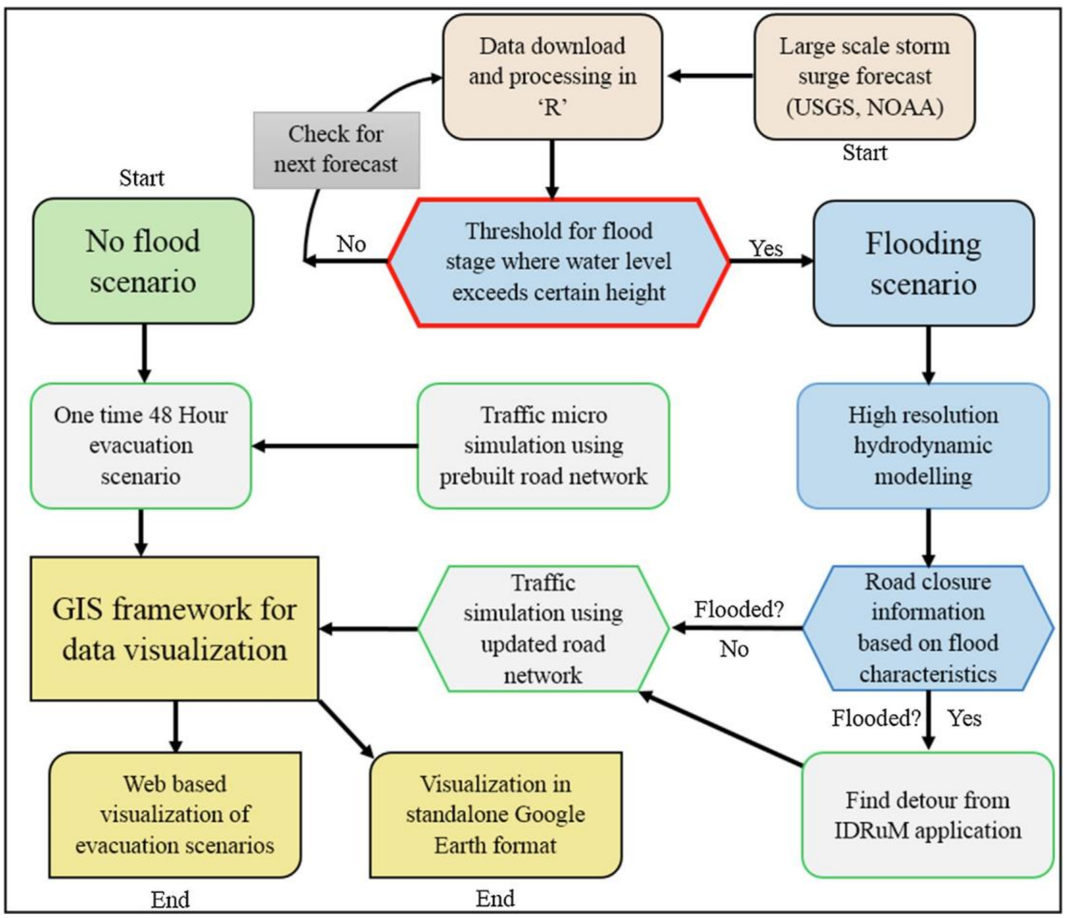

Fig. 11. Implementation framework for the proposed evacuation management during extreme storm events.

spreadsheet format containing binary information about open or closed road segments is generated and passed to a prebuilt and calibrated VISSIM environment for the purposes of traffic simulation controlled by a script written in Visual Basic. The rerouting information due to road closure is obtained from the IDRuM, as discussed in Section 2.1.3, thus ensuring a smooth evacuation without traffic congestion. Currently, the IDRuM framework is not fully coupled with the proposed evacuation framework. A possible ex- tension of this study could focus on integrating the IDRuM framework with the traffic microsimulation through a web-based API so that the two applications can communicate with each other without manual intervention. This technique would certainly reduce the evacuation forecast time to enable robust emergency evacuations during extreme storm events. The last but most significant part of this framework is the visualization and dissemination of the results of the hydro-traffic evacuation simulations for utilization. Fig. 11 shows the implementation framework for both scenarios.

The traffic simulation results for both cases (i.e., no flooding and with flooding) are exported into a spreadsheet format that contains the traffic speed for each of the road segments modeled in the traffic microsimulation. This information is later imported and spatially combined in a GIS framework to produce color-coded maps of traffic pattern and road closure information, as discussed in Section 3.3. After performing painstaking quality control of the finalized maps, the results are converted into a Google-Earth-com- patible format (i.e., kmz and kml) for decision-making purposes. The results are also uploaded into a pre-built ArcGIS server de- veloped by the research team, which is hosted by Amazon Web Services (AWS). For more information, readers are encouraged to visit http://njfloodalert.com/.

CONCLUSIONS and RECOMMENDATIONS

In this study, a framework was developed to facilitate emergency evacuation management during extreme storm events. The framework was applied to an area highly vulnerable to extreme storm events where evacuation plays a significant role in emergency preparedness and disaster management. This framework only focuses on evacuation scenarios when any vulnerable region does not receive an early evacuation notice or a sudden change occurs in the storm pattern and direction, which forces an emergency evacuation from the vulnerable region. Our study sufficiently modeled Hurricane Sandy as an extreme storm event, which was later validated against observed data from several sources to ensure the accuracy of the hydrodynamic modelling. We developed an optimum set of model parameters, including surface roughness, mesh/grid resolution, boundary conditions, and timestep of simulation to overcome the uncertainty arising from model parameterization in hydrodynamic modelling.

The hydrodynamic modelling results were successfully integrated into the transportation modelling framework through an algorithm developed for the study area. Traffic congestion or bottlenecks formed in some parts of the evacuation routes due to road closures on certain road segments. The efficiency of the traffic microsimulation was increased by applying optimization techniques that reduced travel time by 6% and rerouting traffic to less congested areas to get people out of harm's way. The standalone application for final visualization could be easily utilized both online and offline and has the capacity to be integrated with any emergency management system. This unique integration of hydrodynamic and transportation modeling could help in the evaluation of real-world extreme-weather-event evacuation strategies. Furthermore, this combination of hydrodynamic and traffic modeling can provide useful information to communities, agencies, and decision-makers to facilitate optimal and useful emergency evacuation planning during extreme storm events.

Several state and federal agencies, such as DOTs, the Office of Emergency Management (OEM), Department of Community Affairs (DCA), and FEMA play important roles during emergency evacuation processes in the United States. The proposed framework could serve as an integrated medium for assessing the effect of certain decisions such as road closings, rerouting, and lane reversals on evacuation routes. The road-closure decisions made for this study were solely based on flooding characteristics during an extreme storm event and subsequent rerouting decisions, with bottleneck formation already having been considered in the traffic model developed in the VISSIM environment. However, if any state or federal agency mandates road closures for any specific evacuation route, subsequent changes in traffic patterns could be assessed within the framework aside from road closures due to flooding. Currently, road closure information due to flooding depends on forecasts from NOAA or FEMA, which take a considerable amount of time to generate, implement, and disseminate to various agencies. These products also come with considerable degrees of uncertainty due to the coarse spatial scale of flood inundation, whereas the proposed framework is robust enough to capture any changes provided to the traffic network and to produce an optimum and accurate evacuation scenario in terms of traffic volume and speed. However, we propose that to provide congestion-free and smooth traffic flow during evacuation, government agencies could assign more local routes as evacuation routes during an emergency to improve traffic conditions, which could also be modeled in our framework.

As in any research, this study also had several limitations. First, with respect to model calibrations and the limited availability of data, we did not model driver behavior with respect to mass evacuation traffic. In this study, the effects of driver-to-driver or other communications to motorists from sources such as navigation apps were not considered. Moreover, due to lack of actual data regarding vehicle speeds, traffic volume, and congestion formation and dissolution during hurricane evacuation, the model was calibrated using normal day traffic conditions with different approximating assumptions regarding emergency traffic conditions.

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