EXTREME RAINFALL-RUNOFF MODELING DURING REMNANTS OF IDA IN NEW YORK

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INTRODUCTION

Coastal flooding associated with strong storms creates hazardous conditions nearshore such as coastal erosion, property damage and loss of life. While the effects of wind and pressure on coastal waters can generate large storm surges that lead to coastal flooding, storm surge represents only one driver of flooding. In reality, flooding is often driven by the combined action of several geophysical drivers (Couasnon et al., 2020; Zscheischler et al., 2018). Formally compound flooding is defined as the combined action of meteorological forces, tidal forces,, fluvial, and pluvial discharge (Zscheischler et al., 2018). Recent events such as the extreme rainfall associated with the remnants of Hurricane Ida in the Northeast United States have demonstrated the need to model the rainfall-runoff impact (i.e., pluvial flooding) and its downstream impact (i.e., fluvial flooding).

In extreme rainfall cases in which large quantities of precipitation fall in short periods, urban environments often flood, and wastewater collection systems often exceed their design limit. In severe scenarios, surcharged sewer systems can significantly exacerbate urban flooding. While several existing flood risk methods consider storm surge in them approach, it remains active research topic concerning how and when rainfall-runoff processes should be incorporated in flooding models to assess site-specific flood risk. Often an approach is pursued that involves loosely coupling multiple numerical models each modeling a particular flood driver; however, this approach can become cumbersome. Instead in this work we pursue a different approach in which compound flooding can be resolved in a single numerical model (herein termed a monolithic approach).

Compound coastal flood models have varied applications. For instance, they can be employed to issue forecast warnings for predictions of coastal flooding, and these can help mitigate the loss of life, and property damage. It currently remains an active research question regarding how rainfall-runoff processes can be incorporated in assessing flood risk (Gori, Lin, & Xi, 2020; Villarini et al., 2021), which have historically neglected rainfall-runoff and potentially dramatically under-estimated flood risk (Algeo & Mahoney, 2011; Khanam et al., 2021). In Y. Zhang et al. (2004), the importance of simulating compound flooding processes on a single grid through comparisons between the results of simulations with all drivers (i.e., surge, fluvial and pluvial, tidal) to simulations where each driver was applied individually, Huang et al. (2021). The authors concluded large errors up to 90% could result in the Hurricane Harvey case if the flooding drivers were considered independently.

MODEL SIMULATIONS

In this work, we developed an integrated numerical model for the prediction of combined, hurricane-induced rainfall run-off, tides, wave induced set-up (although possible, waves were not simulated in this work) and storm surge. The model solves the full non-linear, depth-averaged, long wave equations and is optionally augmented with both spectral wave and rainfall runoff models. Our developments are implemented within the well-validated openTELEMAC suite of codes (Hervouet, 2007). An important feature of the model is the use of a single unstructured computational triangular mesh that can reliably simulate street-level scales obviating the need for several models. Further, the configurations and numerics used in our simulations are robust demonstrating numerical stability despite street-level mesh resolution. Two model simulations were performed for this presentation that spanned October 28th, 2012, to October 31st, 2012 (3 days). Two model events were carried out: Hurricane Sandy and Hurricane Sandy with Hurricane Ida's remnant rainfall which has been time shifted to align with the peak surge of Hurricane Sandy. While the secondary simulation is hypothetical, the purpose of the is to illustrate the model's ability to handle extreme flooding scenarios and highlight the model's capabilities.

MODEL DESCRIPTION

Hydrodynamics are resolved by solving the Non-Linear Shallow Water (NSLW) equations using a finite element discretization. A variable resolution unstructured triangular mesh is used to discretize the computational domain. The mesh extends to the mid-Atlantic bight to model tidal processes and seamlessly extends overland in the region of focus (Figure 1). To generate the mesh, we apply an automatic mesh generator called OceanMesh2D (Roberts et al., 2019). In this mesh generation approach, element sizes are distributed following mesh sizing functions based on geospatial datasets and mesh around building footprints. Specifically, element size ranges are specified through parametric functions of distance to building footprints and shoreline features, significant topo-bathymetric gradients, while respecting numerical-specific aspects such high-geometry quality element shapes, sufficiently smooth element-to-element size transitions and the CFL condition.

FLOW & RAINFALL-RUNOFF MODELING

Following Kelly et al., (2018) modifications were made to the TELEMAC2D source code to support spatially distributed and temporally varying rainfall. Rainfall is introduced as a mass source term in the governing equations. For the simulation of rainfall infiltration, we employ the Soil Conversation Service Curve Number (CN) approach. A spatially varying parameter CN is introduced to represent the soil/land cover properties also considering the antecedent soil conditions. The initial value of the parameter CN has been derived from the USDA USA SSURGO - Soil Hydrologic Group and NOAA C-CAP Land cover databases. Atmospheric forcing, winds, surface pressures, and rainfall rates are obtained from nowcasts from the High-Resolution Rapid Refresh (HRRR) weather model and are mapped to the computational mesh at a 15-minute timestep prior to simulation. Since the rainfall is a mass source in the equations, it can be traced to investigate the components that contribute to the overland flooding and help assess damage to infrastructure (e.g., saline vs freshwater flood damage).

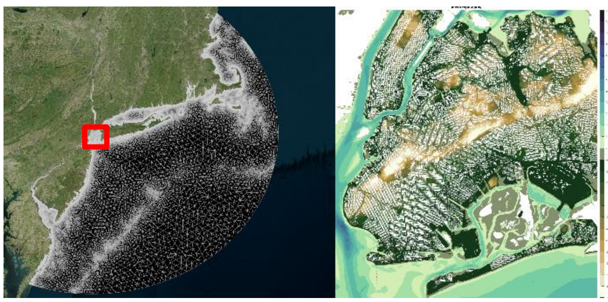

Figure 1 – Model mesh and extent (left panel), topo-bathymetric colored close-up (red box in left panel) view of the street scale mesh.

MODEL VALIDATION and RESULTS

The model results from a tide-only simulation and during Hurricane Sandy were compared to the water level time series obtained from the publicly available NOAA tidal gage at the Battery, NY location (Figure 2) and demonstrates the model predicts both the phase and amplitude of both predicted tides and observed water levels.

Figure 3 and Figure 4 are examples of products derived from the results of our compound flood model. Figure 3 depicts maximum water depth (on land) after Hurricane Sandy and Figure 4 shows the combined impact of Hurricane Ida remnant rainfall alongside the Hurricane Sandy storm surge. During the simulation (or in post-processing) maximum water levels and their occurrence time stamps can be derived. These products are useful to mitigate loss of life and damage to infrastructure.

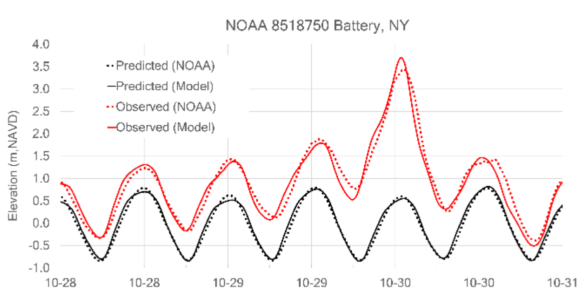

Figure 2 – Comparison of model generated observed (red solid) and predicted (black solid) to NOAA observed (red dashed) and predicted (black dashed) water levels.

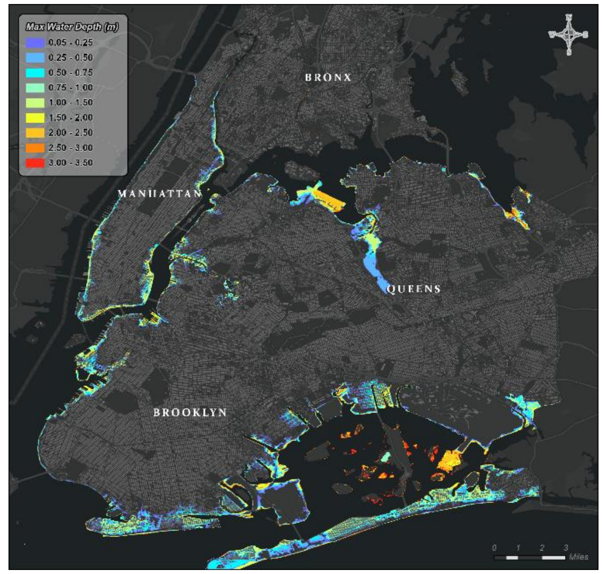

Figure 3 – Maximum water depth on land (Hurricane Sandy)

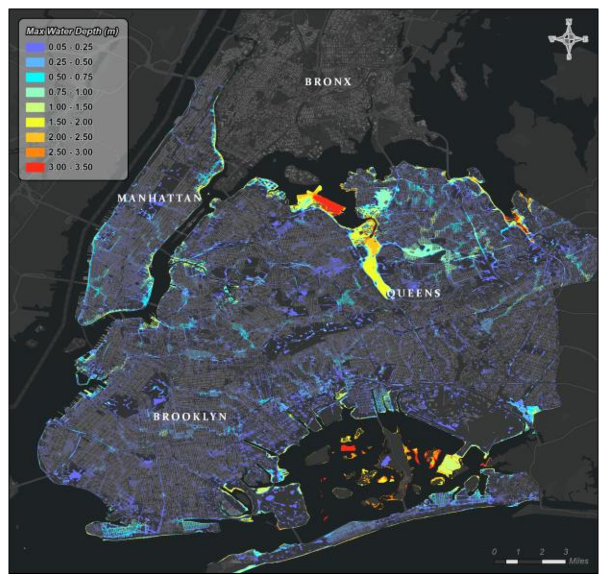

Figure 4 – Maximum water depth on land (Hurricane Sandy + Hurricane IDA remnant rainfall)

COMPUTATIONAL PERFORMANCE

Our premise is that a combined or integrated modeling approach that uses a single computational mesh is practically advantageous as it reduces the mesh/model generation time. On the other hand, modular approaches to the simulation of compound flooding require the configuration and validation of several potentially independent models, which can become cumbersome and site-specific. One of the reasons for the wide application of modular approaches is the computational expense of an integrated modeling approach that resolves a variety of length scales in the same computational mesh. Through improvements to file I/O of atmospheric forcing, the presented model can generate results within reasonable timeframes using reasonable desktop computers. In the case of a forecasting / emergency management operation, the compound flooding results can be generated in under 5 hours (runtime: 3 days, element count 9.5 million).

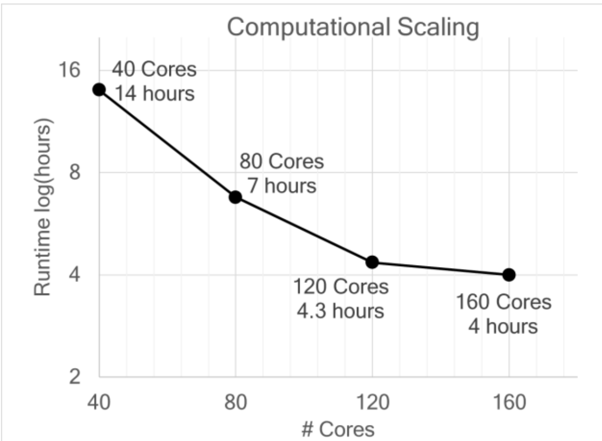

Figure 5 - Computational expense scaling with # cores used

OTHER POTENTIAL APPLICATIONS

The detailed nature of our model resolves flooding from storm tides and ponding on streets throughout the passage of the storm, which lends itself to various engineering applications. Despite the high level of detail, we demonstrate the computational performance of the model is suitable to be deployed for forecasting to inform emergency management operations. We demonstrate such a use to evaluate hazard impacts associated with flooding on roads in the New York metropolitan area using outputs from our model. When the road network experiences a flood depth over a certain threshold, a hazard report with road closures is generated. By generating real-time hazard inputs, the combined system can be used to predict road closures and hazards associated with both storm tide and rainfall-runoff flooding.

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