Chesapeake Community Research Symposium 2026

Session 16: Recent Modeling Advances in Compound Flooding, a 10-year Retrospective of Technological Innovations in Hydrodynamic Modeling and Monitoring Since 2016 Hurricane Matthew

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Joseph Zhang (Virginia Institute of Marine Science)

A 25-year Reanalysis of Compound Flooding Hazard in US East and Gulf Coast

We present the first comprehensive, physics-based long-term reanalysis of compound flooding hazards along the U.S. East and Gulf coasts. The reanalysis was produced by assimilating NOAA water-level observations into a previously validated three-dimensional hydrodynamic model (SCHISM) and represents the best available estimate of flood hazards over the past 25 years.

The analysis provides new insights into the uneven impacts of long-term sea-level rise on local mean sea level and water-level variability, from coastal regions into upstream rivers. In addition to improving understanding of historical flood risk, the dataset can serve as a benchmark for evaluating ensemble prediction methods and improving projections of future flood hazards.

HaoCheng Yu (Virginia Institute of Marine Science), Lars Nerger, Fei Ye, Y. Joseph Zhang, Hyungju Yoo, Saeed Moghimi, Gregory Seroka, Zizang Yang, Edward Myers, Carsten Lemmen, S. Chin

Elevation Skill Enhancement from an Efficient Ensemble-Based Assimilation Method in a Large Application STOFS-3D-Atlantic

Data assimilation (DA) is widely used to improve model performance, but its computational demands can limit applications at large spatial scales. In this research, we utilize the cost-effective features of the Ensemble Optimal Interpolation (EnOI) data assimilation method and apply it to a large three-dimensional baroclinic model, NOAA's STOFS-3D-Atlantic.

The additional computational cost of the assimilation process was only about 2%, while model skill improved significantly. Root mean square error for total water level from a year-long simulation was reduced from 14.8 cm to 9.2 cm through assimilation of observations from 156 NOAA stations. Incremental Analysis Updating (IAU) was also applied when updating model states to avoid sudden shocks in the pressure field during data assimilation updates. The approach is computationally efficient and can be readily exported to other large-scale modeling applications.

Jon Derek Loftis (Virginia Institute of Marine Science)

Hydrodynamic Modeling of Compound Flooding During 2016 Hurricane Matthew: Then, Now, and Storms Like It in the Future

Accurate inundation forecasting depends on a model's ability to resolve flood depth, spatial extent, and persistence prior to extreme events. This challenge becomes particularly complex during compound flooding, when precipitation, storm surge, and tidal forcing interact nonlinearly to amplify impacts. Model performance in these situations depends heavily on atmospheric forcing such as wind fields, atmospheric pressure, and rainfall intensity, as well as terrestrial boundary conditions including soil moisture, infiltration, land cover, and stormwater infrastructure capacity.

Over the past decade, major advances in data availability and computational methods have transformed compound flood modeling capabilities. High-resolution remote sensing data, dense water-level monitoring networks, and near–real-time data assimilation have improved model calibration and boundary condition specification. Combined with modern hydrodynamic and hydrologic solvers and emerging machine learning approaches, these developments enable more physically consistent and operationally relevant forecasts.

This presentation revisits compound flood modeling of the 2016 Hurricane Matthew event—one of the most significant compound flooding events in Chesapeake Bay over the past decade—and compares modeling capabilities from 2016 to 2026. The analysis focuses on reassessing compound flooding risks in economic development areas across Hampton Roads and explores scenario planning for future Matthew-like storms under projected sea-level rise and land subsidence through 2050.

Zanko Zandsalimi (University of Virginia), Mehdi Taghizadeh, Majid Shafiee-Jood, Negin Alemazkoor

Explicit Interdomain Learning of Rainfall–Tide Coupling for Compound Flood Forecasting Using Graph Neural Networks

Compound flooding in coastal watersheds arises from dynamic interactions between rainfall-driven runoff and coastal water-level forcing. Coastal boundary conditions can propagate inland through connected drainage networks, altering stage–discharge relationships, inducing backwater effects, delaying runoff drainage, and in extreme cases reversing flow direction. Conversely, rainfall-driven storage and runoff can influence the timing and inland penetration of coastal water levels.

Physics-based hydrodynamic models simulate these processes by synchronizing exchanges between boundary and interior states at each time step, but their computational cost limits their use for ensemble forecasting and real-time applications. Deep-learning flood surrogates provide efficiency gains but often treat rainfall and tidal drivers implicitly, limiting interpretability and robustness under new forcing conditions.

This study introduces a connectivity-aware graph neural network surrogate that explicitly learns rainfall–tide interactions through interdomain message passing on a drainage connectivity graph. Coastal boundary nodes and interior drainage nodes are represented within a unified graph structure, allowing bidirectional and time-varying information exchange under combined rainfall and coastal water-level forcing. Using high-resolution hydrodynamic simulations as ground truth, the model's predictive skill is evaluated for reproducing inland water levels and compound flood responses across varying forcing scenarios.

Hyungju Yoo (Virginia Institute of Marine Science), Y. Joseph Zhang, Zhengui Wang, Fei Ye, Haocheng Yu

Enhancing Thermal Process Representation in Intertidal Areas through Soil-Air-Water Heat Exchange: A Case Study of Charleston Harbor

Accurately representing water temperature in shallow intertidal zones remains a major challenge in hydrodynamic modeling of estuarine systems with frequent wetting and drying. In environments influenced by compound forcing from tides, surge, and precipitation, repeated inundation of shallow regions can significantly alter thermal processes. Conventional wetting–drying formulations do not explicitly represent heat exchange between newly rewetted soils, overlying water, and the atmosphere, often resulting in unrealistic temperature fluctuations.

This study introduces a simplified soil–air–water heat exchange formulation within a three-dimensional hydrodynamic modeling framework based on SCHISM. The method is applied to Charleston Harbor to evaluate its impact on thermal dynamics in shallow estuarine environments.

Combined with improved mesh resolution in inundation zones, the formulation enables more gradual and physically consistent temperature evolution during repeated wetting and drying cycles. Simulation results show reduced nonphysical temperature spikes and improved spatial coherence in modeled temperature patterns, achieved without altering predicted inundation dynamics.

Jon Derek Loftis (Virginia Institute of Marine Science), Yash Kishor Sanap, Sridhar Katragadda, Russ Lotspeich

High-Precision River Stage Estimation via Passive Video Imagery Using Deep Learning and Image Segmentation

Recent advances in computer vision and deep learning have enabled the development of passive remote sensing systems for monitoring surface water levels using fixed-position cameras. In collaboration with the U.S. Geological Survey's Next Generation Water Observing System and the City of Virginia Beach, this project evaluated integrated hardware and software systems for near–real-time river stage estimation from optical imagery.

Using 4K-resolution cameras with infrared night vision, time-lapse video imagery was processed using deep learning and edge-detection algorithms to identify waterline positions relative to fixed elevation benchmarks. Data were obtained from the USGS Hydrologic Imagery Visualization and Information System at flood-prone tidal and non-tidal locations across the United States.

Machine learning model accuracy was validated against proximal USGS radar water-level sensors. Across ten monitoring sites, site-specific models achieved a root mean square error of 0.214 cm using fewer than ten training epochs per site. A generalized model trained across all sites produced a higher error of 0.586 cm. Results indicate that reliable water level detection is achievable when cameras are installed within 15.24 m (50 ft) of the target benchmark location, although measurement uncertainty increases with greater distance.

Jon Derek Loftis (Virginia Institute of Marine Science)

Spatial Evaluation of Flood Resilience Solutions Combining Real-Time Water Level Sensors, Hydrodynamic Modeling, and High-Resolution Aerial Inundation Observations

Coastal communities increasingly implement hybrid green and gray infrastructure to reduce nuisance flooding and storm surge impacts. However, methods for evaluating the effectiveness of these resilience interventions at site scales remain limited.

This study presents a spatial evaluation framework that integrates dense networks of real-time water-level sensors, operational hydrodynamic modeling, and high-resolution drone observations. The approach is demonstrated at several flood-prone locations in Norfolk, Virginia, including sites with recently constructed earthen berms and living shoreline projects.

Observed water levels from federal and regional sensor networks were combined with historical six-minute tide gauge records to quantify baseline flooding frequencies and assess design elevations. Hydrodynamic forecasts were generated using the SCHISM-based Tidewatch modeling system, which produces hourly street-level inundation predictions up to 36 hours in advance. Drone-derived orthomosaics collected during king tides and storm events in 2025 were used to validate modeled flood extents.

Modeled and observed inundation patterns showed strong agreement, with mean horizontal deviations below 10 meters and floodwater volume differences under 10%. Additional validation was provided through community science observations collected using the Sea Level Rise smartphone application. Together, these integrated datasets enable quantitative assessments of floodwater reduction attributable to resilience interventions and support data-driven planning for coastal adaptation under accelerating sea-level rise.