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Pluvial and compound flooding in a coupled coastal system modeling framework: New York City during post-tropical cyclone Ida (2021)

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Abstract

Coastal-urban areas, like all urban areas, are highly vulnerable to extreme pluvial flooding exacerbated by limitations in stormwater system capacity, but with the additional potential for flooding to be compounded by storm surge, tides, and waves. Understanding and simulating these processes can improve prediction and flood risk management. Here, we improve the Regional Ocean Modeling System (ROMS) within the Coupled Ocean-Atmosphere-Wave-Sediment Transport framework (COAWST) to simulate post-tropical cyclone Ida (2021) pluvial flooding for the Jamaica Bay watershed of New York City (NYC). We modify the model to capture the volumetric effects of rainfall and parameterize soil infiltration and a stormwater conveyance system as a drainage rate. We generate a spatially continuous flood map of Ida with RMS error of 28 cm when compared to high water marks, useful for understanding Ida's impacts and subsequent mitigation planning. Results show that over 37.2 km^2 of urban area in the watershed were deeply flooded (deeper than 0.3 m) during Ida. Sensitivity analyses are used to study the broader risk from events like Ida and compound flooding. Spatial shifting of the storm track within typical 12-hour forecast track uncertainty reveals a worst-case scenario that increases the deeply flooded area to 74.7 km^2. Shifting Ida's rainfall to coincide with high tide increases deeply flooded area by 0.3 km^2, a relatively small change due to the lack of significant storm surge and the significant pluvial flood area. The application of COAWST to this storm event addresses a broader goal of developing the capability to model compound flooding by simultaneously representing coastal storm processes such as rain, tide, waves, erosion, and atmosphere-wave-ocean interactions. The sensitivity analysis results underscore the need for detailed flood risk assessments, showing that Ida, already NYC's worst rain event, could have been even more devastating with slight shifts in storm track.

Key words: Modeling, Pluvial flood, Compound flood, Ida, Jamaica Bay, New York City

1. Introduction and motivation

Coastal regions offer numerous socio-economic and ecological advantages to humans yet face an increasing susceptibility to the detrimental impacts of coastal storms and rising sea levels. Such disturbances precipitate a cascade of geomorphological and hydrodynamic changes along shorelines, defined by intense wave action, coastal inundation, erosion, and strong currents, that pose severe threats to human life. An increase of flooding is anticipated due to global warming influences that raise sea levels and augment the atmospheric capacity for moisture retention, thereby increasing the frequency of intense rainfall events (Slater and Villarini, 2016; Trenberth, 2011; Zhu, 2013). In the United States, coastal counties, which house nearly 40% of the population, face substantial risks of flooding due to their low-lying, densely populated, and often extensively developed nature (National Oceanic and Atmospheric Administration, 2023). As such, communities and authorities in flood-prone areas are increasingly confronted with the need to prepare for or respond to these escalating risks (Zinda et al., 2021).

Understanding the underlying mechanisms of these coastal processes and improving predictive models is imperative for informed coastal management and storm preparedness. These improvements can upgrade emergency management by capturing more aspects of coastal storm hazards in forecasts. They can also enable planners and coastal managers to increase awareness, minimize loss of life and property, and support sustainable development by better managing coastal resources.

Coastal flooding can arise from tides, storm surges, waves and intense precipitation, with the latter influencing direct runoff (pluvial) or increased river discharge (fluvial). The concurrence of these flood drivers, termed compound flooding, amplifies the potential for inundation of low-lying coastal areas, surpassing the risk associated with each mechanism in isolation. Recent studies of compound coastal flooding have primarily been statistical, bivariate copula, assessing the joint probability of water level variability due to the tides or storm surge and rainfall (Zellou and Rahali, 2019; Jane et al., 2022; Kim et al., 2022). A bivariate copula is a statistical tool used in compound flood research to capture and analyze the joint dependance of variables such as river discharge and coastal water levels (Genest and Favre, 2007). An investigation of historical data showed a higher possibility of co-occurrence of storm surge and heavy rainfall for the Atlantic and Gulf coasts in comparison with the Pacific coast (Wahl et al., 2015). The same study found an increase in such compound events in some coastal cities including New York City (NYC) over the past century due to a shift in weather patterns.

In the field of flood modeling, development of coupled hydrologic, hydraulic, and coastal models is rare. It is critical to shift towards modeling frameworks that comprehensively integrate these physical processes, or we may underestimate flooding. A comprehensive review of compound inundation models highlighted previous research emphasizing the importance of integrating the hydraulic and oceanic models to accurately predict fluvial compound flooding, showcasing the complex interactions between storm surge and river discharge (Santiago-Collazo et al., 2019). However, it also mentioned that despite these advances, no existing model fully integrates all possible interaction between storm surge and rainfall runoff (pluvial compound), which should be the focus of future researches (Santiago-Collazo et al., 2019). A recent review underscored a concerning neglect of the pluvial flood driver in compound flood risk assessment, showing the essential need for more comprehensive models (Bulti and Abebe, 2020). The Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) coastal system model couples the Regional Ocean Modeling System (ROMS) with atmospheric, wave, and sediment transport models, enabling the simulation of interactions and feedbacks between these systems (Bao et al., 2022). Unlike models such as Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) (Peters, 1998), Interconnected Channel and Pond Routing (ICPR)

(Schroeder et al., 2022), and Storm Water Management Model (SWMM) (Rossman and Huber, 2016), which fundamentally investigate inland hydrological and stormwater system processes, COAWST also incorporates three-dimensional hydrodynamics which is important for coastal and estuarine areas.

This research improves the COAWST modeling system to enable pluvial and compound flood simulations and applies it to the recent impact of Ida in 2021 on New York City. Ida caused the 5th wettest day in NYC history with over 17.8 cm (7 inches) rain in total (at Central Park) and set the single-hour rain record at 8 cm (3.15 inches). (New York City Government, 2023; Fema, 2023; National Severe Storms Laboratory, 2021). Smith et al. (2023) documented the extreme short duration rainfall and the flooding caused by Ida in eastern Pennsylvania and New Jersey, emphasizing the role of supercell thunderstorms. In this study, we use the modeling system to investigate impacts of Ida on the Jamaica Bay watershed within NYC, including examining the dependence of the flooding on the storm track and timing through alternative scenarios. Section 2 details the methodology of the coupled modeling framework to simulate urban-pluvial flood by handling volumetric effects of rainfall and urban stormwater drainage. Section 3 presents model calibration and validation using empirical High-Water Marks, which sets the stage for a discussion on the model's predictive strengths and areas of potential improvement. To investigate whether Ida, already NYC's most extreme rainfall event, could have been worse, we study multiple scenarios. Sensitivity analysis then illustrates Jamaica Bay's vulnerability to storm track variations and temporal shifts of the storm. Section 4 discusses the findings and implications of the study. Section 5 summarizes the key findings and presents the conclusion of the research.

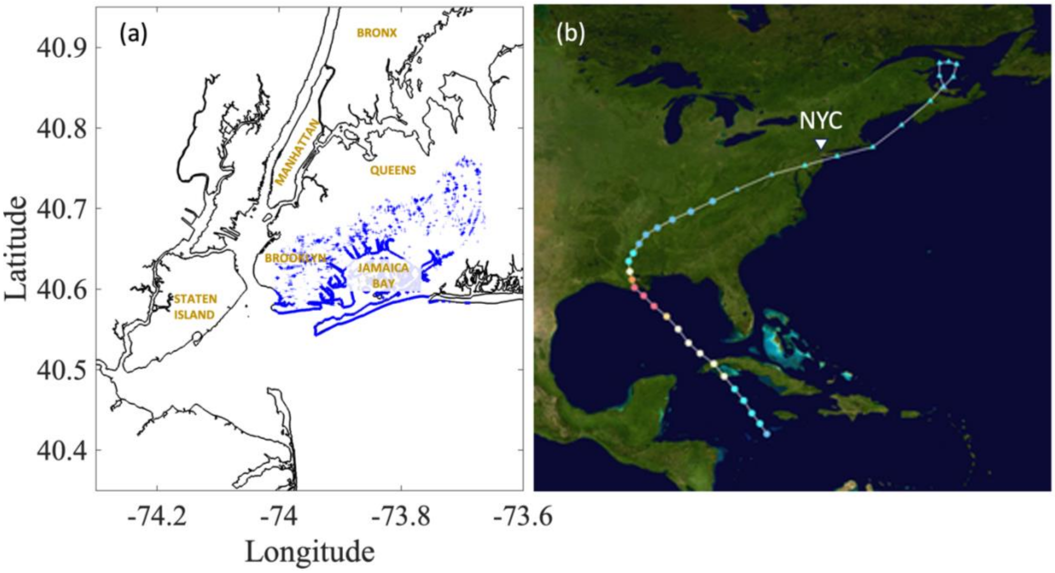

Figure 1. a) Jamaica Bay location in New York City and its watershed area (shown with blue contour), b) Ida storm track (modified from: https://en.wikipedia.org/wiki/Hurricane_Ida)

2. Methods

2.1. Storm event and study site

Ida formed in the western Caribbean Sea southwest of Jamaica near 23 Aug 2021, 12:00 UTC. It first hit western Cuba as a Category 1 hurricane and later transformed into an extratropical low. The tropical cyclone travelled northwest and strengthened as it entered the Gulf of Mexico. Sea surface temperatures near 30ºC led to continued intensification and the storm became a Category 4 before making landfall as a Category 4 hurricane at the Louisiana coast near Port Fourchon on 29 Aug 2021, 16:55 UTC. After landfall, the storm continued to travel across the United States and resulted in severe rainfall and deadly flooding in Pennsylvania, New Jersey, New York, Connecticut and Maryland (Beven et al., 2022). At NYC, the storm's sustained rainfall overwhelmed stormwater conveyance systems (sewers) and turned streets into rivers in many places, including severe flooding in all five boroughs (Finkelstein et al., 2023).

The coastal embayment and surrounding watershed of Jamaica Bay is a part of New York City (NYC) that experienced extensive pluvial flooding during Ida (Fig. 1). Over 2.8 million people live in Jamaica Bay watershed (NYC-DEP, 2018), and many are situated within range of a realistic 5-meter coastal flood (Orton et al., 2015). Jamaica Bay has an area of 72 km^2, encompassing over 15 km^2 of marshes and 4.6 km^2 of intertidal unvegetated areas, hosting a wide range of habitats and wildlife and offering a variety of recreational opportunities (Orton et al., 2020a; Orton et al., 2020b; Swanson et al., 2016).

2.2. Modeling

The COAWST modeling system integrates multiple components to comprehensively simulate coastal system interactions (Warner et al., 2010). These components include models for the ocean, atmosphere, surface waves, sediment transport, a coupler to exchange data fields, and a re-gridding method. This gives COAWST capabilities that are not typically available with urban hydraulic-hydrologic models (see Sec. 4 for examples), which are used to design improvements to water infrastructural systems and for predicting urban water cycle processes. These include the interaction between the ocean and atmosphere, such as sea-surface temperature, or wave dynamics such as wave generation and propagation. In addition, it models sediment transport and coastal morphodynamics.

2.2.1. Hydrodynamic Model

The ocean model is the Regional Ocean Modeling System (ROMS), which is a three-dimensional, free-surface, terrain-following hydrodynamic model (Shchepetkin and McWilliams, 2005; Haidvogel et al., 2008). It employs finite-difference approximations of the Reynolds-Averaged Navier-Stokes (RANS) equations under the hydrostatic and Boussinesq assumptions (Haidvogel et al., 2000; Chassignet et al., 2000). In ROMS, the hydrostatic primitive equations are approximated through the utilization of boundary-fitted, orthogonal curvilinear coordinates on a staggered Arakawa C-grid. The vertical dimension uses stretched terrain-following coordinates.

We adapt the ROMS component in COAWST model for this study to account for rain as a volumetric addition to the grid cell, enabling rain-on-grid over water or dry land (COAWSTv3.8). The rain rate is included as an additional spatially and temporally varying meteorological forcing variable. The model can also implicitly account for spatially

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varying floodwater infiltration and flow into stormwater sewers with drain rates that are subtracted from the rain rate. The drain rate can be a negative when it is locally greater than the rain rate. For the Jamaica Bay watershed simulations, we assume a uniform, constant drain rate for the land area and use it as a calibration parameter, as described in Sect. 2.4. Volume of the rain that is removed from the domain with this drain term could be routed in the ocean with additional modifications to model, but this is left for future work as it is not an essential component for this study.

2.2.2. Model domains, nesting and setup

A nested modeling application is used for Ida, with existing larger scale coastal and estuarine domain providing boundary conditions for a higher-resolution Jamaica Bay domain. The model grid of the Jamaica Bay watershed has 818 x 734 cells, averaging 46 x 51 m in size with slight variation across the domain, and 8 uniformly spaced vertical sigma layers. The bare-Earth Digital Elevation Model (DEM) for model bathymetry is created by merging three datasets (with descending order of preference): National Park Service data (Flood, 2011), NOAA-NCEI ninth arc-second resolution DEM (Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado, 2014) and third arc-second resolution bathymetric data (Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado, 2014) (Fig. 2). We use a spatially varied bottom roughness, in which the quadratic bottom roughness coefficient was calculated based on the land cover (Fig. 3). The Coastal Change Analysis Program (C-CAP) is a nationally standardized effort by the NOAA Office for Coastal Management that provides raster-based inventories of land cover for U.S. coastal regions, derived from the analysis of remotely sensed imagery to ensure consistency over time and geography (National Oceanic and Atmospheric Administration, 2016). We use the corresponding manning number for each value of C-CAP (ranges from 0.02 to 0.13) (Mattocks and Forbes, 2008); further we calculate the Zo (bottom roughness) and the quadratic bottom roughness coefficient consecutively. The internal (baroclinic) time step for the simulation is 2.5 seconds, each with 20 external (barotropic) time steps. The COAWST simulation commences from a state of rest and temperature and salinity are initialized as spatially constant values. For wetting and drying, the minimum depth to allow flow out of the cells, Dcrit, is set to 5 cm (Warner et al., 2013).

The Jamaica Bay model is forced with boundary conditions derived from a ROMS simulation of Ida using a larger scale grid that includes the Hudson River estuary and surrounding coastal region, as described by Ralston (2022). The open boundaries are forced with tidal water levels and currents were extracted from the ADCIRC database (Mukai et al., 2002). Additionally, subtidal water levels calculated from observations at the NOAA tide gauges at Sandy Hook (NJ; NOAA station 8531680) and Kings Point (NY; NOAA station 8516945) were added to the boundaries in New York Bight and western Long Island Sound to represent the storm surge. Atmospheric forcing is from the North American Mesoscale Forecast System (NAM) 12 km analysis product. Simulations (in the regional model) are run for the period 10 Aug 2021 to 10 Sep 2021 to allow for model spin-up prior to Ida hitting NYC. Evaluation of this larger-scale model against previous observations of water level, currents, and salinity are reported with skill metrics in Ralston (2022).

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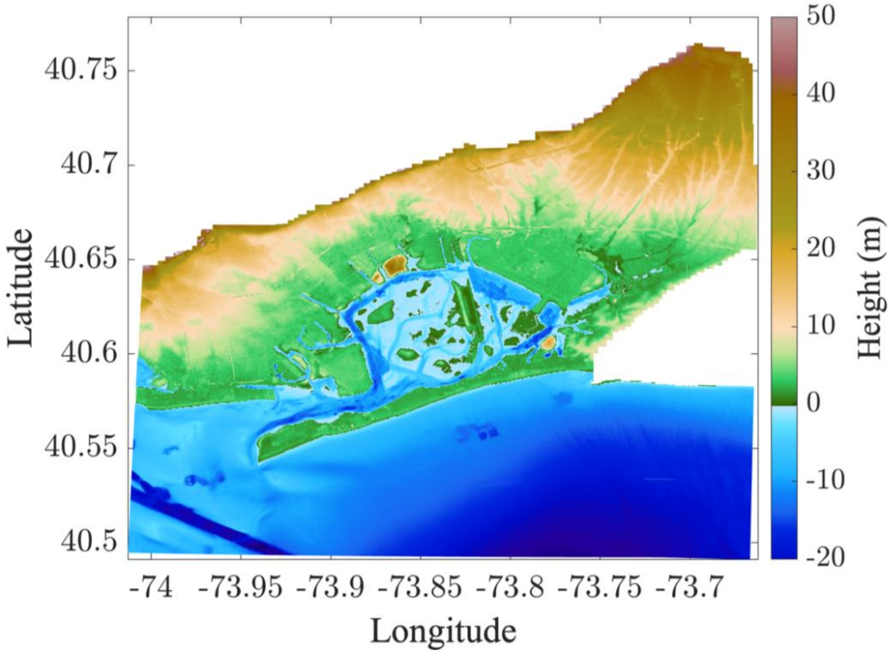
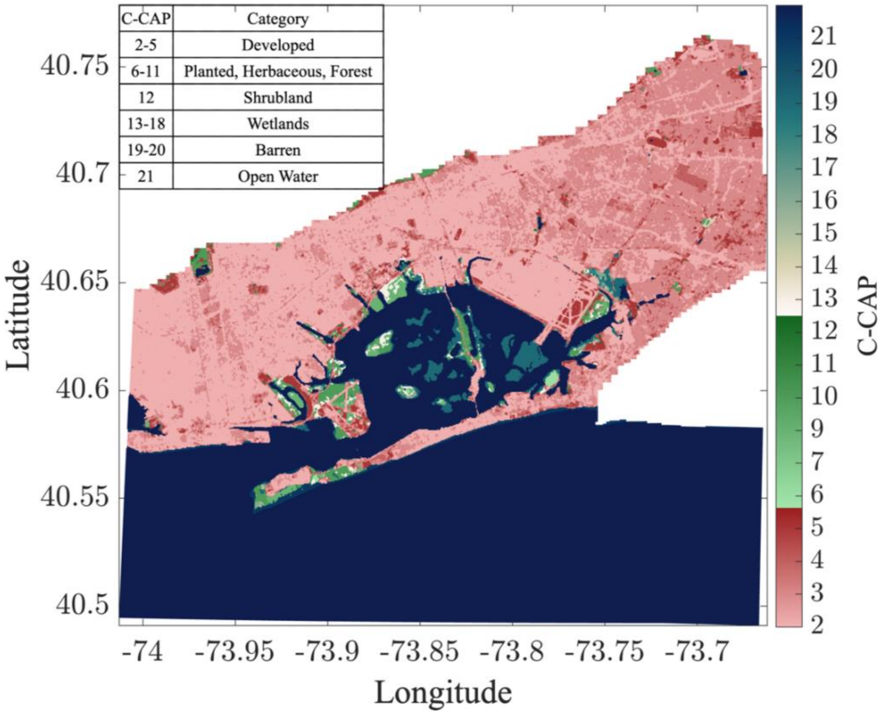


Figure 2. COAWST model DEM (m) covering the Jamaica Bay watershed



C-CAP	Category
2-5	Developed
6-11	Planted, Herbaceous, Forest
12	Shrubland
13-18	Wetlands
19-20	Barren
21	Open Water

Figure 3 Coastal Change Analysis Program (C-CAP) values and the land-cover categories

2.3. Application to post-tropical cyclone Ida

The model is applied to investigate Ida impacts for the Jamaica Bay watershed. All simulations (for the nested model) are initiated with a model time of 28 Aug 2021, 00:00 UTC, when the storm just passed Cuba, and simulations last for six days to 03 Sep 2021, 00:00 UTC. Ida generated only pluvial flooding, since the hour of the most extreme rainfall occurred between low and high tide and the non-tidal anomaly peaked at 0.6 m. At this instance, the observed water level at the Stevens Institute's tide gauge at Bergen Basin in Jamaica Bay was 0.21 m NAVD88, which is not enough to cause coastal flooding or pluvial street flooding. This water level is far below the street level, so should not block outflow through the stormwater drainage system. The coastal water level range during the 6-day simulation period was -0.4 to 1.1 m NAVD88 in Jamaica Bay (Fig. 8).

The simulation incorporates meteorological forcing from the North American Mesoscale (NAM) WRF model product (Center Environmental Modeling, 2017) and rain forcing from the Multi-Radar/Multi-Sensor system (MRMS). The WRF-NAM model provides east and north winds, atmospheric pressure, relative humidity, air temperature, and short and long wave radiation data on a 12-km spatial grid and 3-hour temporal resolution. The MRMS quantitative precipitation estimation (QPE) data have 1.11 km spatial and 1 hour temporal resolution. MRMS, recently developed by the National Centers of Environmental Prediction, merges data from approximately 180 radars to create a high-resolution 3D mosaic that covers the contiguous United States and southern Canada with 1 km spatial and 2 min temporal resolution. The radar-based data are combined with atmospheric environmental data, satellite data, and lightning and rain gauge observation to generate advanced weather monitoring and QPE products. This integration results in a hourly data product with bias correction and integration of multiple sources of information (Zhang et al., 2016). Hourly data provide a robust value for simulating the event, but sub-hourly data could have higher intensities that would create more impact. However, the time resolution of the forcing data precludes sub-hourly analysis. Figure 4 and Figure 5 show maximum hourly intensity and accumulated rain during Ida for the simulation duration. The maximum hourly rainfall intensity noted is 70 mm/hour during the event of Ida, with greater intensity observed on the western side of Jamaica Bay. Additionally, the maximum temporal accumulated rainfall, over 5 days of simulation (mostly happened during a three-hour period starting at 02 Sep 2021, 01:30 UTC), reaches 160 mm. Figure 6 presents time series of rainfall to show how the rain evolves over the 6-day simulation. In this paper, basemaps are generated using MATLAB's 'geobasemap' function with 'topographic' base layer (The Mathworks Inc., 2023).

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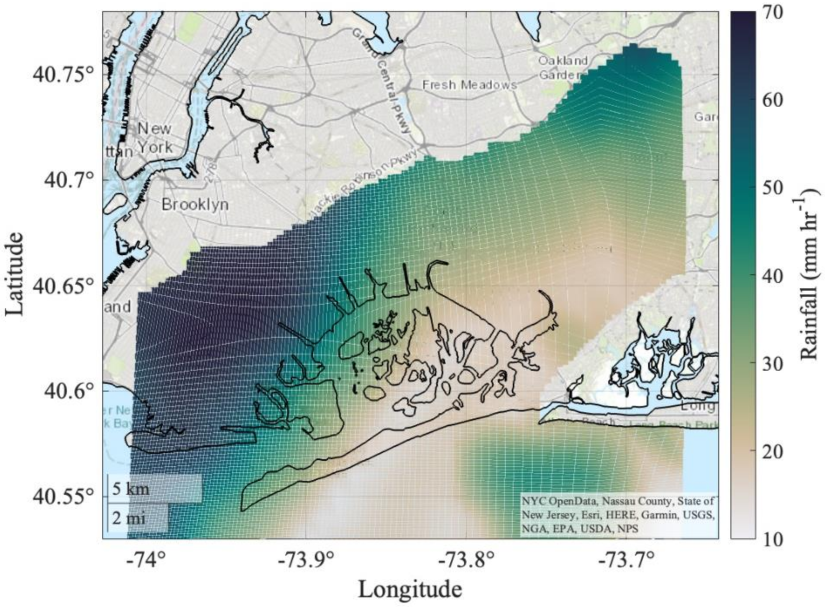

195 **Figure 4. Maximum hourly rain intensity for Ida (topographic base map from MATLAB, hosted by Esri®)**

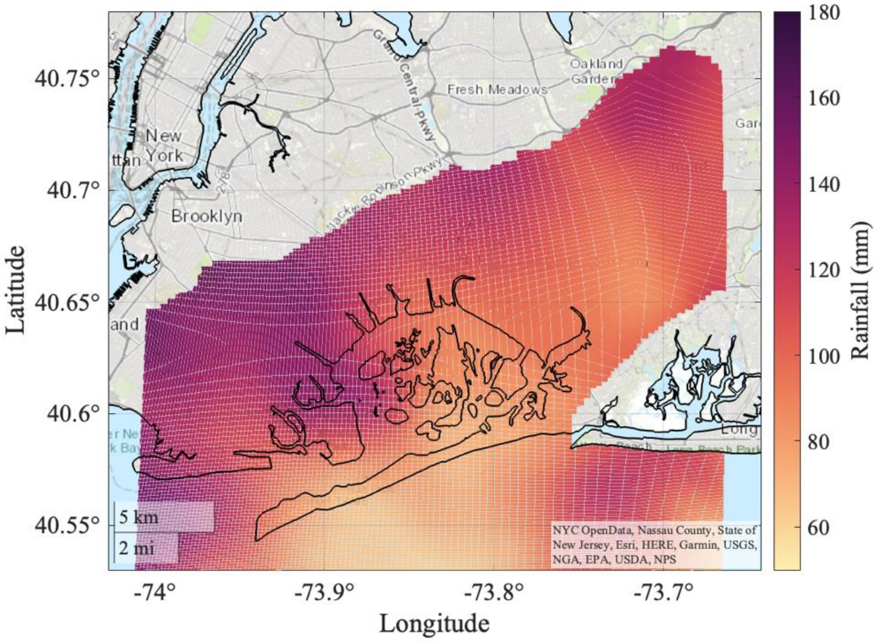

Figure 5. Total accumulated rain during Aug 28, 2021, to Sep 02, 2021, for Ida (topographic base map from MATLAB, hosted by Esri®)

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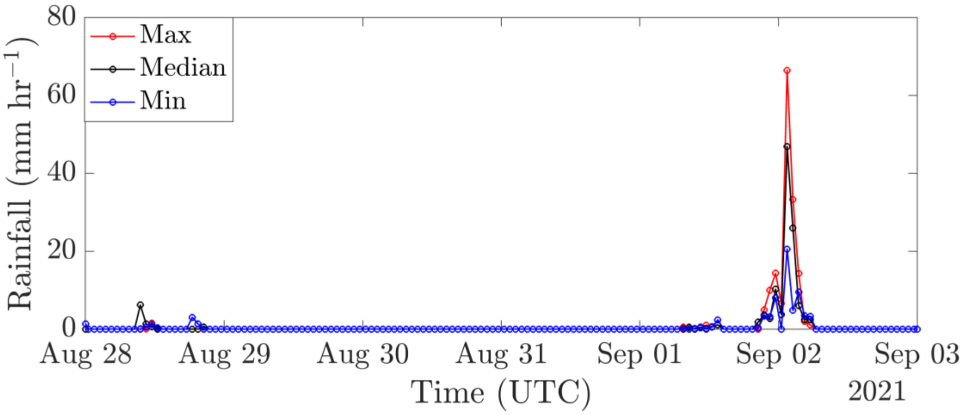

Figure 6. Rainfall time series at (Max) location with the maximum accumulated rain, (Median) location with the median accumulated rain, and (Min) location with the minimum accumulated rain over 6-day simulation.

2.4. Drain rate calibration and context

Rainfall into the study region can have several fates, including infiltration, ponding, surface flow, or interception and export through the drainage system. Because the model does not explicitly include infiltration or a stormwater system, we account for the drainage with what were hereafter refer to as a "drain rate". The drain rate can be influenced by different factors such as the characteristics of the sewer network, land use, soil infiltration rates, and potential blockages in the stormwater system. Given its impact on the results and its relatively unconstrained nature, we start by applying a spatially uniform drain rate and treat it as a calibration parameter. The sensitivity of results to the assumed drain rate is explored with several different values. First, we perform a base simulation with no drain rate with realistic rainfall and atmospheric forcings. This base Ida simulation is initially compared with observations of high-water mark data points, and then drain rates of 6, 13, and 19 mm/hour are investigated to improve the model calibration.

It is informative to compare our calibrated drain rate with an estimate of the required drainage during Ida, the volume of water that stormwater infrastructure must effectively manage to prevent flooding. The Curve Number (CN) method (Cronshey, 1986), a cornerstone in hydrological modeling, is employed to estimate runoff (the required drainage) from this event. This method is defined by the equation Eq. (1):

$$Q\ (mm) = \left(\frac{(P-0.2S)^2}{P+0.8S}\right) \quad (1)$$

where Q represents the runoff, P denotes total precipitation, and S signifies the potential maximum retention after runoff initiation, calculated based on Eq. (2):

$$S\ (mm) = \left(\frac{25400}{CN}\right) - 254 \quad (2)$$

where CN is typically ~90 percent for urban areas (Cronshey, 1986). We consider the rainfall associated with Ida as a concentrated 3-hour period of precipitation (as vast majority of the rain is over three hours according to MRMS), starting at 02 Sep 2021, 00:30 UTC. During this period the rainfall generates approximately 74 mm (2.9

inches) of total accumulation. Using this formula, we determine that Ida would result in 48 mm (1.9 inches) of runoff. This finding, which is based on the rainfall forcing of the event, provides useful context as it denotes the volume of water that the urban stormwater infrastructure must efficiently channel to avert flooding.

2.5. Sensitivity analysis

The sensitivity of flooding in the Jamaica Bay watershed was evaluated using multiple scenarios based on the realistic forcing buy shifting the track and timing of the storm. These hypothetical storm cases are designed to represent worst case and best-case precipitation conditions from Ida for the Jamaica Bay watershed.

At the time Ida passed the New York City metropolitan area, the region with the most intense and widespread rainfall was over New Jersey, 48 km to the west of Jamaica Bay (Fig. 7). Thus, to examine sensitivity, we shift Ida rainfall spatially to the east, to have an approximate “worst case scenario”. This shift is well-within the potential track uncertainty for Ida, given that the National Hurricane Center (NHC) forecast cone of uncertainty at 12 hours prior to storm passage is 48 km. For comparison, we create a “best case scenario” by shifting Ida northward the same distance, which results in much less precipitation over the Jamaica Bay watershed.

Ida’s rain averaged across the Jamaica Bay watershed was 71 mm (2.8 inches) over 3 hours, which is a 10-year return period (between 5 and 25 years) based on NOAA Precipitation Frequency Data Server (GIS data for the Northeastern states (National Weather Service)). While Ida’s rain set records at Central Park and other locations, much of the Jamaica Bay had far lower rainfall rates. Shifting the storm track east by 48 km increases this amount to 145 mm (5.7 inches), which represents a 3-hour rain event with 500-year return period based on NOAA Precipitation Frequency Data Server, and close to a 100-year storm under climate projections (129.54 mm) based on Northeast Regional Climate Center extreme precipitation projections (Cornell University). During this worst-case scenario, all the Jamaica Bay watershed area experiences maximum hourly rain intensity greater than 30 mm/hour, and the watershed area experiencing rainfall intensity greater than 60 mm/hour more than doubles. In addition, total rainfall in this scenario over the six days increases by 48% to 237 mm. In the best-case scenario, the watershed experiences 60% less total rainfall, equal to 64 mm. Figure 7 shows Ida rainfall over the simulation domain (white rectangle), and the regions that the rainfall came from for the eastward shift (red rectangle, with dot line) and the northward shift (blue rectangle, with dash-dot line).

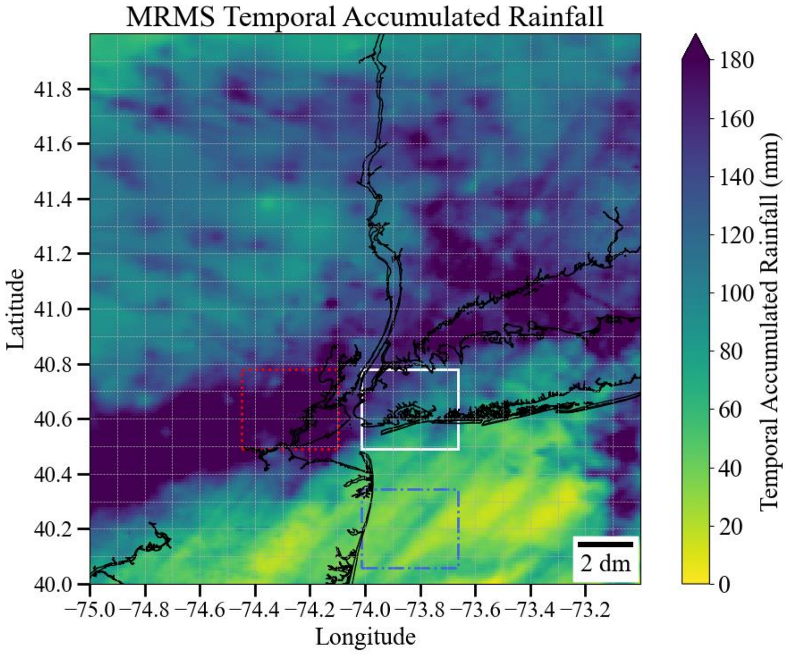

Figure 7 Ida total rain is shown as color shading (temporally accumulated rainfall over the 6-days simulation time). The white box shows the Jamaica Bay domain, whereas the red box (dot line) shows the rain that would fall over the domain if the rain were displaced eastward (worst case scenario), and the blue box (dash-dot line) shows what rain would fall over the domain for a displacement northward (best case scenario).

We also analyze the timing of Ida with tidal conditions to ascertain whether the synchronization of the peak rainfall rates with high tide could exacerbate flooding. Figure 8 illustrates tidal observation from Bergen Basin (location shown in Fig. 9) throughout the simulation period. The most intense rainfall during Ida happened on 02 Sep 2021, 01:30 UTC. We consider two alternative temporal scenarios: 1) positioning the maximum intensity of the Ida rain six hours prior to its actual occurrence, corresponding with the earlier high tide, and 2) a delay of nineteen hours to examine the effects of the storm's peak overlapping with the highest tide during the simulation period. The time of the storm’s peak rain will be shifted from observed timing (when the water level is 0.3 m NAVD88) to occur when the observed water levels are 1.01 m and 1.15 m NAVD88, respectively.

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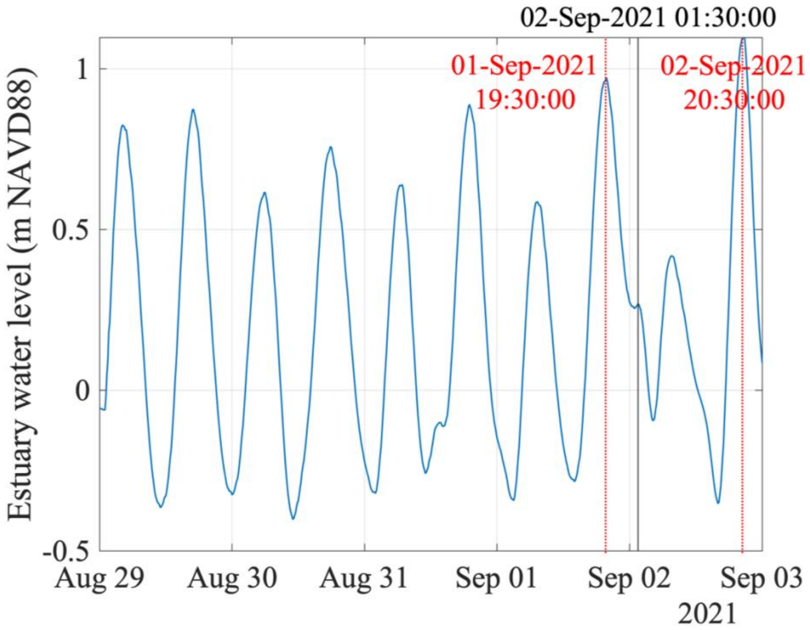


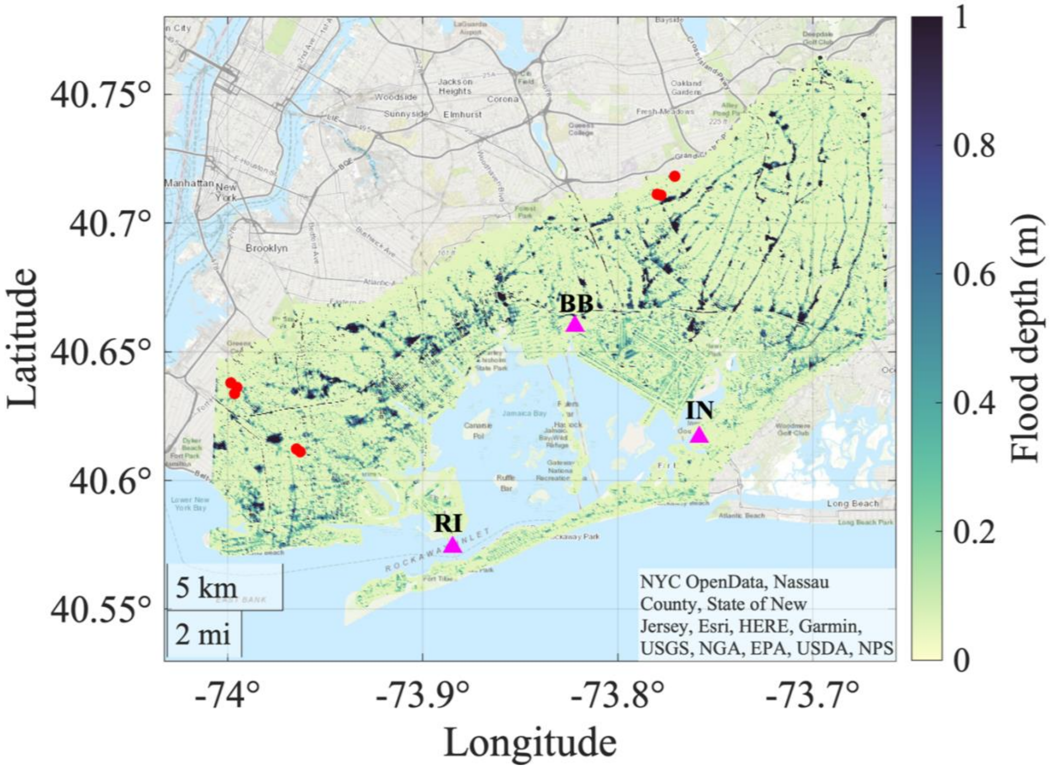
Figure 8 Tide gauge water elevation at Bergen Basin

3. Results

3.1. Model Calibration and Validation

For the base model (no infiltration, no spatial or temporal shifting of rain, no temporal shifting of rain) hydrodynamic simulations for Ida's flood impact on Jamaica Bay, the flood depths vary spatially throughout the domain (Fig. 9, discussed below). Flood depths below Dcrit (5 cm) are not tallied in flood depth mapping and calculations. For model validation, we reference empirical High-Water Marks (HWMs) from USGS website for the event, finding seven locations within our modeled area, one more HWM is from Community Flood Watch Project (for these datasets, see Data Availability section). All the HWMs are shown as red dots in Fig. 9. Both observed and modeled High-Water Mark flood depths are relative to the observed (surveyed) land elevation, for an apples-to-apples comparison. The analysis shows that the measured data are not near the locations of maximum inundation in the model. It reveals a tendency for the model to predict higher flood levels, with a Root Mean Square Error (RMSE) of 49 cm and the Mean Error of 13 cm (Fig. 10-a). This discrepancy is likely attributed to the model's omission of infiltration and storm water drainage. To rectify this, we test different drainage rates in the model, as summarized below. In addition to the HWMs, we investigate the tide gauge data at three stations: Inwood (USGS station 01311850 (U.S. Geological Survey)), Rockaway (USGS 01311875 (U.S. Geological Survey)), and Bergen Basin (a station managed by Stevens Institute of Technology) (Fig. 9). For the comparison of the calibrated model, we evaluate the peak water level during the simulation (the first high tide after Ida), where the model has error of +8, +7 and +6 cm for Inwood, Rockaway, and Bergen Basin gauges, respectively. These tide gauge results are not utilized in the calibration process, as the peak tidal water levels in Jamaica Bay during Ida does not occur during the period of rainfall and were controlled by ocean forcing.

To simulate the sewer system's capacity within our hydrological models, we introduce drain rates of 6 mm/hour (0.25 inch/hour), 13 mm/hour (0.5 inch/hour), and 19 mm/hour (0.75 inch/hour). Figure 10 depicts the improvement of the Root Mean Square Error from 49 cm to 28 cm, and the Mean Error from 13 cm to 2 cm with applying 6mm/hour (0.25 inch/hour) drainage rates.



290 **Figure 9 Flood depth above ground level (model with no drainage), red circles and purple triangles show HWMs and tide gauge locations, respectively. BB, RI, IN stands for Bergen Basin, Rockaway, and Inwood tide gauge locations, respectively. (topographic base map from MATLAB, hosted by Esri®)**

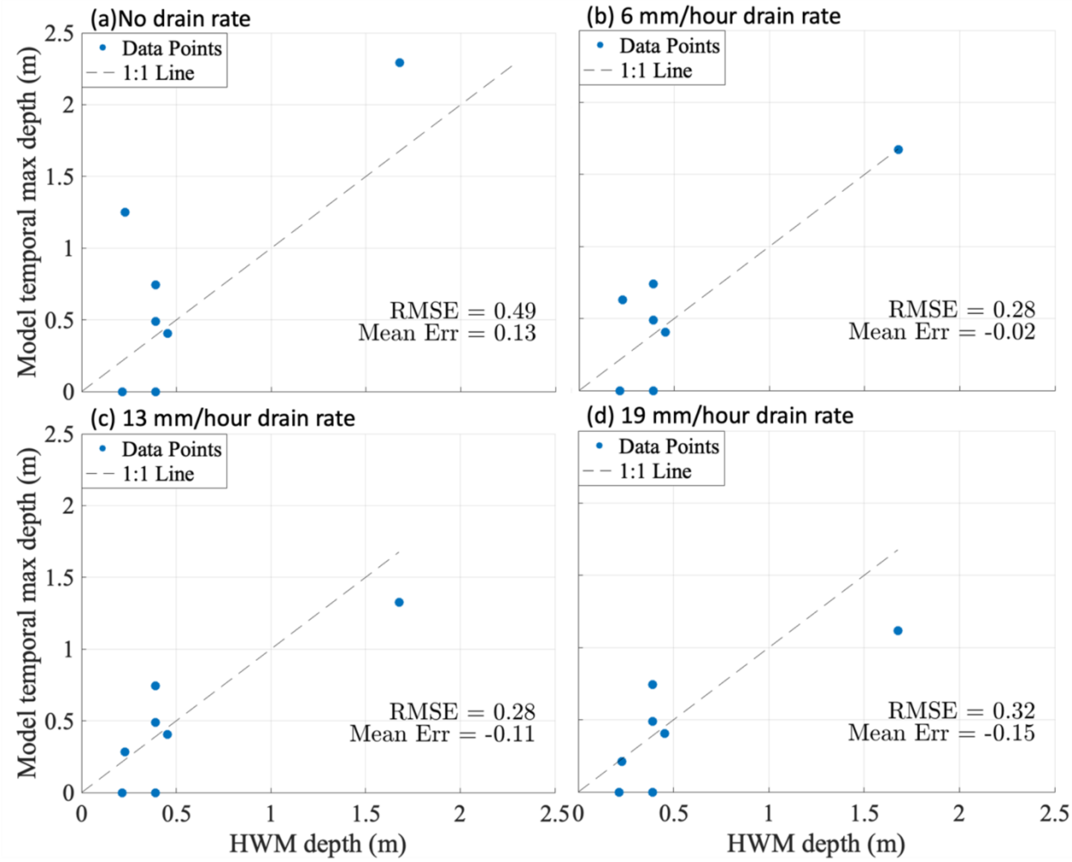


Figure 10 Model results vs observed HWMs for different drainage rates

According to the CN calculations in Sect. 2.4, which is based on hourly rainfall, there is a necessity to manage a runoff rate of 16 mm/hour (0.64 inch/hour). This stems from the 48 mm total runoff over 3 hours and establishes a reference point for stormwater drainage. The model's empirical validation is achieved by comparing simulated flooding depths against observed data, yielding root mean square errors (RMSE) of 28, 28, and 32 cm for drain rates of 6, 13, and 19 mm/hour, respectively. Notably, the 6 mm/hour drain (0.25 inch/hour) rate most accurately reflects observed flooding with the least under/over estimation according to the RMSE and Mean Error values. Further Ida results in this study such as the Ida flood map, flood speed, and the control model to evaluate sensitivity analyses utilize this drainage rate (6 mm/hour). We address the realism of this best-fit drainage rate in the discussion section below. Upon closer examination, incorporating drainage into the model improves the results when comparing to the high-water marks (HWMs), particularly for the elevated HWMs that are ponding. The non-zero depth HWMs that remain unchanged with respect to drain rates are elevated, steep locations where water rapidly flows and does not accumulate.

3.2. Model results

The simulations provide estimates of peak water depths across the city, showing water depths greater than 1 m are generally aligned along major streets or in isolated confluence areas (Fig. 11). For this study, we created general categories of flooding in addition to the maps of depth and extent of the flooding. Flooding up to 0.3 m ("shallow") typically causes minor inconveniences, such as water accumulation and disruptions to pedestrian and vehicular traffic. Floodwaters ranging from 0.3 to 0.9 m ("deep") can interfere with vehicle operation and damage structures, causing moderate damage and inconvenience. In instances where water depths surpass 0.9 m ("extreme"), there is a substantial risk to both individuals and property, with potential outcomes including the movement of vehicles, mandatory evacuations, and extensive property damage. In the model results, 29% of the urban area in the watershed experiences water depths greater than 0.05 m (Fig. 11). Of the urban flooded area (water depth > 0.05 m), 21% is categorized as shallow flood (102 km^2), 6% is deep flood (30 km^2) and 1.5% is extreme flood (7.1 km^2). Focusing on Sep 02, 2021, and looking at the flood duration shows about 6% of the urban area (26.4 km^2) experiences more than 10 hours of severe flooding (flood depth > 0.3 m) and 21 km^2 of these areas are flooded for more than 20 hours. The severely flooded areas include some major streets, and mostly low-lying areas.

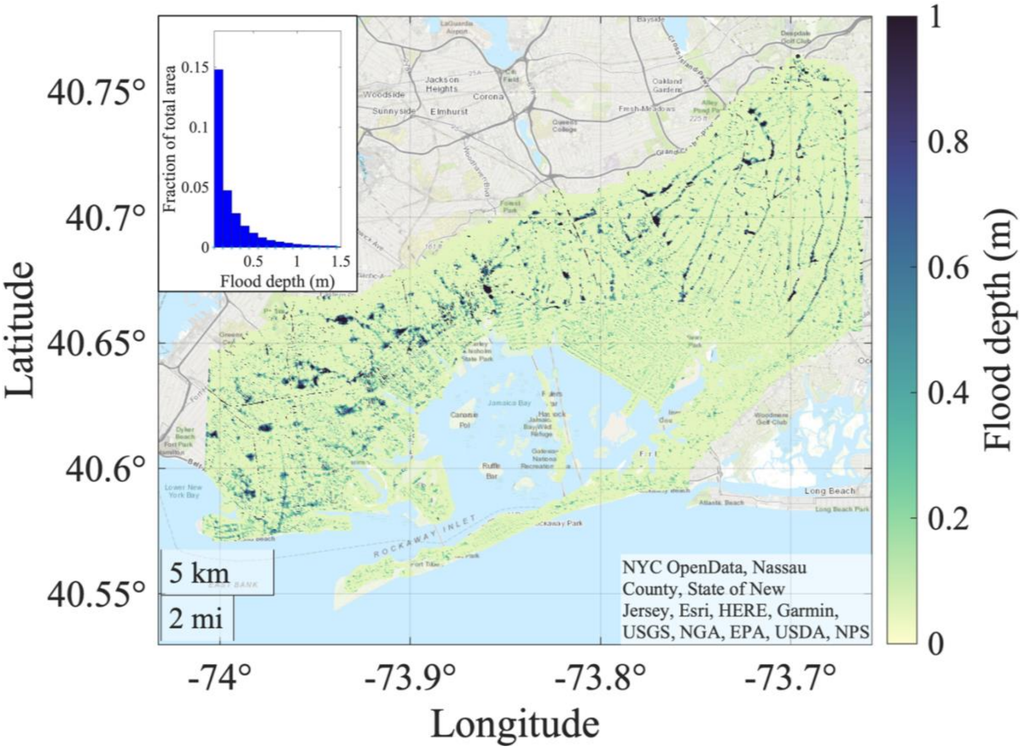


Figure 11 Map of Ida modeled flood depths, and flood histogram (topographic base map from MATLAB, hosted by Esri®)

The model results allow for diagnosis of maximum water velocities in flooded areas. The highest speeds, often greater than 1 m/s, occurred primarily in steep areas and along streets (Fig. 12). High speed zones (>1 m/s) affect 1.18% of the urbanized domain, equivalent to approximately 5.7 km^2, while moderate water velocities (0.5-1 m/s)

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account for 3.18% or roughly 15.4 km^2 and lower speed regions (<0.5 m/s) constitute the remaining 95.6%, which translates to approximately 462 km^2. The maximum flood speed across the domain during Ida reached 4 m/s. These estimates of water speed can help identify the potential zones for delineating flood risk and informing mitigation strategies. High-speed areas pose substantial structural and safety challenges, moderate velocities require caution for potential impacts on transport and infrastructure, and low velocities primarily pose concerns related to static inundation of structures and streets. However, it is important to acknowledge that our velocity data has limitations, as it does not account for buildings, cars or other roughness elements.

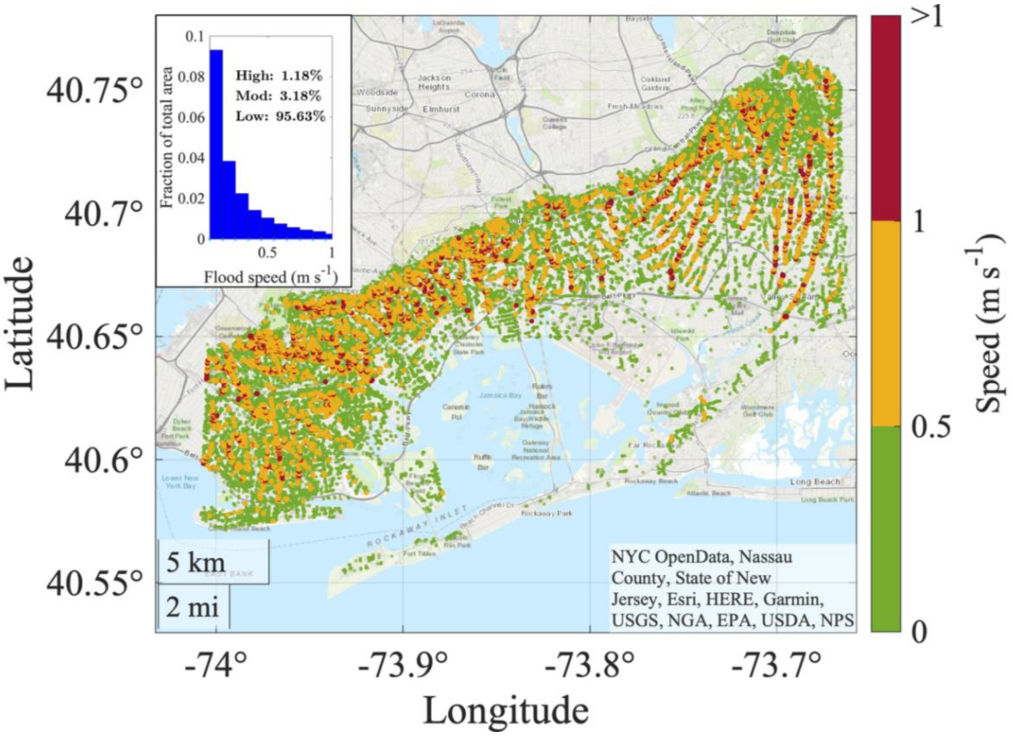

Figure 12 Flood speed greater than 0.05 m/s, and flood speed histogram (High, Mod, and Low stands for High speed, Moderate speed, and Low speed, respectively). (topographic base map from MATLAB, hosted by Esri®)

3.3. Sensitivity analysis results

3.3.1. Spatial shifting of the storm

The sensitivity testing demonstrates that large differences in flooding result from relatively small changes in storm track. Shifting the rainband eastward shows that the flooded area could increase by 43% from 139 km^2 to 199 km^2 in total. Moreover, the areas classified as extreme flood (> 0.9 m) and deep flood (0.3-0.9 m) increases by 141% (17.12 km^2) and 92% (57.6 km^2), respectively. Maximum flood depth in the land area rises by 14% from 8.4 m to 9.6 m, and the area with high water velocities (>1 m/s) increases by 145% (13.96 km^2) (Fig. 13-a). Adjusting the rainband northward by 48 km and simulating the best-case scenario, there is a 50% reduction in predicted urban flooded area, but importantly, this does not eliminate the flooding in the watershed. Although the flood map result shows a reduction in maximum flood depth in this scenario (from 8.4 m to 4 m), still we can see 62 km^2 of the urban classified as shallow flood (Fig. 13-b). In addition, further investigation of the whole region (not just the urban area) shows there are some areas that are always flooded, such as marshes and the edges of the bay (Fig. 13-c, d). Extended analysis between worst case scenario, Ida rainfall, and best-case scenario shows that as the storm gets milder, the flooded area becomes shallower with significantly less deep and extreme flooding.

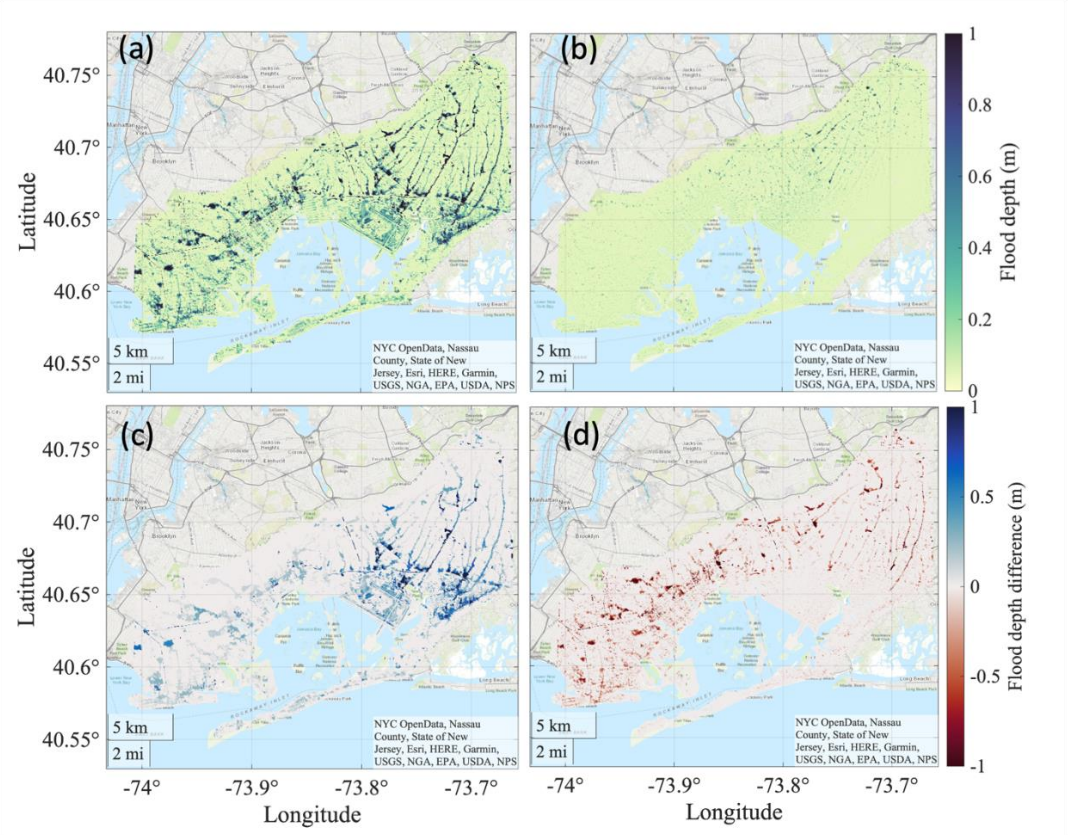

Figure 13 Flood map for sensitivity analysis for rain shifted eastward (a), and northward (b), as well as flood depth difference in comparison with Ida (flood depth minus control, shown in Fig. 11) for shifted rainband eastward (c), and northward (d). (topographic base map from MATLAB, hosted by Esri®)

3.3.2. Temporal shift of the storm

Model scenarios with temporal shifts in the storm are examined to investigate the potential amplification of flood severity due to compounding of rainfall, storm surge, and tides. The results indicate that the spatial extent of the inundation mostly remains the same as for the results from the control simulation (Ida simulation). However, looking more closely at the coastal flood plain, and comparing the water level change from Ida and the two temporal shift scenarios reveals evidence of compounding in the second scenario but not the first. In particular, the Hamilton Beach area under the second scenario (Fig. 14) depicts excessive flood depth of as much as 30-40 cm in the neighborhood.

These findings underscore the model's utility in representing compound flooding events, such as for hurricanes that bring both extreme rainfall and storm surge (Chen et al., 2024).

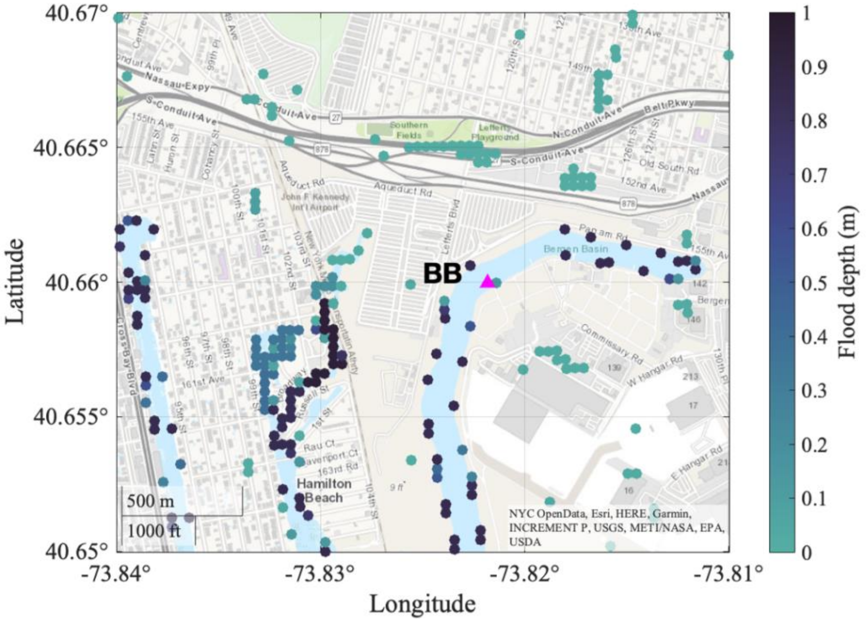

Figure 14 Model grid cells that exhibit additional flood depth around the Hamilton Beach neighborhood due to compounding, when the timing of Ida's rainfall is aligned to match the highest tide of the 24-hour period (temporal shift scenario2). The magenta triangle (BB) marks the Bergen Basin tide gauge location. (topographic base map from MATLAB, hosted by Esri®)

4. Discussion

This study creates the first spatially continuous flood map of Ida, which can help identify and understand Ida's effects far beyond the scattered high water mark data. While static or bathtub mapping can in some cases be effective for coastal floods (New York, 2015), the bathtub mapping effort for the pluvial flooding of Ida was limited to areas within only 250 m of high water marks rather than a spatially continuous map (Capurso et al., 2023). The absence of flood maps for events like Ida highlights that accurate pluvial flood modeling and mapping technologies are not yet broadly available. As a result, our modeling, despite its simplifications, holds significant potential to inform emergency management and mitigation efforts.

To fully comprehend urban pluvial flood risk, it is important to understand how every part of a city responds to extreme rainfall, yet only certain areas of NYC experienced rainfall rates above 50 and up to 70 mm/hour during Ida. The spatial shift (Fig. 7) exploring both the worst-case scenario, and the best-case scenarios depicts the inherent vulnerability of the Jamaica Bay watershed to flooding. Our findings indicate that even a small perturbation in Ida's storm track would have caused even more severe flooding, affecting both the extent and depth of inundation. Furthermore, during the best-case storm scenario, the area still experiences widespread shallow flooding.

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Additionally, understanding whether, where, and how pluvial and coastal flood drivers interact is vital to assessing a coastal city's flood risk. Compound pluvial-coastal flooding remains poorly understood, including such aspects as whether compounding causes an increase in flood area, increase in depth, or both. The temporal shifting of the storm to coincide the most intense rainfall with the high tide shows greater depths of flooding of coastal neighborhoods and a greater extent of inundation (increase by 0.44 km^2). This indicates that compound flooding can cause greater danger in coastal flood zones, due to deeper water than a single-driver coastal flood scenario. The greater footprint of compound flooding could negatively influence emergency management activities (e.g. by blocking roadways in pluvially affected flood areas). These results illustrate the capability of the COAWST to capture compound flood processes and effects, and its utility for future modeling of a wider range of coastal-pluvial forcings to improve our understanding of coastal-urban flood hazard.

Our model's ability to represent spatial variations of flood depth with improved accuracy (Fig. 11) when using a 6 mm/hour drain rate, relative to the simulation with no drainage (Fig. 9), underscores the importance of integrating drainage considerations into urban hydrodynamic simulations. Detailed hydrologic and hydraulic models that aim to fully represent urban stormwater systems and coastal water level boundary conditions are under development. However, the data required to build and validate these models are often unavailable, and such models are rarely applied (Rosenzweig et al., 2021). In their place, new simplified models that represent the Earth system are being utilized for city-scale (Sebastian et al., 2021) and national-scale compound flood modeling (Bates et al., 2021). The approach of calibrating the model to a constant drain rate used in the present study can be of use in these simplified modeling efforts.

According to the curve number method (Eq. 1), the peak runoff rate of Ida which needs to be managed is 16 mm/hour. The calibrated drain rate of 6 mm/hour from our model is less than the calculated run off rate. Since our model and the curve number method are based on hourly rainfall data, we can compare them with each other, and this comparison highlights the limitations in storm water systems as the calculated run off rate exceeds the model's calibrated drain rate. However, we should consider that it is likely that rain intensity peaks occurred on durations shorter than one hour and overwhelmed the system to cause most of the flooding, not the hourly-accumulated MRMS rain rates. This could be a reason that the calibrated drainage rate in our model (6 mm/h) is less than the supposed design storm water system capacity, 44 mm/hour (NYC-MOCEJ, 2023). Also, stormwater systems often become blocked in heavy rain events, due to garbage or vegetation. As a result, our modeling approach may be more applicable for extreme rain events, though it likely also has a declining accuracy, or need for new tuning, for weaker rain events. Our model results suggest that the deepest flooding occurs in major streets, turning them into river-like pathways. However, the assumption of spatially uniform drain rates may lead to misestimation of the spatial distribution of flood depths. Although major streets may possess better stormwater infrastructure than minor streets, our final high-water mark (HWM) results indicate that the model maintains good accuracy.

The improved COAWST model has the potential to more comprehensively simulate the coastal system and factors contributing to flooding, relative to typical urban hydraulic-hydrologic models. The result is a coastal system model capable of simulating tides and storm surge, rainfall, wind wave overtopping, erosion and air-sea-wave interactions. Research made possible by this new model includes infrastructure adaptation planning for urban coastal pluvial flood studies, analyses of rain influence on estuary hydrodynamics, coupled pluvial-coastal flood-induced sediment transport and erosion. This capability is not readily available in many existing models, which often require separate or one-way coupled models to achieve similar results.

The model also has the potential for improving flood hazard, risk and adaptation assessment. Many recent studies have assessed joint probability of rain and surge for an urban environment (e.g. Kim et al., 2022; Zellou and Rahali, 2019), yet very few have modeled flooding for a range of these scenarios. Our sensitivity analyses, incorporating the potential variability in storm tracks and storm timing, demonstrate the promise of the model to capture a wide range of flood forcing scenarios and show the importance of storm track variability and timing for flooding.

Despite these advancements, this study is not without limitations. The model simplifications in this research, such as spatially constant drain rates, a bare-Earth land surface, and moderate spatial resolution, could be modified in future work to capture a more complex and thorough evaluation of urban flooding. For example, future work could experiment with applying spatially varied drain rates based on storm water system data and land use type data. The empirical validation could also benefit from more extensive HWMs or spatial maps of observed flooding to more fully evaluate the model's reliability. These future improvements are possible but large undertakings, as the detailed information on storm water pipe systems are not easy to gather and include, and the data for validation from this storm are limited. However, a concurrent rapid increase in urban flood observations (Gold et al., 2023; Mydlarz et al., 2024) could be a remedy for this data shortage, which could help for future flood events and more detailed model development.

5. Summary and Conclusions

In this research, a coastal system model (COAWST) is enhanced to capture the volumetric effect of rainfall in the ocean and on floodplains. A simplified drain rate capability is added to account for stormwater system and infiltration effects on flooding. These improvements are applied in a simulation of flooding by post-tropical cyclone Ida in the Jamaica Bay watershed of New York City. The calibration and resulting accuracy of the model compared with empirical High-Water Marks (RMS error 28 cm) and maximum water levels in the estuary illustrate the model's predictive capabilities yet suggests a need for improvements in modeling detail or sophistication for capturing a wider range of rain intensity events.

Outcomes of the research include a spatially continuous flood map of Ida, and improvements to our understanding of the flood risks posed by extreme rain events, as well as a developed model capable of investigating compound pluvial-coastal events for the Jamaica Bay area. The sensitivity analysis depicts Jamaica Bay's vulnerability to change in storm track and timing. It reveals that Ida could have been worse due to more rain or compounding by high tides. Capturing the compounding effect is particularly important, given that compound floods are expected to become more common and important as sea levels continue to rise (e.g. Mita et al., 2023). Effective translation of this scientific knowledge into coastal and urban planning is imminent, requiring interdisciplinary efforts and long-term studies of the risks of future climate challenges.

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6. Competing interests

The authors declare that they have no conflict of interest.

7. Acknowledgements

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8. Dataset Availability

The improvements to COAWST are embedded in v3.8, which is available for download at: https://code.usgs.gov/coawstmodel/COAWST. The model setup files, flood depth dataset, Bergen Basin tide gauge dataset can be accessed: https://stevens0-my.sharepoint.com/personal/skasaei_stevens_edu/_layouts/15/onedrive.aspx?id=%2Fpersonal%2Fskasaei%5Fstevens%5Fedu%2FDocuments%2FData%5Favailability&ga=1.These and the final flood map for Ida are being published in Mendeley (citation TBD; a collaboration with NYC Emergency Management). Meteorological forcing for the Jamaica Bay model was provided by the WRF model, North American Mesoscale (NAM) product, the data can be accessed: https://www.ncei.noaa.gov/thredds/catalog/model/model.html. USGS High Water Mark data points can be accessed: https://stn.wim.usgs.gov/FEV/#2021Ida. Community Flood Watch HWM data point can be accessed: https://mycoast.org/search-reports?state=ny&fwp_categories=highwater%20. Tide gauge data from USGS can be accessed: https://maps.waterdata.usgs.gov/mapper/index.html.

9. Author contribution

The paper and the experiments were conceptualized by SK, PMO and JCW; the parent (regional model) simulation was performed by DKR, and Jamaica Bay simulations by SK. The COAWST model improvements were done by JCW; statistical analyses by SK with help from PMO. The original draft was written by SK with help from PMO; further review done by PMO, DKR, and JCW, and the edits done by SK with help from PMO. Project administration was performed by JCW and PMO, and funding acquisition was done by JCW and PMO.

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