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).

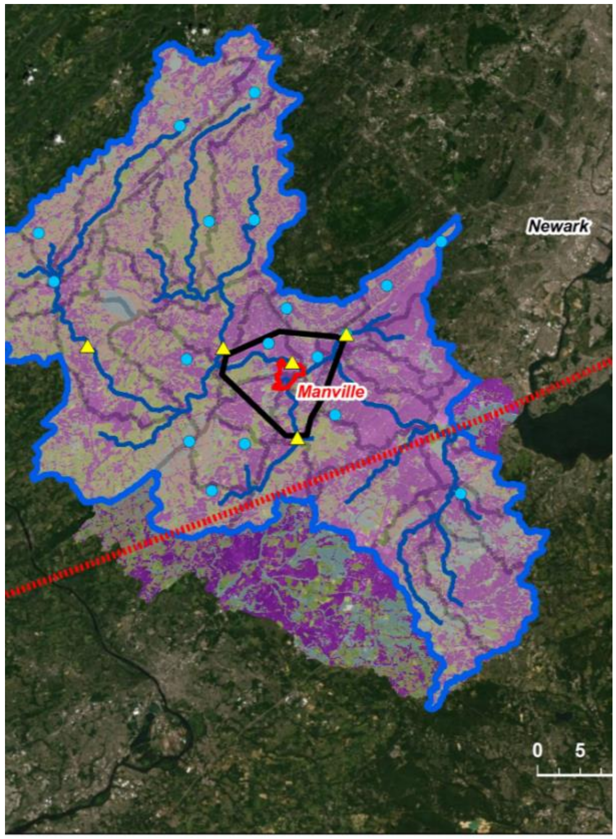

Figure 1 The study area: Manville Township

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.

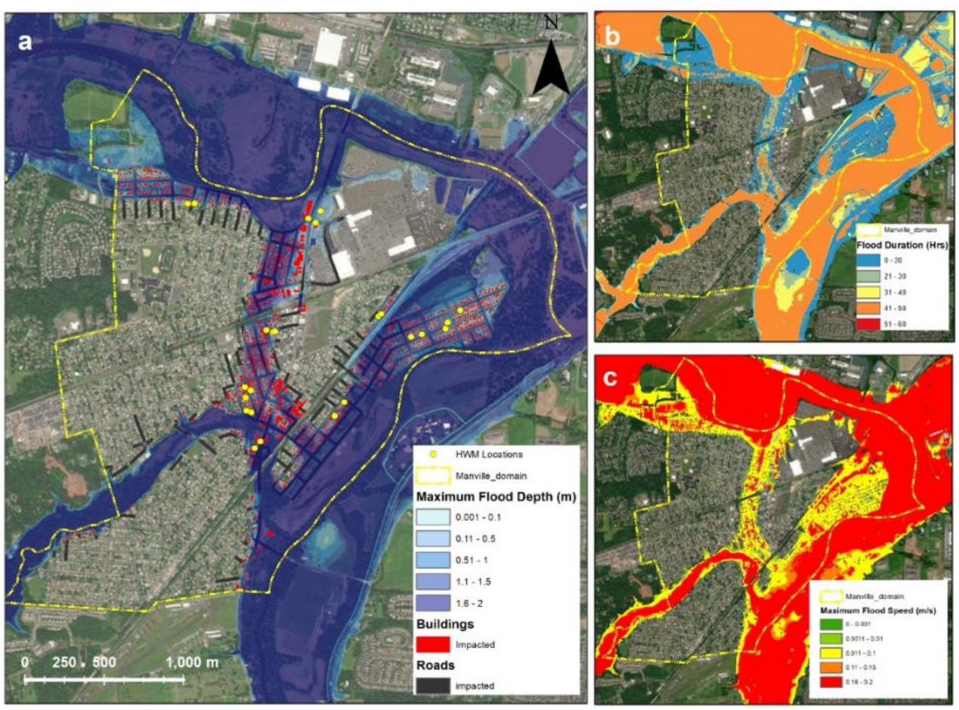

Figure 2 An overview of the simulated flood conditions during hurricane Ida in Manville Township includes a) maximum flood depth in meters, b) flood duration in hours and c) maximum flood speed in

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

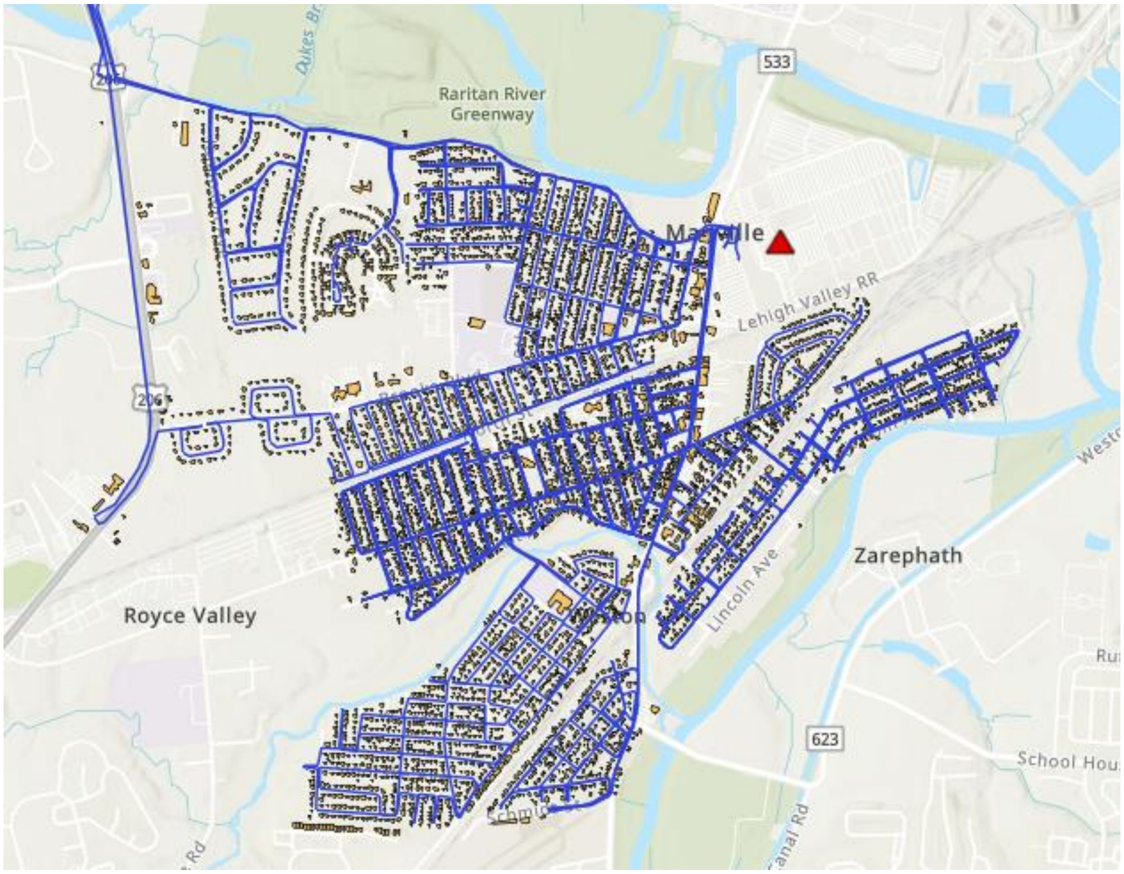

Figure 4 Mapping paths in Manville

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).

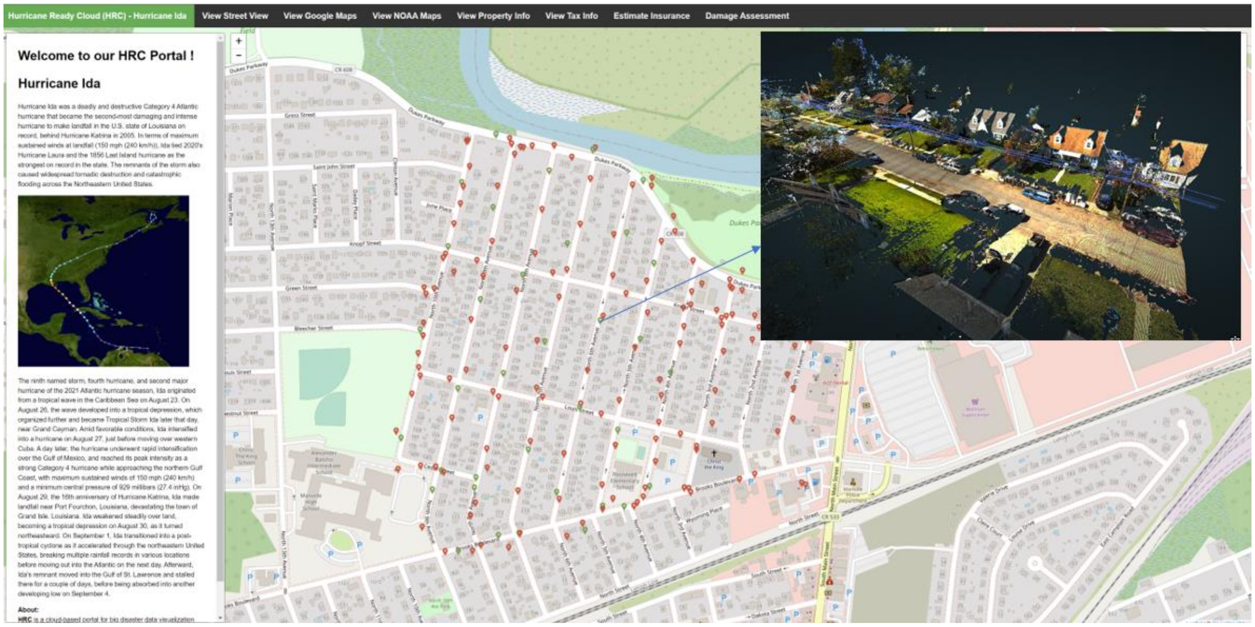

Figure 5 Web-based LiDAR data visualization and elevation data extraction

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?

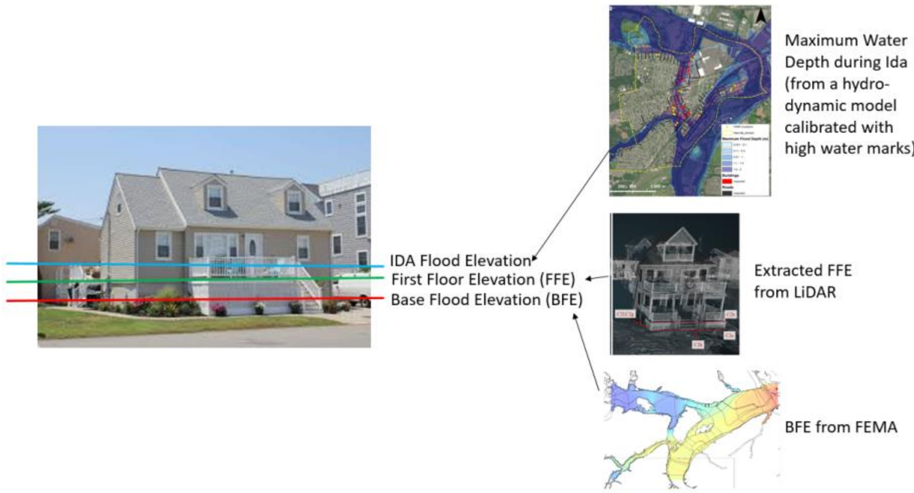

Figure 7 Flood impact analysis to buildings in Manville

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.

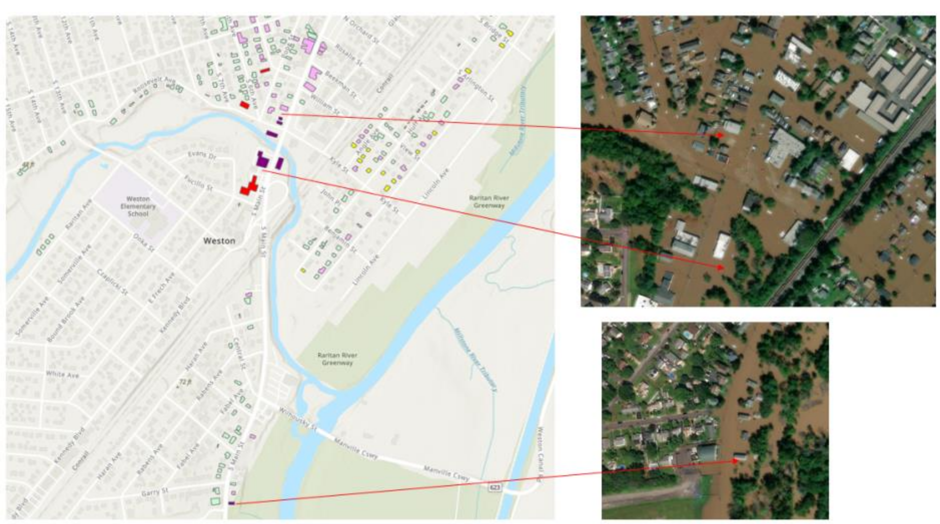

Figure 8 Flood impact to buildings during hurricane Ida

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).

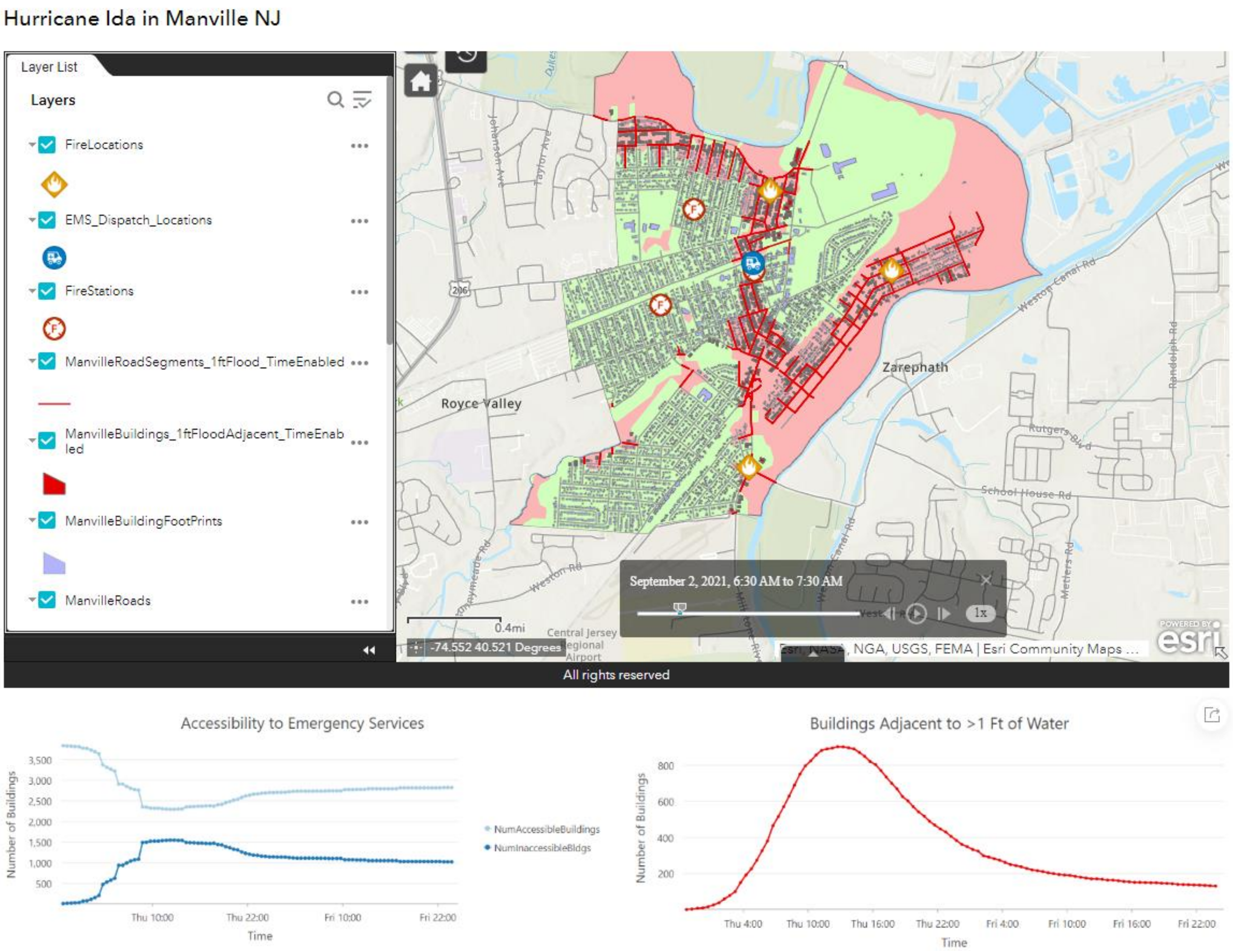

Figure 9 Road network degeneration and essential service disruptions

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

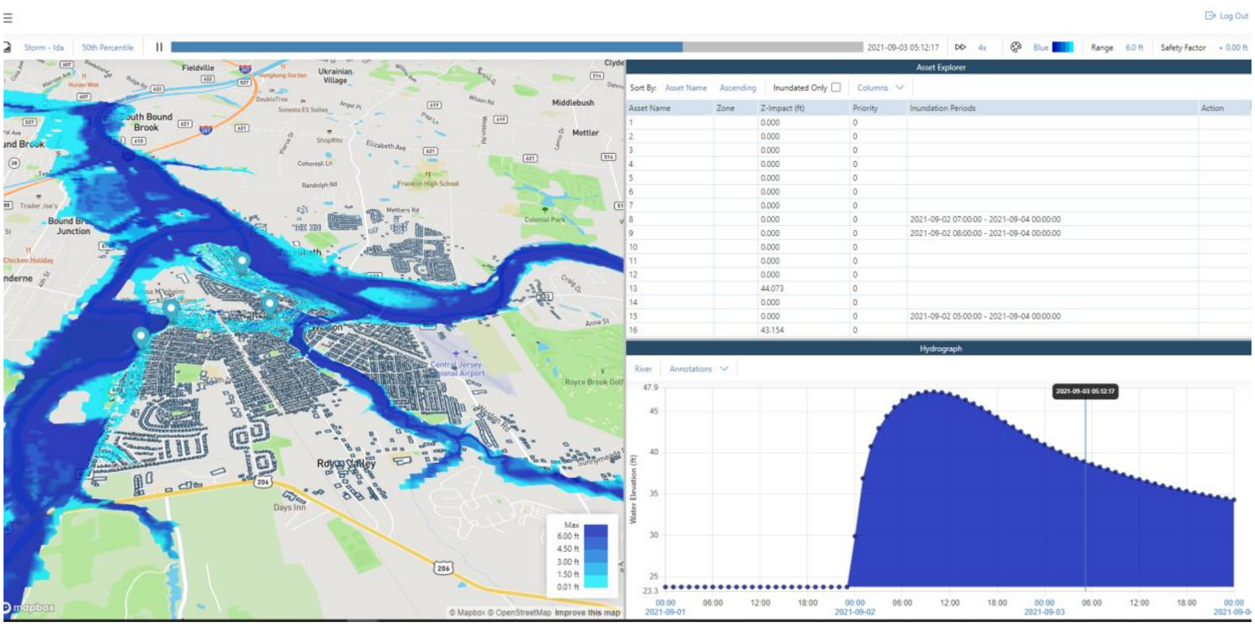

Figure 10 Community-scale flood impact viewer

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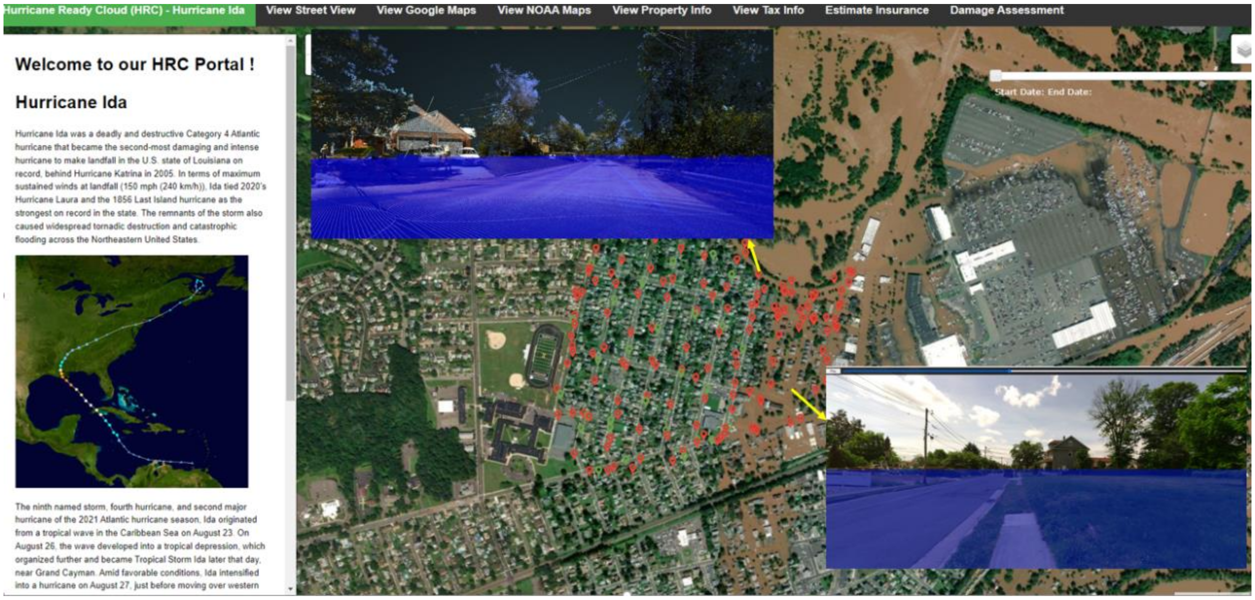

Figure 11 Building-scale viewer for flood impact

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.

REFERENCES

Abdessamed, D., & Abderrazak, B. (2019). Coupling HEC-RAS and HEC-HMS in rainfall–runoff modeling and evaluating floodplain inundation maps in arid environments: case study of Ain Sefra city, Ksour Mountain. SW of Algeria. *Environmental Earth Sciences*, *78*(19), 586. https://doi.org/10.1007/s12665-019-8604-6

Alfieri, L., Burek, P., Dutra, E., Krzeminski, B., Muraro, D., Thielen, J., & Pappenberger, F. (2013). GloFAS – global ensemble streamflow forecasting and flood early warning. *Hydrology and Earth System Sciences*, *17*(3), 1161–1175. https://doi.org/10.5194/hess-17-1161-2013

Alsubeai, A., & Burckhard, S. R. (2021). Rainfall-Runoff Simulation and Modelling Using HEC-HMS and HEC-RAS Models: Case Study Tabuk, Saudi Arabia. *Natural Resources*, *12*(10), 321–338. https://doi.org/10.4236/nr.2021.1210022

Balbhadra, T., Ranjan, P., Ajay, K., Sajjad, A., & Ritu, G. (2022). Coupling HEC-RAS and HEC-HMS in Precipitation Runoff Modelling and Evaluating Flood Plain Inundation Map. In *World Environmental and Water Resources Congress 2017* (pp. 240–251). https://doi.org/doi:10.1061/9780784480625.022

Beretta, R., Ravazzani, G., Maiorano, C., & Mancini, M. (2018). Simulating the influence of buildings on flood inundation in Urban areas. *Geosciences (Switzerland)*, *8*(2). https://doi.org/10.3390/geosciences8020077

Bessar, M. A., Choné, G., Lavoie, A., Buffin-Bélanger, T., Biron, P. M., Matte, P., & Anctil, F. (2021). Comparative analysis of local and large-scale approaches to floodplain mapping: a case study of the Chaudière River. *Canadian Water Resources Journal / Revue Canadienne Des Ressources Hydriques*, *46*(4), 194–206. https://doi.org/10.1080/07011784.2021.1961610

Bharath, A., Shivapur, A. V, Hiremath, C. G., & Maddamsetty, R. (2021). Dam break analysis using HEC-RAS and HEC-GeoRAS: A case study of Hidkal dam, Karnataka state, India. *Environmental Challenges*, *5*, 100401. https://doi.org/https://doi.org/10.1016/j.envc.2021.100401

Brunner, G. W. (2021). *HEC-RAS HEC-RAS 2D User ' s Manual*. *January*, 171.

Bureau United States Census. (2021). *QuickFacts: Manville borough, New Jersey*. United States Census Bureau.

Buta, C., Mihai, G., & Stănescu, M. (2017). Flash floods simulation in a small drainage basin using HEC-RAS hydraulic model. *Ovidius University Annals of Constanta - Series Civil Engineering*, *19*(1), 101–118. https://doi.org/doi:10.1515/ouacsce-2017-0009

City of New York. (2013). *a Stronger , More Resilient New York*. http://s-media.nyc.gov/agencies/sirr/SIRR_singles_Lo_res.pdf

Costabile, P., Costanzo, C., Ferraro, D., Macchione, F., & Petaccia, G. (2020). Performances of the New HEC-RAS Version 5 for 2-D Hydrodynamic-Based Rainfall-Runoff Simulations at Basin Scale: Comparison with a State-of-the Art Model. In *Water* (Vol. 12, Issue 9). https://doi.org/10.3390/w12092326

Didier, D., Baudry, J., Bernatchez, P., Dumont, D., Sadegh, M., Bismuth, E., Bandet, M., Dugas, S., & Sévigny, C. (2019). Multihazard simulation for coastal flood mapping: Bathtub versus numerical modelling in an open estuary, Eastern Canada. *Journal of Flood Risk Management*, *12*(S1), e12505. https://doi.org/https://doi.org/10.1111/jfr3.12505

Ehret, U., Götzinger, J., Bárdossy, A., & Pegram, G. G. S. (2008). Radar-based flood forecasting in small catchments, exemplified by the Goldersbach catchment, Germany. *International Journal of River*

Basin Management, *6*(4), 323–329. https://doi.org/10.1080/15715124.2008.9635359

Emerton, R. E., Stephens, E. M., Pappenberger, F., Pagano, T. C., Weerts, A. H., Wood, A. W., Salamon, P., Brown, J. D., Hjerdt, N., Donnelly, C., Baugh, C. A., & Cloke, H. L. (2016). Continental and global scale flood forecasting systems. *WIREs Water*, *3*(3), 391–418. https://doi.org/https://doi.org/10.1002/wat2.1137

Gallegos, H. A., Schubert, J. E., & Sanders, B. F. (2012). Structural Damage Prediction in a High-Velocity Urban Dam-Break Flood: Field-Scale Assessment of Predictive Skill. *Journal of Engineering Mechanics*, *138*(10), 1249–1262. https://doi.org/10.1061/(asce)em.1943-7889.0000427

Garrote, J., González-Jiménez, M., Guardiola-Albert, C., & Díez-Herrero, A. (2021). The Manning's Roughness Coefficient Calibration Method to Improve Flood Hazard Analysis in the Absence of River Bathymetric Data: Application to the Urban Historical Zamora City Centre in Spain. In *Applied Sciences* (Vol. 11, Issue 19). https://doi.org/10.3390/app11199267

Ghanem, R., & Red-Horse, J. (2017). Polynomial Chaos: Modeling, Estimation, and Approximation. In *Handbook of Uncertainty Quantification*. https://doi.org/10.1007/978-3-319-12385-1

Hamdan, A. N., Almuktar, S., & Scholz, M. (2021). Rainfall-Runoff Modeling Using the HEC-HMS Model for the Al-Adhaim River Catchment, Northern Iraq. In *Hydrology* (Vol. 8, Issue 2). https://doi.org/10.3390/hydrology8020058

Hunter, E. (2019). *Rartian River Basin Elevation Data*. Rutgers University.

Jansen, L., Korswagen, P. A., Bricker, J. D., Pasterkamp, S., de Bruijn, K. M., & Jonkman, S. N. (2020). Experimental determination of pressure coefficients for flood loading of walls of Dutch terraced houses. *Engineering Structures*, *216*, 110647. https://doi.org/https://doi.org/10.1016/j.engstruct.2020.110647

Jordi, A., Georgas, N., Blumberg, A., Yin, L., Chen, Z., Wang, Y., Schulte, J., Ramaswamy, V., Runnels, D., & Saleh, F. (2019). A Next-Generation Coastal Ocean Operational System: Probabilistic Flood Forecasting at Street Scale. *Bulletin of the American Meteorological Society*, *100*(1), 41–54. https://doi.org/10.1175/BAMS-D-17-0309.1

Krajewski, A., Sikorska-Senoner, A. E., Hejduk, A., & Hejduk, L. (2020). Variability of the initial abstraction ratio in an urban and an agroforested catchment. *Water (Switzerland)*, *12*(2). https://doi.org/10.3390/w12020415

Kreibich, H., Piroth, K., Seifert, I., Maiwald, H., Kunert, U., Schwarz, J., Merz, B., & Thieken, A. H. (2009). Is flow velocity a significant parameter in flood damage modelling? *Natural Hazards and Earth System Sciences*, *9*(5), 1679–1692. https://doi.org/10.5194/nhess-9-1679-2009

Kundzewicz, Z. W., Kanae, S., Seneviratne, S. I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L. M., Arnell, N., Mach, K., Muir-Wood, R., Brakenridge, G. R., Kron, W., Benito, G., Honda, Y., Takahashi, K., & Sherstyukov, B. (2014). Flood risk and climate change: global and regional perspectives. *Hydrological Sciences Journal*, *59*(1), 1–28. https://doi.org/10.1080/02626667.2013.857411

Loveland, M., Kiaghadi, A., Dawson, C. N., Rifai, H. S., Misra, S., Mosser, H., & Parola, A. (2021). Developing a Modeling Framework to Simulate Compound Flooding: When Storm Surge Interacts With Riverine Flow. In *Frontiers in Climate* (Vol. 2).

Marsooli, R., & Wang, Y. (2020). Quantifying Tidal Phase Effects on Coastal Flooding Induced by Hurricane Sandy in Manhattan, New York Using a Micro-Scale Hydrodynamic Model. *Frontiers in Built Environment*.

Marvi, M. T. (2020). A review of flood damage analysis for a building structure and contents. *Natural Hazards*, *102*(3), 967–995. https://doi.org/10.1007/s11069-020-03941-w

Melillo, J., Richmond, T. (T. C. ., & Yohe, G. (2014). *Climate Change Impacts in the United States: The Third National Climate Assessment*. https://doi.org/doi:10.7930/J0Z31WJ2

Microsoft. (2021). *Building Footprints*. Microsoft.

Milanesi, L., Pilotti, M., & Ranzi, R. (2014). A conceptual model of people's vulnerability to floods. *Water Resource Research*, *51*, 2498–2514. https://doi.org/10.1002/2015WR017200.A

Ming, X., Liang, Q., Xia, X., Li, D., & Fowler, H. J. (2020). Real-Time Flood Forecasting Based on a High-Performance 2-D Hydrodynamic Model and Numerical Weather Predictions. *Water Resources Research*, *56*(7), e2019WR025583. https://doi.org/https://doi.org/10.1029/2019WR025583

Nance, D. V. (2015). *Stochastic Estimation via Polynomial Chaos* (Issue October).

Nguyen, H. Q., Degener, J., & Kappas, M. (2015). Flash Flood Prediction by Coupling KINEROS2 and HEC-RAS Models for Tropical Regions of Northern Vietnam. In *Hydrology* (Vol. 2, Issue 4). https://doi.org/10.3390/hydrology2040242

NJDEP. (2015). *Land Use/Land Cover 2012 Update, Edition 20150217 Subbasin 02030105 - Raritan (Land_lu_2012_hu02030105)*.

OCM Partners. (2021). *CoNED Topobathymetric Model for New Jersey and Delaware, 1880 to 2014*. NOAA National Centers for Environmental Information.

Pappenberger, F., Thielen, J., & Del Medico, M. (2011). The impact of weather forecast improvements on large scale hydrology: Analysing a decade of forecasts of the European Flood Alert System. *Hydrological Processes*, *25*(7), 1091–1113. https://doi.org/10.1002/hyp.7772

Psomiadis, E., Tomanis, L., Kavvadias, A., Soulis, K. X., Charizopoulos, N., & Michas, S. (2021). Potential Dam Breach Analysis and Flood Wave Risk Assessment Using HEC-RAS and Remote Sensing Data: A Multicriteria Approach. In *Water* (Vol. 13, Issue 3). https://doi.org/10.3390/w13030364

Ramachandran, A., Palanivelu, K., Mudgal, B. V, Jeganathan, A., Guganesh, S., Abinaya, B., & Elangovan, A. (2019). Climate change impact on fluvial flooding in the Indian sub-basin: A case study on the Adyar sub-basin. *PLOS ONE*, *14*(5), e0216461.

Ramaswamy, V., & Saleh, F. (2020). Ensemble Based Forecasting and Optimization Framework to Optimize Releases from Water Supply Reservoirs for Flood Control. *Water Resources Management*, *34*(3), 989–1004. https://doi.org/10.1007/s11269-019-02481-8

Rehman, S., Sahana, M., Hong, H., Sajjad, H., & Ahmed, B. Bin. (2019). A systematic review on approaches and methods used for flood vulnerability assessment: framework for future research. *Natural Hazards*, *96*(2), 975–998. https://doi.org/10.1007/s11069-018-03567-z

Romali, N. S., Yusop, Z., & Ismail, A. Z. (2018). Hydrological Modelling using HEC-HMS for Flood Risk Assessment of Segamat Town, Malaysia. *IOP Conference Series: Materials Science and Engineering*, *318*, 12029. https://doi.org/10.1088/1757-899x/318/1/012029

ROSS, C. W., PRIHODKO, L., ANCHANG, J., KUMAR, S., JI, W., & HANAN, N. P. (2018). *Global Hydrologic Soil Groups (HYSOGs250m) for Curve Number-Based Runoff Modeling*. ORNL Distributed Active Archive Center. https://doi.org/10.3334/ORNLDAAC/1566

Saleh, F., Ramaswamy, V., Wang, Y., Georgas, N., Blumberg, A., & Pullen, J. (2017). A multi-scale ensemble-based framework for forecasting compound coastal-riverine flooding: The Hackensack-

Passaic watershed and Newark Bay. *Advances in Water Resources*, *110*. https://doi.org/10.1016/j.advwatres.2017.10.026

Saleh, Firas, Ramaswamy, V., Georgas, N., Blumberg, A. F., & Pullen, J. (2016). A retrospective streamflow ensemble forecast for an extreme hydrologic event: A case study of Hurricane Irene and on the Hudson River basin. *Hydrology and Earth System Sciences*, *20*(7), 2649–2667. https://doi.org/10.5194/hess-20-2649-2016

Schwarz, J., & Maiwald, H. (2008). *DAMAGE AND LOSS PREDICTION MODEL BASED ON THE VULNERABILITY OF BUILDING TYPES*.

Shabani, A., Woznicki, S. A., Mehaffey, M., Butcher, J., Wool, T. A., & Whung, P.-Y. (2021). A coupled hydrodynamic (HEC-RAS 2D) and water quality model (WASP) for simulating flood-induced soil, sediment, and contaminant transport. *Journal of Flood Risk Management*, *14*(4), e12747. https://doi.org/https://doi.org/10.1111/jfr3.12747

Sweet, W. V, Horton, R., Kopp, R. E., LeGrande, A. N., & Romanou, A. (2017). Sea level rise. In D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, & T. K. Maycock (Eds.), *Climate Science Special Report: Fourth National Climate Assessment, Volume I* (pp. 333–363). U.S. Global Change Research Program. https://doi.org/10.7930/J0VM49F2

Tamiru, H., & Dinka, M. O. (2021). Application of ANN and HEC-RAS model for flood inundation mapping in lower Baro Akobo River Basin, Ethiopia. *Journal of Hydrology: Regional Studies*, *36*, 100855. https://doi.org/https://doi.org/10.1016/j.ejrh.2021.100855

Thakur, B., Parajuli, R., Kalra, A., Ahmad, S., & Gupta, R. (2017). Coupling HEC-RAS and HEC-HMS in Precipitation Runoff Modelling and Evaluating Flood Plain Inundation Map. *World Environmental and Water Resources Congress 2017: Hydraulics and Waterways and Water Distribution Systems Analysis - Selected Papers from the World Environmental and Water Resources Congress 2017*, 240–251. https://doi.org/10.1061/9780784480625.022

Thieken, A. H., Müller, M., Kreibich, H., & Merz, B. (2005). Flood damage and influencing factors: New insights from the August 2002 flood in Germany. *Water Resources Research*, *41*(12). https://doi.org/https://doi.org/10.1029/2005WR004177

U.S. Army Corps of Engineers. (2021). Creating Land Cover, Manning's n Values, and Impervious Layers. *HEC-RAS 2D User's Manual*.

USACE. (2000). Hydrologic Modeling System Technical Reference Manual. *HEC-HMS Technical Reference Manual*, *March*, 148.

Wang, Y., & Marsooli, R. (2021a). Dynamic modeling of sea-level rise impact on coastal flood hazard and vulnerability in New York City's built environment. *Coastal Engineering*, *169*, 103980. https://doi.org/https://doi.org/10.1016/j.coastaleng.2021.103980

Wang, Y., & Marsooli, R. (2021b). Physical Instability of Individuals Exposed to Storm-Induced Coastal Flooding: Vulnerability of New Yorkers During Hurricane Sandy. *Water Resources Research*, *57*(1), e2020WR028616. https://doi.org/https://doi.org/10.1029/2020WR028616

Werner, M., Cranston, M., Harrison, T., Whitfield, D., & Schellekens, J. (2009). Recent developments in operational flood forecasting in England, Wales and Scotland. *Meteorological Applications*, *16*(1), 13–22. https://doi.org/https://doi.org/10.1002/met.124

Xia, J., Falconer, R. A., Wang, Y., & Xiao, X. (2014). New criterion for the stability of a human body in floodwaters. *Journal of Hydraulic Research*, *52*(1), 93–104. https://doi.org/10.1080/00221686.2013.875073

Xing, Y., Liang, Q., Wang, G., Ming, X., & Xia, X. (2019). City-scale hydrodynamic modelling of urban flash floods: the issues of scale and resolution. *Natural Hazards*, *96*(1), 473–496. https://doi.org/10.1007/s11069-018-3553-z

Ynaotou, Jayadi, R., Rahardjo, A. P., & Puspitosari, D. A. (2021). Identification of Flood-prone Areas using HEC-HMS and HEC-RAS, the Case of Ciberang River Basin, Lebak District of Banten Province. *IOP Conference Series: Earth and Environmental Science*, *930*(1), 012082. https://doi.org/10.1088/1755-1315/930/1/012082

Zhang, H. L., Wang, Y. J., Wang, Y. Q., Li, D. X., & Wang, X. K. (2013). The effect of watershed scale on HEC-HMS calibrated parameters: a case study in the Clear Creek watershed in Iowa, US. *Hydrology and Earth System Sciences*, *17*(7), 2735–2745. https://doi.org/10.5194/hess-17-2735-2013

Zheng, Y., Li, J., Dong, L., Rong, Y., Kang, A., & Feng, P. (2020). Estimation of Initial Abstraction for Hydrological Modeling Based on Global Land Data Assimilation System–Simulated Datasets. *Journal of Hydrometeorology*, *21*(5), 1051–1072. https://doi.org/10.1175/JHM-D-19-0202.1