CAIT-UTC-REG34

Assessing and mitigating transportation infrastructure vulnerability to coastal storm events with the convergence of advanced spatial analysis, infrastructure modeling, and storm surge simulations

FINAL REPORT
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In cooperation with

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16. Abstract

In this project, the research team studied the convergence of remote sensing, digital twin, web technologies, and flood simulation for creating an advanced flood preparedness system. The project used Manville, a frequently flooded township in New Jersey, as an exemplar case. The team created a calibrated hydrodynamic model for the entire township and beyond. The team also mapped out the entire township with a high-resolution 3D mapping system, and created a digital twin for the entire township. We extracted key elevation information for buildings and critical infrastructure systems, and used them in joint with the hydrodynamic models to assess flood impacts. The flood impacts focused on buildings and accessibility to emergency services. We created two modules of assessment tools for these purpose so that they are generalizable to other places. At the end, we created a flood information dashboard which serves a center place to visualize hydrodynamic model results and flood impacts to communities and to support decision making in flood mitigation choices. The project is the first application of integrating mobile lidar derived city level data with hydrodynamic models for flood impact visualization and analysis.

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INTRODUCTION

Description of the Problem

New Jersey is the second most vulnerable state in the country to coastal flooding. As the climate system becomes increasingly aggressive, extreme precipitation is posing increasing risk of flooding to the vast infrastructure systems in the state of New Jersey. Sea level rise is an additional stressor which further amplifies flood risks in the region. The joint impact of these threats is that we expect more flooding disruption in New Jersey - a recent report showed that "flood height return periods that were ~500 year during the preindustrial era have fallen to ~25 year at present and are projected to fall to ~5 year within the next three decades" in the New York/New Jersey area. Facing the fast moving threats and the large uncertainty in flood prediction, infrastructure stakeholders have been struggling to prioritize their resiliency rebuilding actions while treading through the water of balancing climate risk, economic benefits, and societal impacts.

Relevance to Strategic Goals

The focus of this project is particularly relevant to several USDOT strategic goals, which are also the primary focus of this consortium. The first and foremost strategic goal that this project contributes to is infrastructure resilience. The second goal supported by this project is state of good repair because the project helps the reduction of damage caused by flood. Lastly, by providing tools and data that can be used by infrastructure stakeholders to prioritize their investments on addressing infrastructure vulnerabilities to coastal flooding, the project can help prolong the life of infrastructure.

Background

Research Goals and Objectives

To protect the security of the public transportation infrastructure and the enormous amount of public assets, the proposed study will develop a decision support tool that can assist infrastructure stakeholders in making decisions at the day-to-day operation level (i.e. evacuation or shutting down of roads and bridges) to protect communities from impeding flooding events as well as in making long-term decisions in mitigating future flood risks facing their current infrastructure assets and their future projects (in particular those related to storm surge and extreme rainfall events).

Overview of the Report

This report documents the research approach, methodology, findings, conclusions and recommendations of this collaborative research project. The following sections outline the approach and methodology. The next section presents the findings, followed by sections documenting the conclusions and making recommendations for future work and application in Life-Cycle Management of Transportation Infrastructure Projects

APPROACH

Central to our proposed approach is a reliable flood risk management platform that integrates storm surge numerical model, high resolution models of transportation infrastructure assets (a combination of LiDAR data, GIS models, and City Information Models), a flood impact analysis system (consisting of inundation visualization, impact analysis, early warning and evacuation planning), and cloud computing infrastructure. These essential elements are explained as below.

Integration with storm surge models: A storm surge hydrodynamic model, which considers future climate change pathways, will be used and customized to predict the storm surge flooding risk to the NJ coastal communities. The model resolves the water level and velocity of the shallow water equation using the finite element method with ADCIRC. It is important to note that this project does not focus on the development of new storm surge models. The focus is on integrating simulation results from existing storm surge models with high resolution 3D models of coastal communities. Because of the time constraints, the project will only consider storm surge flooding. Riverine flooding is out of the scope of this project.

High resolution models of transportation infrastructure assets: This component involves deploying a mobile lidar system to survey several frequently flooded communities along the New Jersey coastal line and developing digital twins for coastal communities. Upon completion of these surveys, we will convert these lidar data into digital twin models such as building/civil information models which contain rich information about the facilities.

Flood impact analysis: A challenging task in protecting communities against coastal flooding is to characterize the dynamic impacts of flooding as a weather system (i.e. hurricane) gradually approaches. Based on storm surge prediction, the project team will develop approaches to overlay and project predictions onto shoreline communities as well as to evaluate the degeneration of transportation network as the storm approaches. The understanding of the degeneration of transportation network will lead to improved evacuation planning. In addition to analyze the impacts of impeding storms, the project team will also develop tools for understanding and evaluating the inundation risk and economic impact of various storm surge risks in the long-term prediction.

Cloud infrastructure: We plan to make the platform available for public use, especially for infrastructure stakeholders. Given this consideration, we elect to build the tool on a cloud computing infrastructure such as Amazon AWS and Microsoft Azure. In our previous research projects, we have developed a prototype inundation visualization tool called Inundation Risk Information System (IRIS) Viewer. The IRIS viewer is a city-scale flood risk visualization platform. The viewer allows real-time retrieval and visualization of lidar data in conjunction with flooding information in a GIS-driven interface. The viewer allows quick visualization of the extent of flooding at the street level given predicted flood depths. In addition, the users can geocode asset information such as elevations in an interactive manner, and store those information back to GIS databases. Given the geocoded asset information and predicted or observed flood depths, the system is capable of quickly generating flood warnings for critical assets. Building on this prototype tool, we will extend this tool into IRIS 2.0, which will provide seamless integration with storm surge models and have rich analytic capabilities in conducting storm impact analysis and evacuation planning.

Throughout the project, the research team will rely on literature analysis, case studies, prototype development, and technology demonstration with project customers and potential implementers as the primary means to forge a decision support tool for infrastructure and coastal community stakeholders to make better decisions during individual storm events and in the face of long-term flood threats.

METHODOLOGY

The following research tasks are planned in this project.

Task 1: Modeling Coastal Flood Risks with Hydrodynamic Models

Task 2: Mapping and Creation of Digital Twins for Coastal Communities

Task 3: Developing Approaches for Flood Impact Analysis

Task 4: Developing Flood Information Dashboard

Task 5. Technology Demonstration and Mini-workshops

Task 6. Final Report, Conclusion, and Recommendation

FINDINGS

Our findings are organized around the research tasks.

Task 1: Modeling Coastal Flood Risks with Hydrodynamic Models

As an example case, we developed a hydrodynamic model for Manville, New Jersey. Manville Township, located on the confluence of the Raritan River main stem and its tributary Millstone River (Figure 1). It has been prone to the flood hazards induced by intense and durable precipitation during extreme weather events such as tropical cyclones for long time. The communities in Manville experienced frequent flooding over the years since Hurricane Diane in 1966. In Hurricane events like Hurricane Irene, the widespread and deep flash flooding delayed the rescue actions because of the wide traffic interruption. There is 40% population in Manville are Minors under the age of 18 and seniors over the age of 65 (Bureau United States Census, 2021).

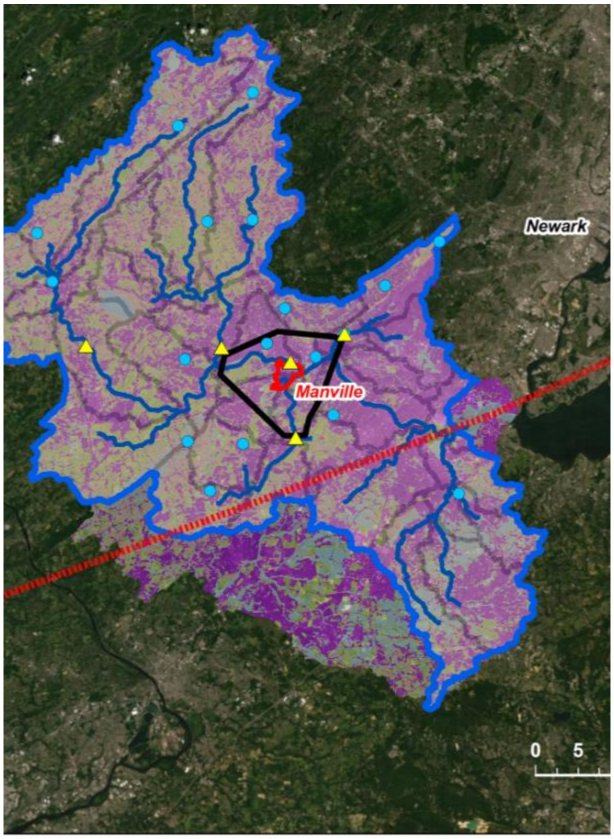


Figure 1 The study area: Manville Township

The constructed flood model framework integrates a calibrated regional hydrologic modeling (HEC-HMS) and calibrated 2-D hydrodynamic model (HEC-RAS). The flood conditions including flood propagation and inundation level are simulated using the latest HEC-RAS 6 Hydrodynamic model. It solves the original shallow water equations (2-D Saint Venant Equations) using implicit finite volume algorithms (Brunner, 2021). HEC-RAS uses the sub-grid bathymetry method, achieved by calculating the relationship of the water depth-volume of each computational cell in the preprocessing. It keeps details of the topography in the relatively coarse computational grid and allows a better representation of flow simulation (Brunner, 2021; F. Saleh et al., 2017). HEC-RAS has wide applications in flooding related studies, including but not limited to compound flooding (Loveland et al., 2021; F. Saleh et al., 2017), inland flash flooding (Abdessamed & Abderrazak, 2019; Buta et al., 2017; Costabile et al., 2020; Tamiru & Dinka, 2021), dam breach flooding (Bharath et al., 2021; Psomiadis et al., 2021), and sediment transportation (Shabani et al., 2021). In this study, a purely 2-D flow domain of HEC-RAS is selected using hydrologic conditions simulated by HEC-HMS boundary conditions.

The HEC-HMS domain covers the 80% area of the Raritan River Basin (Figure 1), delineated into 38 sub-basins based on the flow direction and accumulation estimated from a digital elevation model (DEM). Each sub-basin is parameterized by series of empirically derived parameters. In this study, the meteorological forcing for HEC-HMS such as precipitations is obtained from 15 United States Geological Survey (USGS) rain gages. They are assigned to corresponding basins based on distances. Clark Unit Hydrograph method is used in the transform component to account for the characteristics of each basin over the study area. The recession method is used in the baseflow component to account for the groundwater contributions to stream flow. The constructed HEC-HMS estimates the infiltration capacity and precipitation excess of each basin based on the Soil Conservation Service (SCS) curve number (CN) method. The default SCS CN value of each sub-basin is calculated based on the soil group raster dataset (ROSS et al., 2018), and the land use cover shapefile dataset (NJDEP, 2015) in ArcGIS (USACE, 2000). Both Muskingum equations and Lag equations are applied in river routing components. Since the soil moisture variation could make difference in the estimated runoff by HEC-HMS (Firas Saleh et al., 2016), some critical parameters, such as initial abstraction, curve number and impervious are calibrated based on the observed flow data obtained from USGS, to find the optimal combination of parameters.

Our model results illustrate that there is 43% (2.73 km2) of the area in Manville Township is flooded, impacting 24% of buildings and 44% of streets (Figure 2). Among the inundated area, 10% are located outside of the flood zone of FEMA, representing that there are 0.28 km2 areas with a chance lower than 1% of prone to flooding has been impacted by the flooding induced by hurricane Ida. Focusing on the flood conditions in the urban area, the maximum floodwater reaches more than 1.18 m in 50% of flooded areas and higher than 3.83 m in 5% of the flooded areas. Results indicate that the flood velocity remains relatively slow in the whole urban flooded area. The maximum flood speed is slower than 0.46 m/s in 95% of flooded areas, indicating that the flood water invaded the town slowly induced by the water level increase in the Raritan River due to continued rainfall. More than 50% flooded area remained as flooded for at least 18.83 hours.

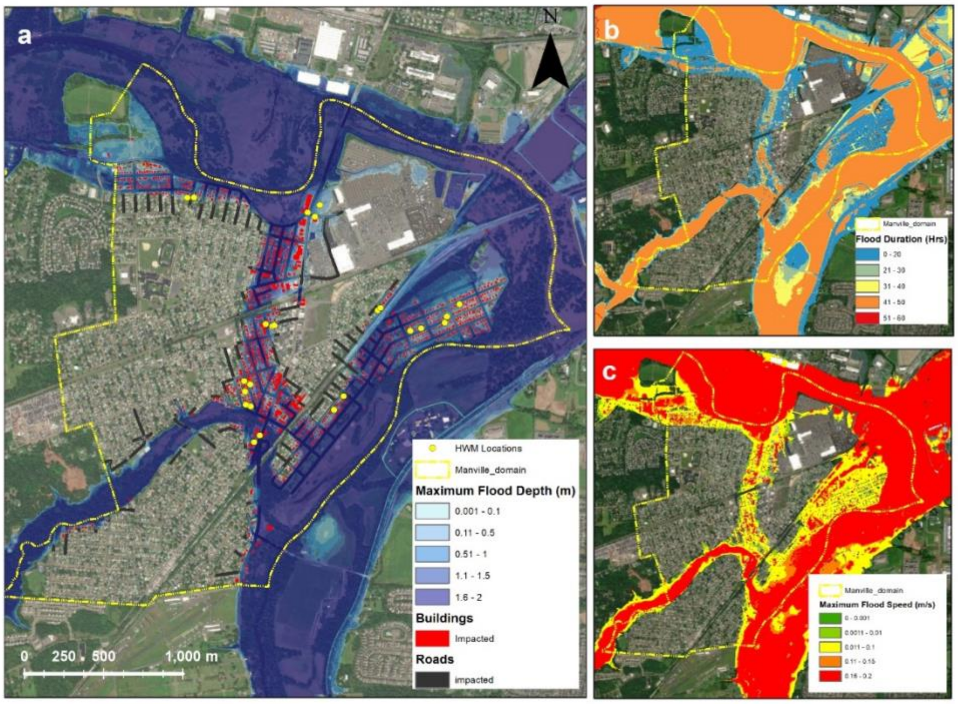


Figure 2 An overview of the simulated flood conditions during hurricane Ida in Manville Township includes a) maximum flood depth in meters, b) flood duration in hours and c) maximum flood speed in

meters per second. The location of the measured HWMs, impacted buildings and roads are also illustrated in a).

Task 2: Mapping and Creation of Digital Twins for Coastal Communities

Under this task, we performed the following activities.

Performed mobile LiDAR and digital imagery acquisition along all road ways in Manville, New Jersey

- Use mobile LiDAR technology to create a current 3D digital elevation model of all homes, businesses and infrastructure in Manville, NJ
- Convert the raw digital LiDAR data into accurate visual models of current ground elevations of individual buildings, streets and neighborhoods.
- Estimate the first floor elevation of each residential building by assuming that the base of the front door frame is an accurate surrogate for the first floor elevation.
- Create a current 3D digital elevation model of all homes, businesses and infrastructure in Ocean County shoreline communities as the baseline data for flood impact analysis

Our mobile mapping system, which can collect 2D images and 3D point cloud data simultaneously, was used to map the entire Manville (Figure 3). The point cloud data are collected through the Z+F PROFILER® 9012, and it is a compact high-speed phase-based laser scanner with great precision, 119 m range and a 360° field of view. With its scan rate of more than 1 million points/sec. and scanning speed up to 200 profiles/sec., very short distances between profiles can be achieved even at high platform speeds. Figure 4 shows the mapping paths in the Manville.

Figure 3 Mobile mapping in Manville, NJ

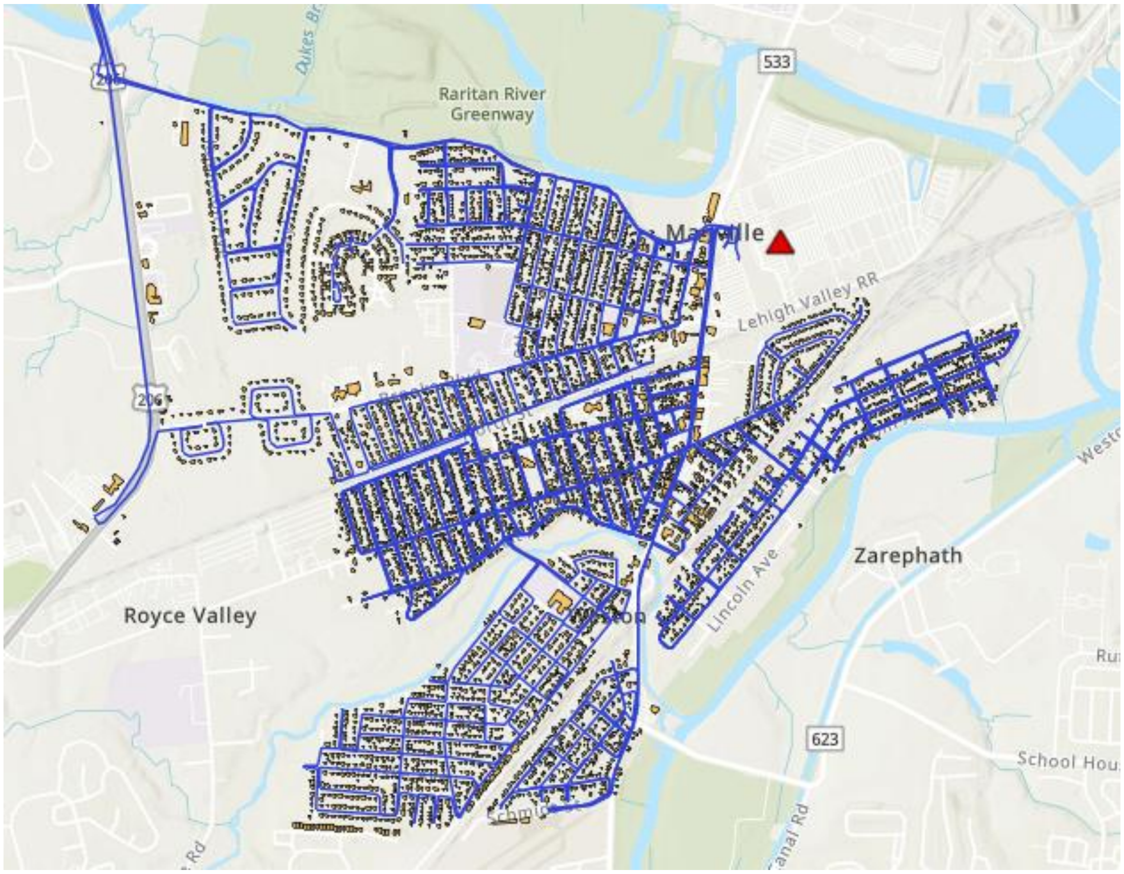
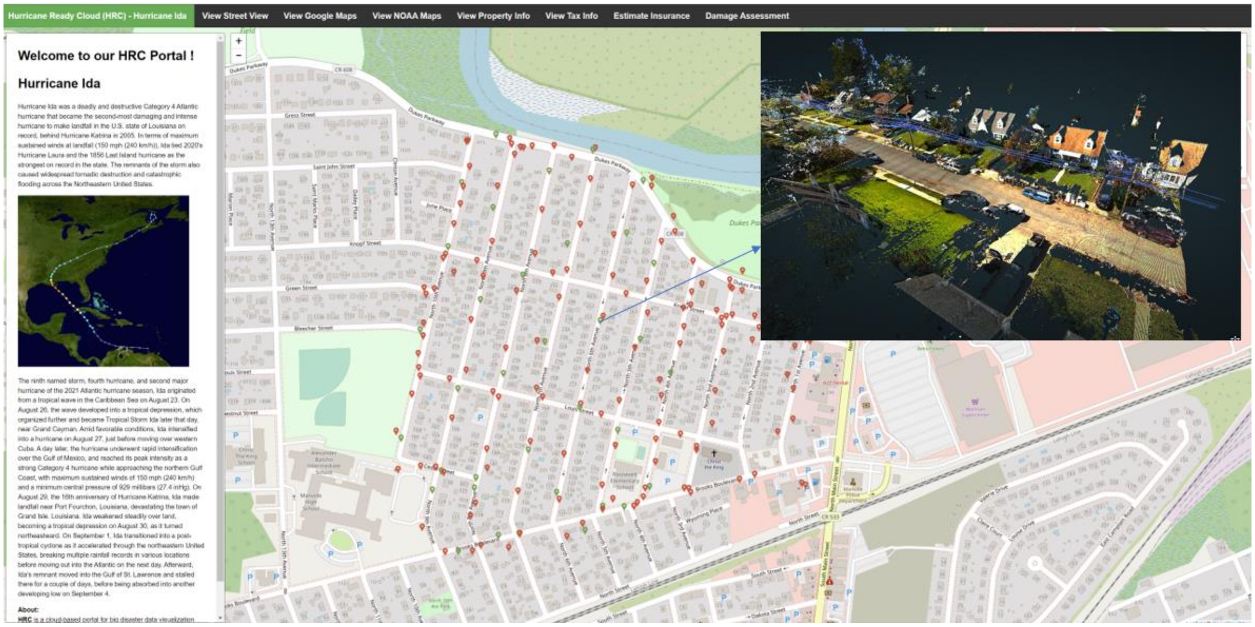


Figure 4 Mapping paths in Manville

The accuracy of post-processed mobile lidar data is directly dependent on the quality of the GPS environment at the time of data collection as well as the length of the baselines between the base location(s) and the collection vehicle. It is possible, with quality GPS signals, free from multipath and obstructions, along with shorter baselines (less than 5 – 7 miles) to achieve sub-5 cm vertical accuracies from the unconstrained post-processed point cloud data. [Vertical accuracy is measured relative to the National Geodetic Survey's (NGS) Continuously Operating Reference Stations (CORS) and respective North American Vertical Datum of 1988 (NAVD 88) of approximately 1 decimeter or 0.33 feet (in areas of adequate GPS) under normal statistical testing at 95% confidence. However, due to inconsistencies and fluctuating qualities of GPS environments throughout the collection areas, it is unrealistic to consistently achieve this level of accuracy throughout without registering the point clouds to control points established along the collection route. We used the airborne lidar data that were collected over Ocean County in 2014 as well as ground control points as the reference data to correct the elevation of mobile lidar data. The airborne lidar data have a nominal accuracy of 0.062 m vertical accuracy at 95% confidence level in open terrain.

The processed LiDAR data was then hosted in a web-based portal for visualization (Figure 5). We also designed an interface for elevation extraction for building and infrastructure assets (Figure 6).



Welcome to our HRC Portal !

Hurricane Ida

Hurricane Ida was a deadly and destructive Category 4 Atlantic hurricane that became the second-most damaging and intense hurricane to make landfall in the U.S. state of Louisiana on record, behind Hurricane Katrina in 2005. In terms of maximum sustained winds at landfall (150 mph (240 km/h)), Ida tied 2020's Hurricane Laura and the 1856 Last Island hurricane as the strongest on record in the state. The remnants of the storm also caused widespread tornadic destruction and catastrophic flooding across the Northeastern United States.

The ninth named storm, fourth hurricane, and second major hurricane of the 2021 Atlantic hurricane season, Ida originated from a tropical wave in the Caribbean Sea on August 23. On August 26, the wave developed into a tropical depression, which organized further and became Tropical Storm Ida later that day, near Grand Cayman. Amid favorable conditions, Ida intensified into a hurricane on August 27, just before moving over western Cuba. A day later, the hurricane underwent rapid intensification over the Gulf of Mexico, and reached its peak intensity as a strong Category 4 hurricane while approaching the northern Gulf Coast, with maximum sustained winds of 150 mph (240 km/h) and a minimum central pressure of 929 millibars (27.4 inHg). On August 29, the 16th anniversary of Hurricane Katrina, Ida made landfall near Port Fourchon, Louisiana, devastating the town of Grand Isle, Louisiana. Ida weakened steadily over land, becoming a tropical depression on August 30, as it turned northeastward. On September 1, Ida transitioned into a post-tropical cyclone as it accelerated through the northeastern United States, breaking multiple rainfall records in various locations before moving out into the Atlantic on the next day. Afterward, Ida's remnant moved into the Gulf of St. Lawrence and stalled there for a couple of days, before being absorbed into another developing low on September 4.

About:
HRC is a cloud-based portal for big disaster data visualization

Figure 5 Web-based LiDAR data visualization and elevation data extraction

Figure 6 Examples of extraction of lowest floor elevation

Task 3: Developing Approaches for Flood Impact Analysis

In this task, we integrated flooding information derived from hydrodynamic models in Task 1 with the geospatial data products developed in Task 2 with the aim to evaluate flood impacts to buildings and infrastructures in the township.

Flood impact to buildings

We developed flood impact analysis methods for buildings based on their first floor elevation (Figure 7). For example, with the digital twin models of the building properties and the hydrodynamic models calibrated for certain events, we can answer questions like: how did the buildings in the FEMA designated flood zone in Manville perform during Hurricane Ida?

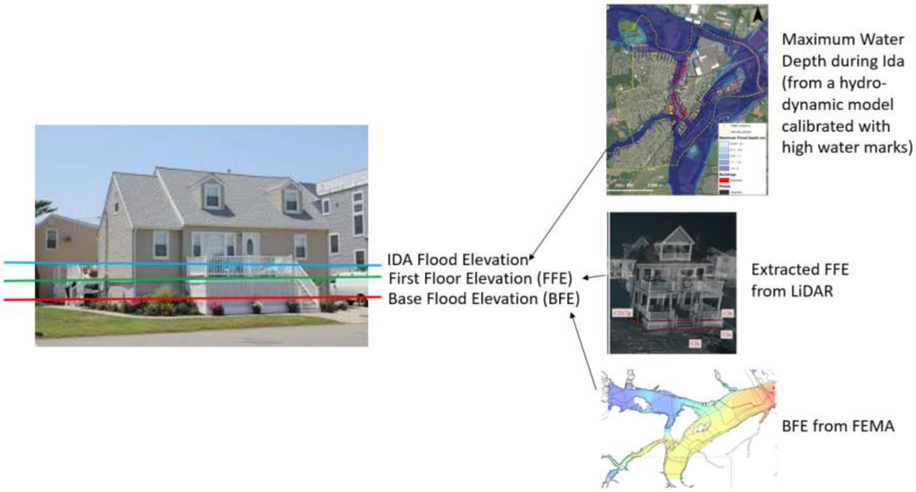


Figure 7 Flood impact analysis to buildings in Manville

For example, in the case of Hurricane Ida, we can provide flood impact results as the following.

Homes sustained at least 3 feet of flood above their FFE	**6.44%**	**27**
Homes sustained at least 2 feet of flood above their FFE	13.13%	55
Homes sustained at least 1 feet of flood above their FFE	23.87%	100
Homes sustained flood above their FFE	36.52%	153

At the same time, we can create visuals as shown in Figure 8.

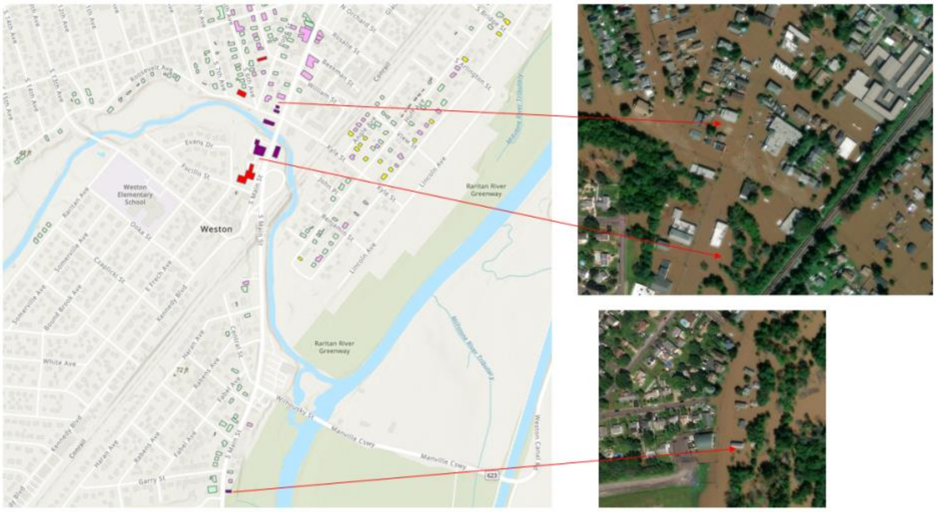


Figure 8 Flood impact to buildings during hurricane Ida

Another type of impact analysis we developed is disruptions to emergency services, which concerns how many home owners lose their accessibility to emergency services due to the inundation of roads. In this sense, this analysis also considers the degeneration of transportation road networks. By combining elevation data we collected for homes, essential service buildings, and roads and infrastructures with the hydrodynamic models, we are able to provide step-by-step predictions how road network degenerates and how many home owners lose their accessibility to essential services (Figure 9).

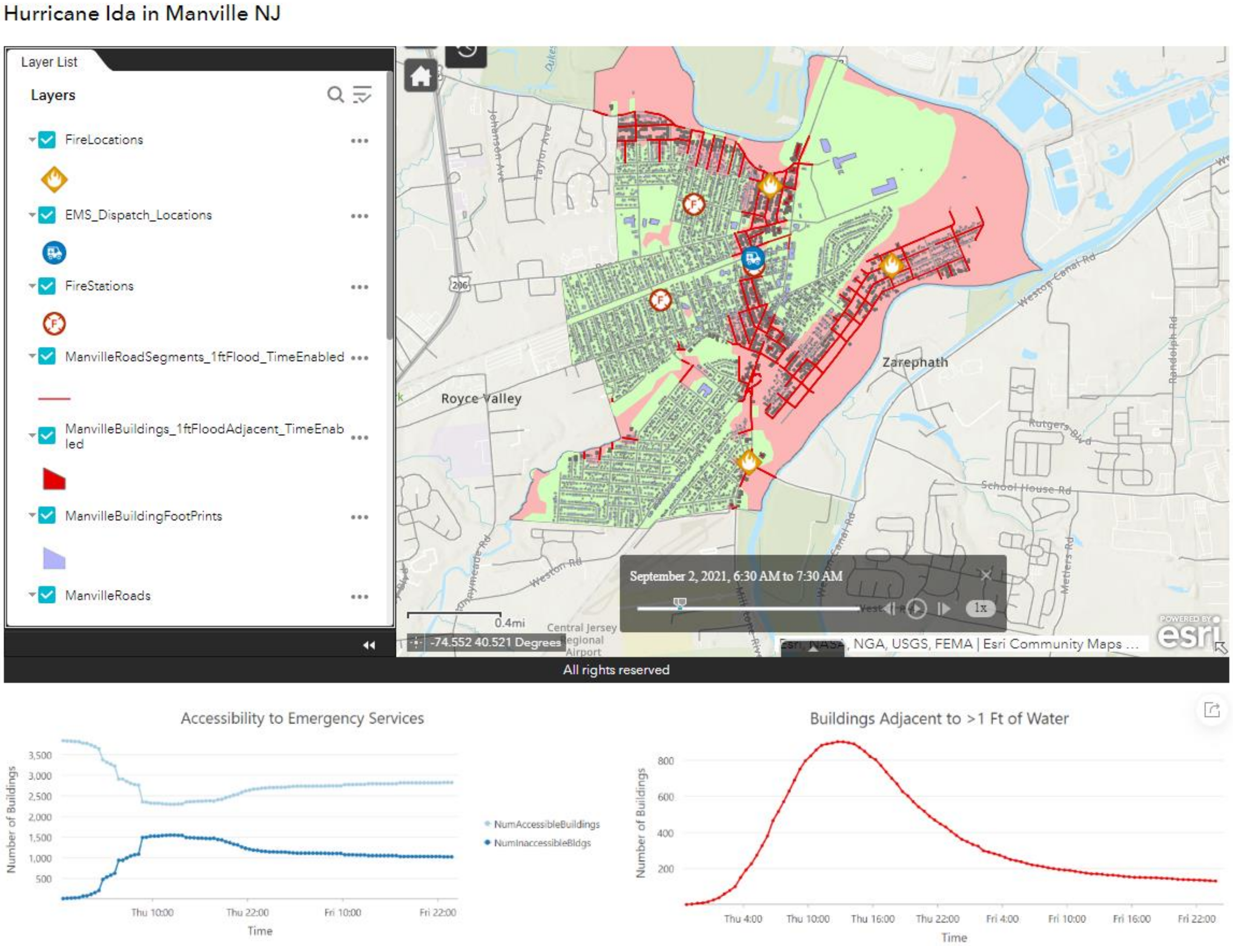


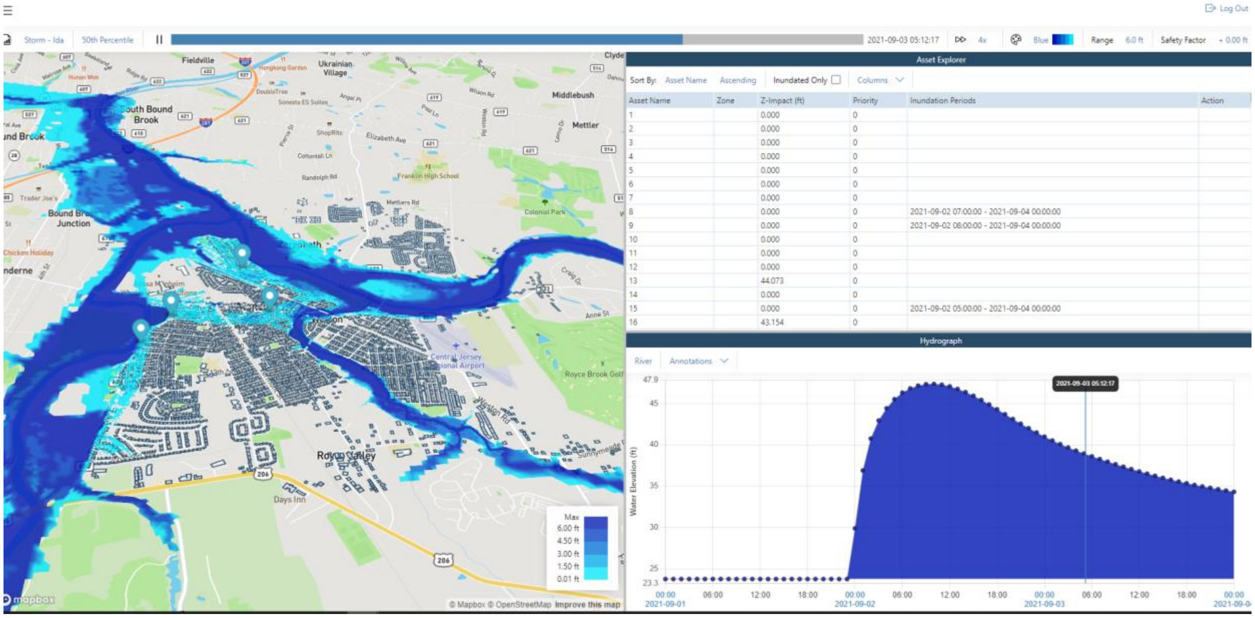
Figure 9 Road network degeneration and essential service disruptions

Task 4: Developing Flood Information Dashboard

This task concerns the development of a dashboard to tailor the need of infrastructure stakeholders. The first major task is to integrate the results from tasks 1, 2, and 3 such that the dashboard can support the visualization and exploration of inundation risks. We also developed a more comprehensive user interface to meet user information needs. More specifically, we developed: (1) a front-end dashboard to present high-level summaries of various information including hydrographs, GIS maps, weather forecast information, etc.; (2) an enhanced IRIS user interface to allow users to specify flood depths in a variety of ways such as percentage of predicted depth; (3) a document management module to allow users to print various information outputs, to document the decision making workflow; and (4) a logging mechanism to automatically time stamp major event information and decision making choices.

More specifically, the dash board contains two elements: (1) a community scale viewer showing the flood development as predicted by hydrodynamic models (Figure 10) and (2) a building scale viewer showing flood extent for individual buildings and infrastructure (Figure 11). The community-scale viewer contains hydrographs, GIS maps, and the predicted flood conditions.

Community-scale flood impact viewer



Asset Name	Zone	Z-Impact (ft)	Priority	Inundation Periods	Action
1		0.000	0		
2		0.000	0		
3		0.000	0		
4		0.000	0		
5		0.000	0		
6		0.000	0		
7		0.000	0		
8		0.000	0	2021-09-02 07:00:00 - 2021-09-04 00:00:00	
9		0.000	0	2021-09-02 08:00:00 - 2021-09-04 00:00:00	
10		0.000	0		
11		0.000	0		
12		0.000	0		
13		44.073	0		
14		0.000	0		
15		0.000	0	2021-09-02 05:00:00 - 2021-09-04 00:00:00	
16		43.154	0		

Figure 10 Community-scale flood impact viewer

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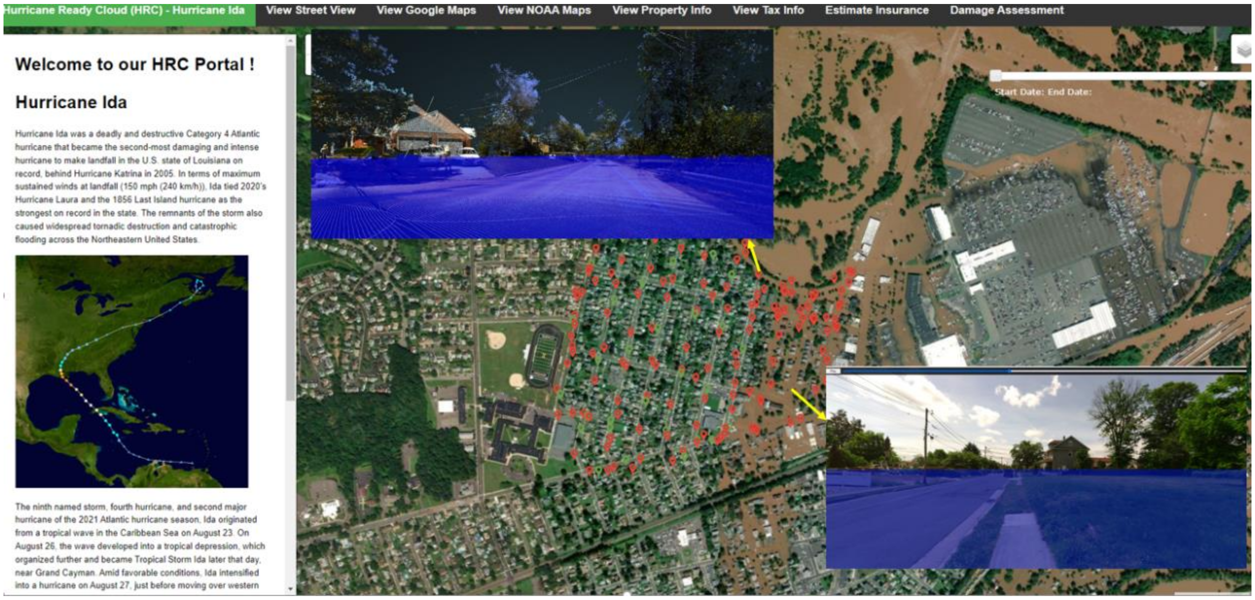

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Figure 11 Building-scale viewer for flood impact

Task 5. Technology Demonstration and Mini-workshops

During the course of the project, we periodically invited stakeholders and practitioners to the visualization lab at Rutgers to demonstrate various prototype tools. We also held a user group meeting at the New Jersey Regional Intelligence Operation Center for state-wide emergency response personnel (city and county OEM coordinators).

Figure 12 Mini-Workshop at the State ROIC Center

CONCLUSIONS AND RECOMMENDATIONS

In this project, the research team studied the convergence of remote sensing, digital twin, web technologies, and flood simulation for creating an advanced flood preparedness system. The project used Manville, a frequently flooded township in New Jersey, as an exemplar case. The team created a calibrated hydrodynamic model for the entire township and beyond. The team also mapped out the entire township with a high-resolution 3D mapping system, and created a digital twin for the entire township. We extracted key elevation information for buildings and critical infrastructure systems, and used them in joint with the hydrodynamic models to assess flood impacts. The flood impacts focused on buildings and accessibility to emergency services. We created two modules of assessment tools for these purpose so that they are generalizable to other places. At the end, we created a flood information dashboard which serves a center place to visualize hydrodynamic model results and flood impacts to communities and to support decision making in flood mitigation choices.

The project produced new ways of evaluating and assessing flood impacts to coastal communities. It is the first application of integrating mobile lidar derived city level data with hydrodynamic models for flood impact visualization and analysis. The tools are web-based and can be repetitively used in other communities. We expect the results of this research will give community stakeholders powerful means to improve the resilience to flood events.

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