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Modeling of Hurricane Surge and Waves in the Built Environment:

Hurricane Ian Workshop #3 Report

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https://doi.org/10.6028/NIST.NWIRP.GCR.1-3

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U.S. DEPARTMENT OF COMMERCE

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MAY 2026

U.S. Department of Commerce
Howard Lutnick, Secretary

National Institute of Standards and Technology
Craig Burkhardt, Acting Under Secretary of Commerce for Standards and Technology and Acting NIST Director

NIST NWIRP GCR 1-3
May 2026

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This publication was produced as part of Interagency Agreement #A2304-013-049-43211 with the National Science Foundation, NSF Award Number #2037914, Natural Hazards Engineering Research Infrastructure: Experimental Facility with Large Wave Flume and Directional Wave Basin 2021-2025 and NIST Work Order #O2407-013-049-34019 with the National Institute of Standards and Technology. The contents of this publication do not necessarily reflect the views or policies of the National Institute of Standards and Technology or the US Government.

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Publication History

Approved by the NIST Editorial Review Board on 2026-01-21

How to Cite this NIST Technical Series Publication

Cox, D., Amini, M., Hubbard, K., Kaihatu, J., Kennedy, A., Velasco-Reyes, E., Sanderson, D.,(2026), Modeling of Hurricane Surge and Waves in the Built Environment: Hurricane Ian Workshop #3 Report, National Institute of Standards and Technology, Gaithersburg, MD, NIST National Windstorm Impact Reduction Program grant (NWIRPG) NIST NWIRP GCR 1-3 https://doi.org/10.6028/NIST.NWIRP.GCR.1-3

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Abstract

This report summarizes the proceedings and outcomes of the third Hurricane Ian Workshop, held on September 5, 2025, in Alexandria, Virginia. The purpose of the workshop was to explore the state-of-the-art in numerical modeling of overland flow in the built environment, focusing specifically on the hazard variables of surge, waves, and currents that critically affect structural integrity during hurricane landfall. The scope included an examination of model complexities and accuracies, ranging from time-averaged models like WHAFIS (used for flood insurance studies) to highly resolved, time-dependent models like OpenFOAM (Open Field Operation and Manipulation) and Delft3D-FM (Delft3D-Flexible Mesh Suite), and their application to events like Hurricane Ian.

The workshop included eleven invited technical talks that covered advancements in large-scale (ADCIRC+SWAN) and local-scale (XBeach, Delft3D-FM, OpenFOAM) hydrodynamic modeling, mesh design, subgrid corrections, the inclusion of building footprints and dynamic collapse, wave-current-debris loading, infragravity waves, wind speed transitions, and translating hazard predictions into end-user quantities. Following the talks, participants engaged in two breakout sessions to discuss (1) research needs for modeling and measurements, and (2) laboratory studies required for model benchmarking.

Key results and discussions highlighted that current models show varying degrees of uncertainty in predicting waves and currents, especially in complex built-up areas. Findings emphasized the critical role of including buildings in models to accurately capture velocity patterns, channeling, and shielding effects. Furthermore, novel research indicated that debris loads can sometimes exceed hydrodynamic loads, and the impact of long waves (infragravity waves) warrants further investigation for structural loading. The workshop identified a consensus on the need for better field data collection and collaboration between coastal and structural engineers.

The conclusions/recommendations synthesized from the discussions resulted in three high-priority actionable items intended to yield advancements in overland flow prediction: (1) preparation of a comprehensive, state-of-the-art review paper on existing overland flow models; (2) initiation of an inter-model comparison study for a fixed domain (*e.g.*, Estero Island) with common boundary conditions to identify modeling gaps; and (3) a scoping study for large-scale laboratory validation experiments to benchmark numerical model performance against real-world, multi-hazard phenomena.

Keywords

Building damage; Built environment; Coastal flooding; Flood hazards; Hurricane Ian; Hurricane landfall; Numerical modeling; Ocean currents; Overland flow; Storm surge; Waves.

Preface

Modeling of Hurricane Surge and Waves in the Built Environment: Hurricane Ian Workshop #3 and this resulting report were conducted in support of NIST's congressionally funded study of Hurricane Ian, through the National Windstorm Impact Reduction Program. The workshop report should also be a valuable tool for any organization, agency or individual conducting research on Hurricane Ian and its impacts. The workshop was chaired by Daniel Cox from Oregon State University (OSU) and co-chaired by Donald Slinn from NIST. Funding to conduct the workshop was provided to OSU from NIST, through an Interagency Agreement between NIST and the National Science Foundation (NSF) that provided supplemental funds to an existing NSF Natural Hazards Engineering Research Infrastructure (NHERI) award to OSU.

Acknowledgements

The authors gratefully acknowledge the many workshop presenters and participants, for sharing their time, expertise and data. Thank you to David Webb and Donald Slinn of NIST for providing technical reviews and editing. The assistance by Tanya Brown-Giammanco of NIST and Joy Pauschke of the National Science Foundation with the Interagency Agreement for workshop funding is also acknowledged.

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1. Workshop Purpose

The third Hurricane Ian Workshop held September 5, 2025, in Alexandria, Virginia, focused on the modeling of overland flow in the built environment, particularly on the hazard variables of surge, wave, and currents that affect the integrity of the built environment. For example, post-disaster observations after hurricane landfall have consistently shown that structural damage is significant in the high hazard flood areas due to the rapid currents and high waves. However, numerical models for overland flow have large uncertainties in their ability to predict waves and currents. These models have a range of formulations, from time-averaged models such as Wave Height Analysis for Flood Insurance Studies (WHAFIS) used by the Federal Emergency Management Agency (FEMA) for coastal flood studies, to highly resolved, time-dependent models such as OpenFOAM used primarily as a research tool but not widely used in practice.

The purpose of this workshop was to explore the state of the art of numerical modeling of overland flow through a series of invited talks. These talks spanned a wide range of model space in terms of complexity and accuracy. After the invited talks, two breakout sessions were held to discuss (1) Research needs for modeling and measurements in the context of overland flow in the built environment and (2) Laboratory studies that can be used to benchmark the development of numerical models. Participants were asked to consider actionable items that could yield advancements in overland flow.

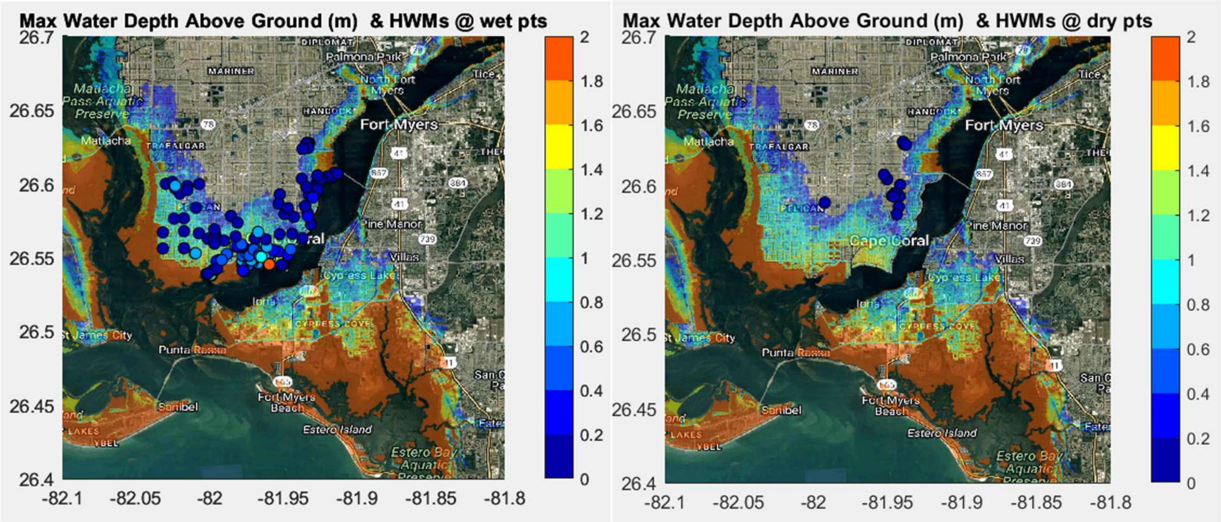
This report is divided as follows: Section 2 provides a synopsis of each of the invited talks. Section 3 summarizes the discussion of each breakout session and summarizes the actionable items. Section 4 summarizes the overall workshop. Appendix A provides the one-day agenda, and Appendix B provides the participant list.

2. Invited Talks

This section gives an overview of the eleven invited talks. Each presenter was asked to prepare a 20-minute talk, including some time for questions and discussion, in the context of the surge and waves flood hazard in the built environment. The presentations are available on the DesignSafe.org website [2].

2.1. Talk 1: *Flood Hazards: Large to Local Scales* by Rick Luettich, University of North Carolina

Rick Luettich discussed the capabilities of ADCIRC and SWAN models at different scales, from large to “sub-kilometer”, given accurate meteorological fields of Tropical Cyclones. Rick demonstrated that the water levels resulting from the ADCIRC+SWAN model generally aligned with observed water levels for Hurricane Ian. The results were achieved using a computational grid with a 50 to 100 m maximum resolution, bathymetric and topographic data of Fort Myers and Estero island, Manning’s n values for the selected area, and meteorological data from Oceanweather Inc (OWI). Dr. Luettich then showed a comparison of the maximum water depth above the ground model results from ADCIRC+SWAN with high water marks documented by UCF in the Cape Coral area (Figure 1). A majority of the high-water mark points were within the region that ADCIRC+SWAN predicted water depths greater than 0 m in Cape Coral, although some high water marks were outside of this region. ADCIRC+SWAN was also used to model water levels for Hurricane Helene, using a computational grid with a 100 to 200 m maximum resolution and meteorological data from NRL COAMPS-TC Reforecast. The model results showed an agreement with observed water levels from eight NOAA water level gauges along the west coast of Florida. Dr. Luettich concluded that given credible tropical cyclone meteorological field data, ADCIRC+SWAN provide credible “sub-kilometer” scale representations of storm surge levels and overland flooding extents. Dr. Luettich then touched on some new numerical techniques to efficiently represent small channels. Dr. Luettich tested this new numerical technique on a channel network in Cape Coral, refining the mesh in this area of interest to approximately 25 m resolution.


Max Water Depth Above Ground (m) & HWMs @ wet pts

Max Water Depth Above Ground (m) & HWMs @ dry pts

Figure 1. ADCIRC Max Water Levels vs UCF Cape Coral Area High Water Marks.

2.2. Talk 2: ADCIRC Developments for Overland Flows affected by (a) Small-Scale Pathways and Barriers, and (b) Coastal Erosion by Casey Dietrich, North Carolina State University

Casey Dietrich gave a talk on recent extensions to the Advanced Circulation (ADCIRC) model using subgrid corrections and on the initial coupling between ADCIRC and XBeach to compute erosion and barrier island breaching during Hurricane Ian. Subgrid corrections are ways to incorporate unresolved small-scale processes into larger scale computational grids. For ADCIRC, they use small scale bathymetry and land cover to allow for partial filling of elements and to modify frictional characteristics in these partially filled cells. These corrections allow connectivity in many instances where standard numerical discretizations would show dry land on the grid scale and would not allow for water to pass through. For tests in complex coastal regions with channels narrower than the grid size, subgrid computations gave similar accuracy as higher resolution simulations but with lower computational cost. The second part of the talk was on the coupling of ADCIRC with XBeach to model breaches during storms (Figure 2) to provide real-time estimates of predicted erosion in advance of storm landfall. Although ADCIRC provides accurate water levels for storm inundation, any significant erosional changes may cause it to lose accuracy. Coupling ADCIRC with XBeach allowed Dr. Dietrich to predict a breach at Midnight Pass during Hurricane Helene. Further work used 1D XBeach to estimate dune erosion along many transects along the Gulf Coast, using ADCIRC forecasts as the driving inputs. Although this work is preliminary, the coupling of larger scale ADCIRC and smaller scale XBeach is a promising step to improve future predictions of storm erosion.

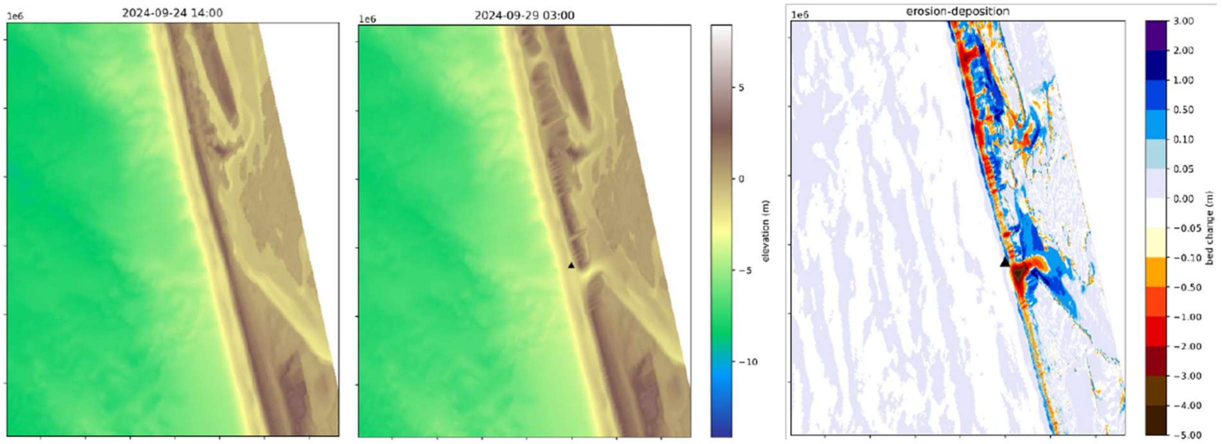


Figure 2. Before (left), and after (middle) XBeach topographies of Midnight Pass before and after Hurricane Helene, showing areas of erosion and accretion (right).

2.3. Talk 3: ADCIRC Developments for Overland Flows and Thoughts for Future Efforts by Matt Bilskie, University of Georgia

Matt Bilskie spoke on ADCIRC modeling of overland flow with two main topics: (1) mesh design for overland flows and (2) ensemble forecasts of water levels prior to hurricane landfall. He showed that careful mesh design that aligns meshes with important topographic blocking features and that uses elevations along the element boundaries rather than averaged elevations improve predictions of areas flooded during severe storms (Figure 3). This improvement in flooded area modeled occurs without increases in mesh resolution, and thus there is no increase in run times. In built up areas with fine resolution meshes, Dr. Bilskie showed that building footprints can be included in mesh design. This may improve predictions of overland flow around structures. There remain many topics in mesh design where research may improve predictions of overland flow.

For evaluating uncertainty in pre-landfall forecasts of hurricane surge, Dr. Bilskie examined ensemble forecasts of Hurricane Ian. Until a hurricane comes close to shore in the last few hours before landfall, uncertainty remains large. Dr. Bilskie showed the evolution of uncertainty with different National Hurricane Center forecasts, and ways in which the uncertainty could be formally evaluated with confidence intervals. This was expected to improve guidance for overland regions in danger of flooding, but there remains room for future improvements. A final short topic showed effects of tsunami debris loading to structures from experimental and numerical tests.

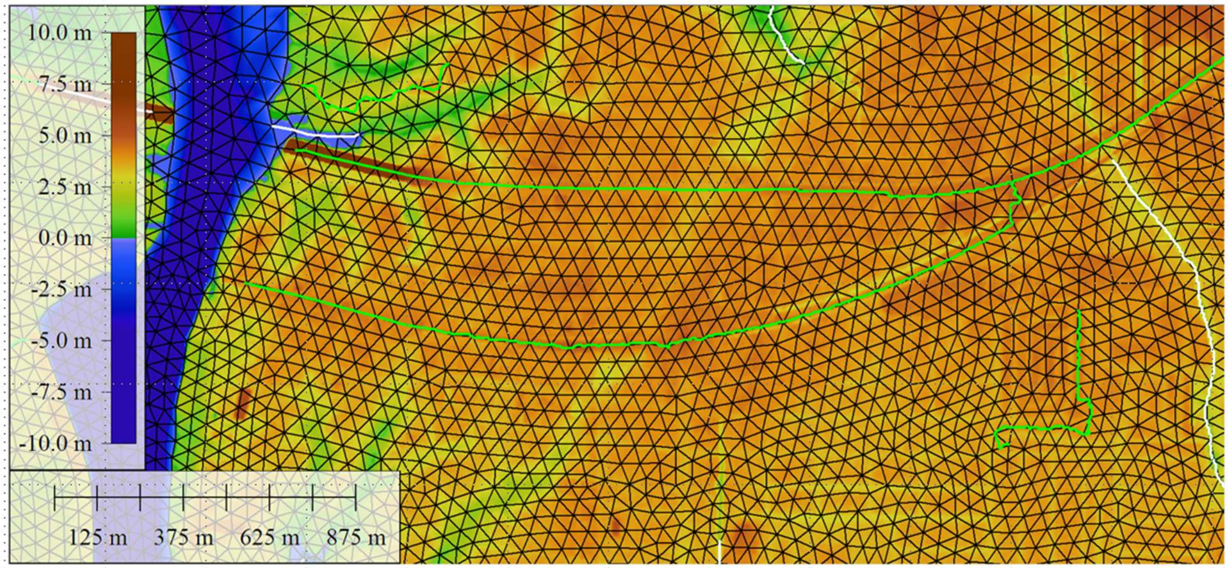


Figure 3. Vertical features (lines) tracked to align with mesh design for improved flood inundation prediction.

2.4. Talk 4: *Modeling Hurricane Waves through the Built Environment* by Don Slinn, National Institute of Standards and Technology

Don Slinn presented on modeling overland waves through the built environment. The talk was divided into two parts: (1) high resolution OpenFOAM modeling of wave runup at laboratory scales (Figure 4a), and (2) ADCIRC/SWAN modeling of Hurricane Ian at large spatial scales (Figure 4b). The OpenFOAM modeling replicated laboratory experiments performed at the O.H. Hinsdale Wave Laboratory at Oregon State University. This experiment analyzed runup through an array of buildings, and OpenFOAM was validated with the experimental model results at multiple gauges. The second half of the talk focused on ADCIRC/SWAN modeling for Hurricane Ian. Time series of ADCIRC/SWAN modeling results were validated offshore against observed wave heights, peak periods, and wind speeds. Model results were further validated overland against observed high water marks and shown to result in an r^2 value of 0.86. The sensitivity of Manning's n for overland flow was discussed. It was shown how applying a bottom friction multiplier to Manning's n overland changed the r^2 value obtained from comparing model results to the observed high-water marks. The r^2 value was shown to be highest when the bottom friction multiplier was set to 1.5. It was additionally shown that wave forces on structures are largest compared to wind and current. Future work was identified as replicating recent 1:3 experiments performed at the O.H. Hinsdale Wave Laboratory.

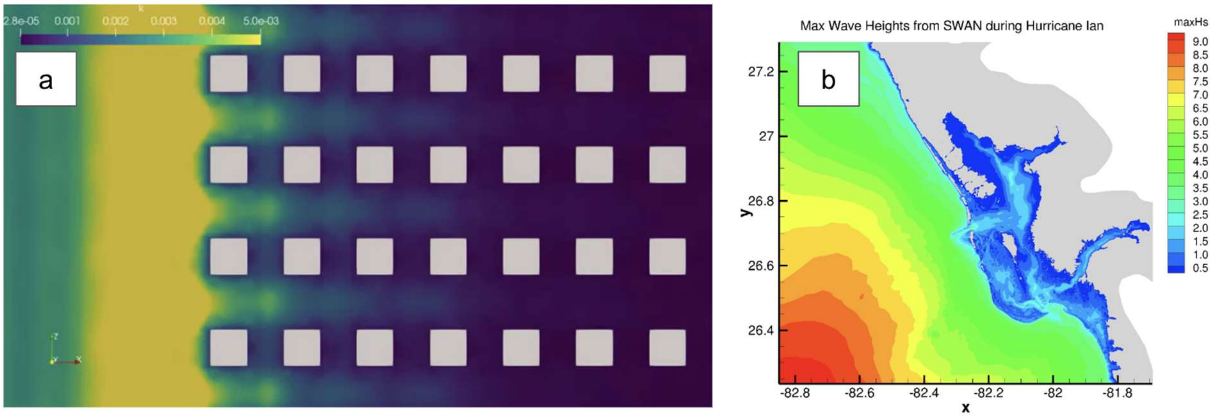


Figure 4. (a) Model results from OpenFOAM replicating laboratory experiments and used as model validation, (b) maximum wave heights obtained from ADCIRC/SWAN model runs for Hurricane Ian.

2.5. Talk 5: *Waves and the Built Environment with XBeach* by Dylan Sanderson, Johns Hopkins University and National Institute of Standards and Technology

Dylan Sanderson presented on overland wave modeling through the built environment using XBeach. His talk focused on Hurricane Ian and Estero Island. Within Estero Island, the modeling focused on a small domain that is 750 m by 882 m at a 1 m resolution. The building inventory used in this work was obtained from the Microsoft Building Footprint inventory and supplemented with first floor elevation data obtained from Amini *et al*. [1]. In total, there are 242 buildings in the model domain. Results from three XBeach model runs with different configurations of buildings were shown: (1) using the Microsoft building inventory as-is with all buildings assumed to be on the ground, (2) removing buildings in the Microsoft building inventory that are identified as elevated by Amini *et al*. [1], and (3) removing all buildings from the model domain. The results show that including buildings in XBeach reduces, on average, the maximum wave heights throughout the model domain. The results also show that in some regions maximum wave heights increase when buildings are present (Figure 5). This was shown to occur between structures and along the first row of houses. The second half of the talk focused on analyzing the observed maximum wave height extracted at each building. The results show that 36 out of 242 buildings experienced a larger maximum wave height when buildings are present compared to the no buildings run. Additionally, 47 buildings resulted in a larger maximum wave height when elevated buildings are removed compared to the no buildings run. Future work was identified as modeling all of Estero island with buildings and parameterizing fragility curves that include maximum wave heights.

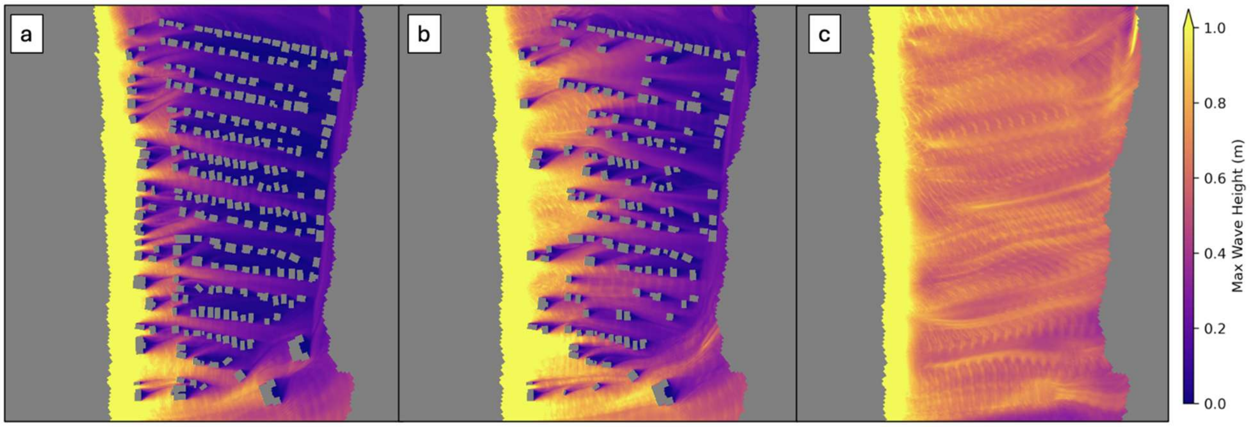


Figure 5. Maximum overland wave height resulting from XBeach model runs with: (a) all buildings, (b) elevated buildings removed, and (c) no buildings.

2.6. Talk 6: *Wave-Current-Debris Loading During Storm Inundation* by Andrew Kennedy, University of Notre Dame

Andrew Kennedy talked about debris loading during storm inundation, and the importance of debris loading during overland flow. Although debris is believed to be a significant source of damage during inundation and overland flow, the understanding and quantification of debris loads is nascent and may not accurately represent all loading types and processes. Recent experiments showed that debris loads were very large and could exceed hydrodynamic loads in many cases (Figure 6). Debris loads with currents only were shown to be much less than debris loads in wave-current overland flow. Some types of debris, particularly flat plate-like objects such as docks and walls, were seen to generate loads that were much higher than predicted by standards. This was attributed to the added mass of the water around the debris that is not accounted for by standard load representations.

Some unknowns that could be addressed in future work include investigations of debris composition and sources in recent hurricanes, the breakup of debris and its limits on maximum loads, and processes related to flat, plate-like debris loading. Existing laboratory and field observations on debris loading might usefully be incorporated into codes and standards.

Figure 6. Plate-like debris in laboratory wave-current flow flipping vertically and impacting an elevated structure. These types of loads were found to consistently have the largest magnitudes when compared to other debris and load types.

2.7. Talk 7: Some Thoughts on Coastal Wave Modeling in the Context of Structural Loading

Pat Lynett, University of Southern California

Pat Lynett presented details on the observation of infragravity waves (IG) and tsunamis (another form of long waves) and the considerations in the context of structural loading. IG waves are omnipresent and responsible for port agitation, significant hydrodynamic loads on structures, extreme runup, overtopping and overland flow, with relevant effects on structure stability, port functionality and personal safety. However, there is still a lack of understanding on the generation, propagation and release of bounded IG waves, and the extent along the coast of its influence and vice versa. IG waves have been observed along the Pacific coast and have been typically associated with the presence of swells propagating for long distances and correlated with the presence of wave groups (sets). Resonance and extreme runup events partially explain the phenomenon, but the underlying physics do not explain some situations and its prediction, understanding and observed major effects along the coast.

On the other hand, observations during a hurricane also showed the presence of IG waves (Figure 7). However, the location of the storm, propagation of wave groups and characteristics of the coastline does not explain fully the formation and presence of IG waves. It is presumed to be connected to white capping, strong wind effects, time-varying location of the breaking point, or through bore-bore capture. Nevertheless, the impact on structure loading, damage, extreme runup and overtopping, subsequent overland flow and changes on morphology are still hazards requiring additional understanding, testing, field measurements and modeling. The value of video recording during events and the potential power of new GPU computing power was highlighted to be able to perform advanced numerical simulation on the generation, propagation and release of IG waves at a coastal meso-scale.

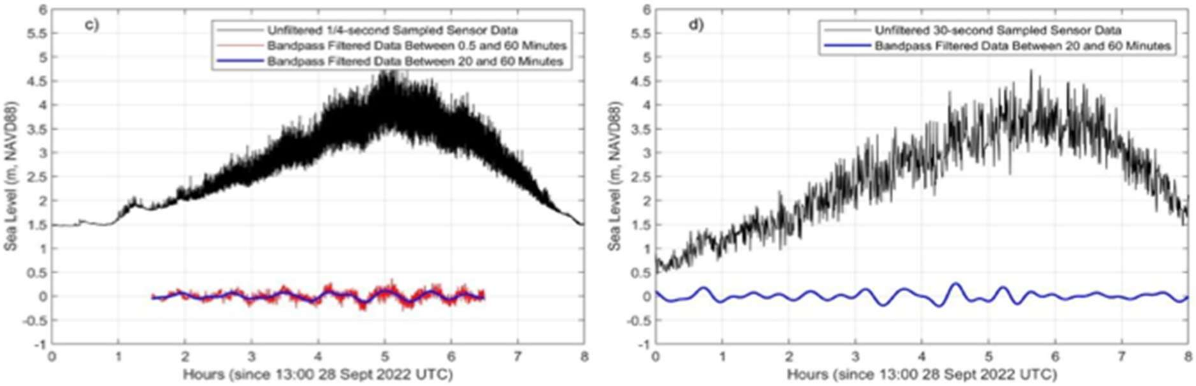
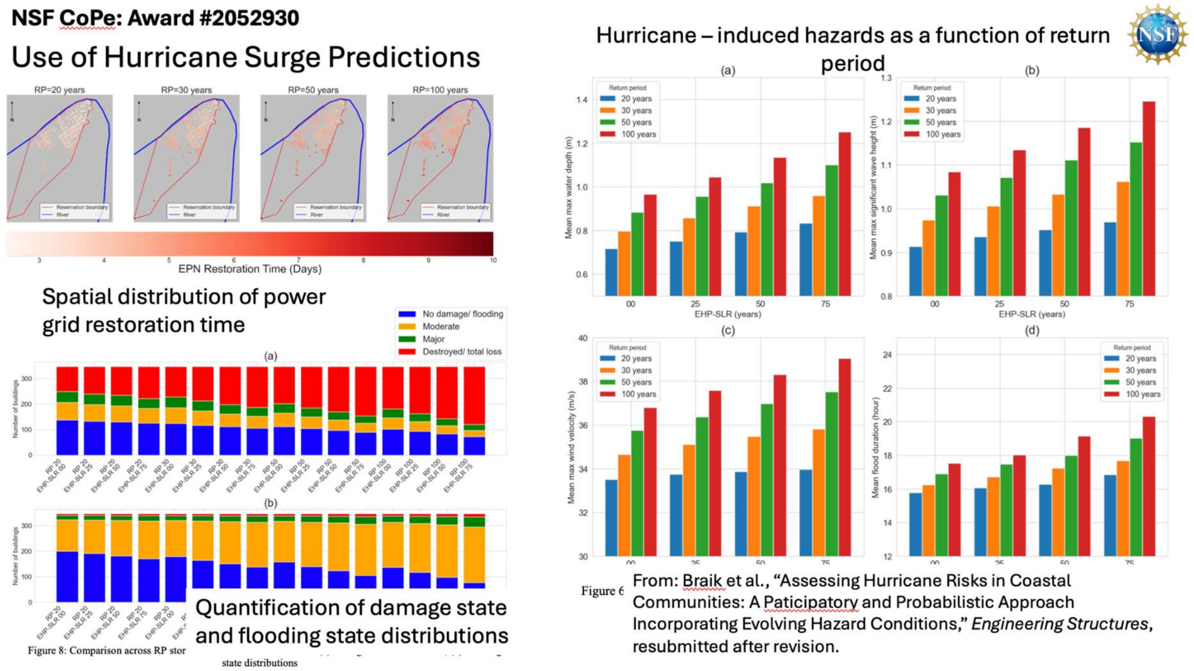


Figure 7. Observations of the total water level and residuals in Sanibel Island and Fort Myers Beach. The residual contains IG waves although there is no clear correlation with the storm location nor the coast configuration.

2.8. Talk 8: Numerical model simulation of flood impacts by Jim Kaihatu, Texas A&M University

Jim Kaihatu discussed aspects of overland flow for two different projects, both of which made use of the Delft3D model suite. The first project discussed is funded by the National Science Foundation to assist a tribal community located near Charenton, LA with flood impacts. The project team consists of structural, geotechnical, and coastal engineers, as well as researchers in archaeology, evacuation, community outreach, policy, and community resilience. Dr. Kaihatu provided information on historical, synthetic historical, and synthetic future hurricane events using the Tropical Cyclone Wind Statistical Estimation Tool (TCWiSE) hurricane model, focusing on six communities in St Mary Parish, including Charenton. This model is an advance over the Joint Probability Model-Optimal Sampling (JPM-OS, United States Army Corps of Engineers, USACE) in that it also allows for the evolution of hurricane parameters over its motion over its track. A 200 km circle around the communities was established, and only storms making landfall inside this circle were considered. These synthetic storms were further modified by including warming impacts on hurricanes. Statistical analysis of the resulting suite of simulations showed that the impact of sea level rise had far greater impact on inundation in these communities than the impact of warming on hurricanes. The statistics also reflected the impact of varying water level on communities, due primarily to both elevation and proximity to major waterways. This information was then transferred to structural engineering teams using agent-based modeling to determine recovery (e.g., power restoration, building damage states) for these communities in the wake of storms. The second project used the models to determine the impact of overland flow on toxic flooding and contaminant transport characteristics from petrochemical facilities in communities near the Houston Ship Channel. Flood levels, flood retention time, and contaminant transport distances were used to help evaluate the vulnerability of communities and facilities to adverse impacts. The results were synopsized in a microsite (https://createnbs.org/) that can be updated as more information is made available to re-evaluate vulnerability. Figure 8 shows impacts of hurricane-induced inundation on various recovery and damage characteristics for the community of Charenton LA.

The main takeaway messages are: 1) There is a need to ensure that characterizations of flooding are translated into forms usable by structural engineers and other end users. 2) The createnbs.org microsite can serve as an exemplar of an updateable digital resource for community resilience.



NSF CoPe: Award #2052930

Use of Hurricane Surge Predictions

Spatial distribution of power grid restoration time

Quantification of damage state and flooding state distributions

Hurricane – induced hazards as a function of return period

From: Braik et al., "Assessing Hurricane Risks in Coastal Communities: A Paticipatory and Probabilistic Approach Incorporating Evolving Hazard Conditions," *Engineering Structures*, resubmitted after revision.

Figure 8. Impacts of hurricane-induced inundation on various recovery and damage characteristics for the community of Charenton LA. Top left: Power grid restoration time as a function of flooding return period. Bottom left: Dependence of building damage and flooding states on return period. Right: Characterization of flooding and winds speeds resulting from simulations, transformed directly into quantities useful for impact quantification.

2.9. Talk 9: *Hx Ian Building-aware Modeling Using Deflt3D-FM* by Erick Velasco-Reyes, Oregon State University

Erick Velasco-Reyes talked about surge and wave modeling for Hurricane Ian, Estero Island, using Delft3D-FM, and incorporating building footprint with real-time control to simulate dynamic collapse. The model parameters included max mesh resolution of 4 m and Manning-n variables for roughness. The model result in terms of water level forcing conditions was validated with the United States Geological Survey (USGS) gauge. Erick compared the flow depth and flow velocity for two scenarios: (1) without buildings and (2) with buildings (Figure 9). The comparison shows that while the presence of buildings does not change the flow depth, it significantly influences velocity patterns and magnitudes, even in low-density building configurations. The change in velocity fields and bed shear stress can result in higher sedimentation probability in house-dominated neighborhoods (clusters) and higher scour probability in hotspots.

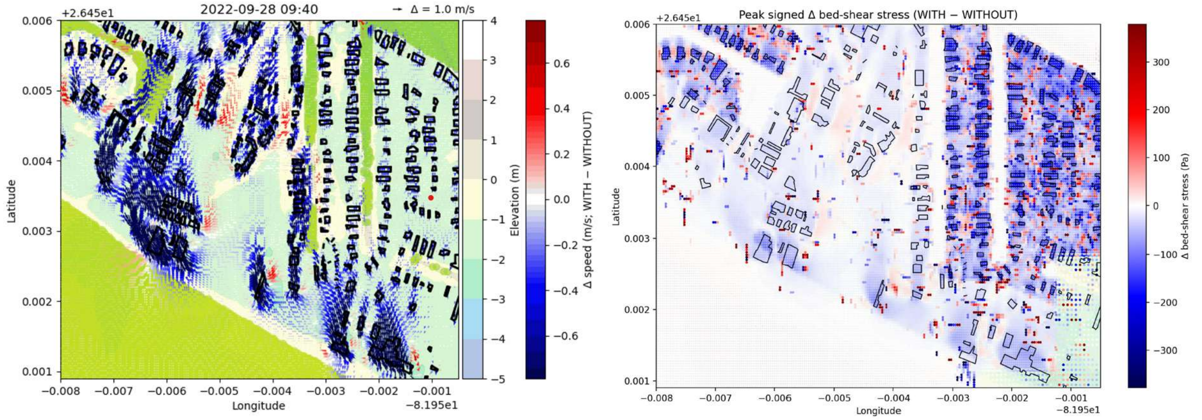


Figure 9. Left: difference in flow speed for domain with and without buildings; Right: difference in bedshear stress for domain with and without buildings

Dr. Velasco-Reyes also extended the model to capture the effect of dynamic collapse of buildings on the flow field. The real-time control (RTC) tools allowed buildings to be represented as disappearing (via gate openings) and updated the computational domain during the time-series simulation. Figure 10 shows the comparison of the flow field when a front row building is removed from the domain. The results show the dynamic collapse of buildings can significantly affect the flow velocity pattern, which can result in changes in shielding and channeling effect. Future works include calibrating drag coefficients and porosities (elevated structures) in the buildings, using fragility curves to make the collapse totally damage state-dependent, and validate the model based on sediment transport and scour observations.

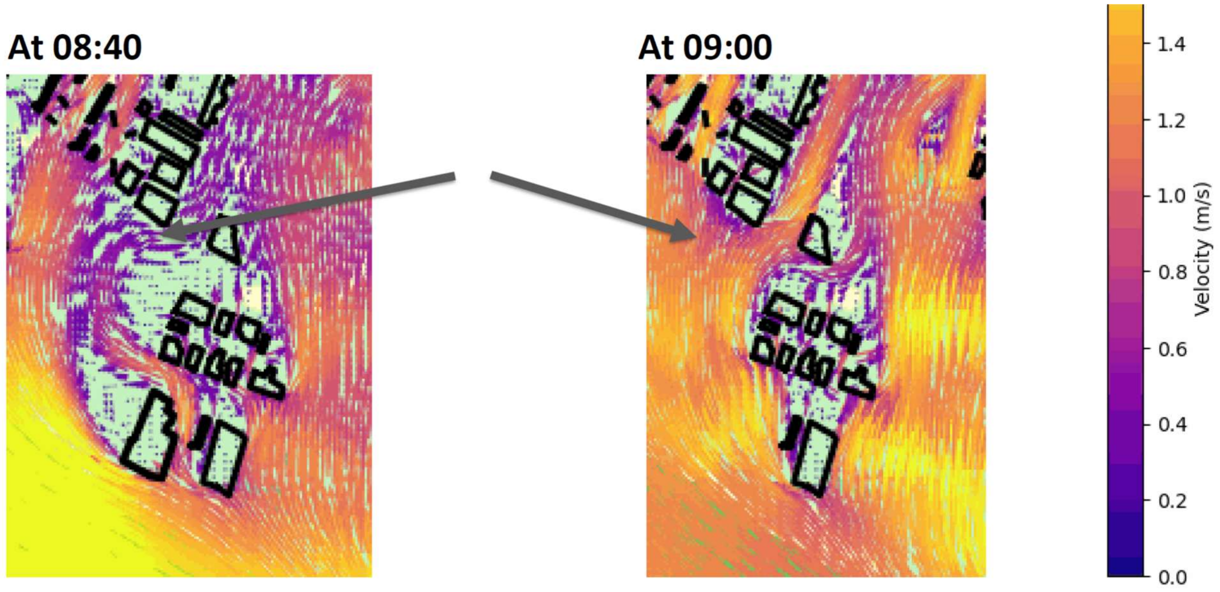


Figure 10. Left: velocity field with building before collapse; Right: velocity field after removing the building in the front line.

2.10. Talk 10: *Sea-Land Transition of Wind Speeds* by Peter Vickery, Vickery Consulting

Peter Vickery explained how wind speeds transition from open sea to populated coastal areas and the implications for hydrodynamic modeling. It highlights the challenges of estimating accurate wind speeds due to (1) boundary layer transitions between sea and land, (2) displacement height effects caused by terrain and built environments, and (3) uncertainty in drag coefficients, which directly affect modeling outputs. The presentation reviewed ASCE 7-22 (ASCE, 2022) [3] exposure categories (B, C, D) and their corresponding surface roughness lengths, comparing the power law and logarithmic law approaches. It emphasizes that while ASCE 7-22 commentary references Engineering Sciences Data Unit (1982, 1983) [4] for gust wind speeds, ESDU (Engineering Sciences Data Unit) provides a more complete framework for transitioning mean wind speeds across terrains. Figure 11 shows the (ESDU, 84011) [4] schematic figure to explain the wind profile transition across different terrains.

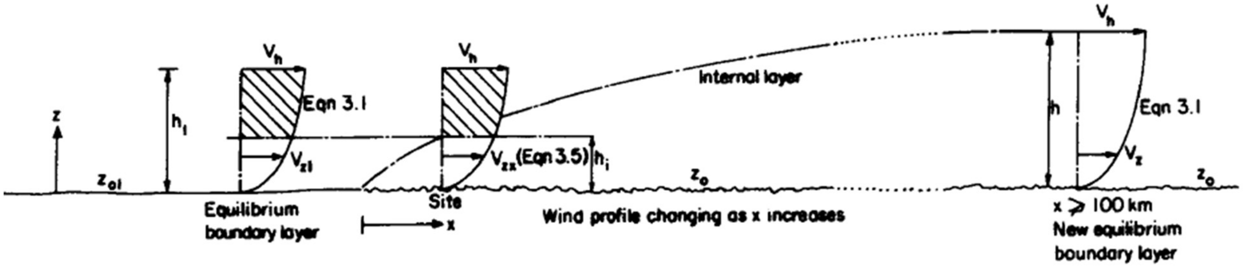


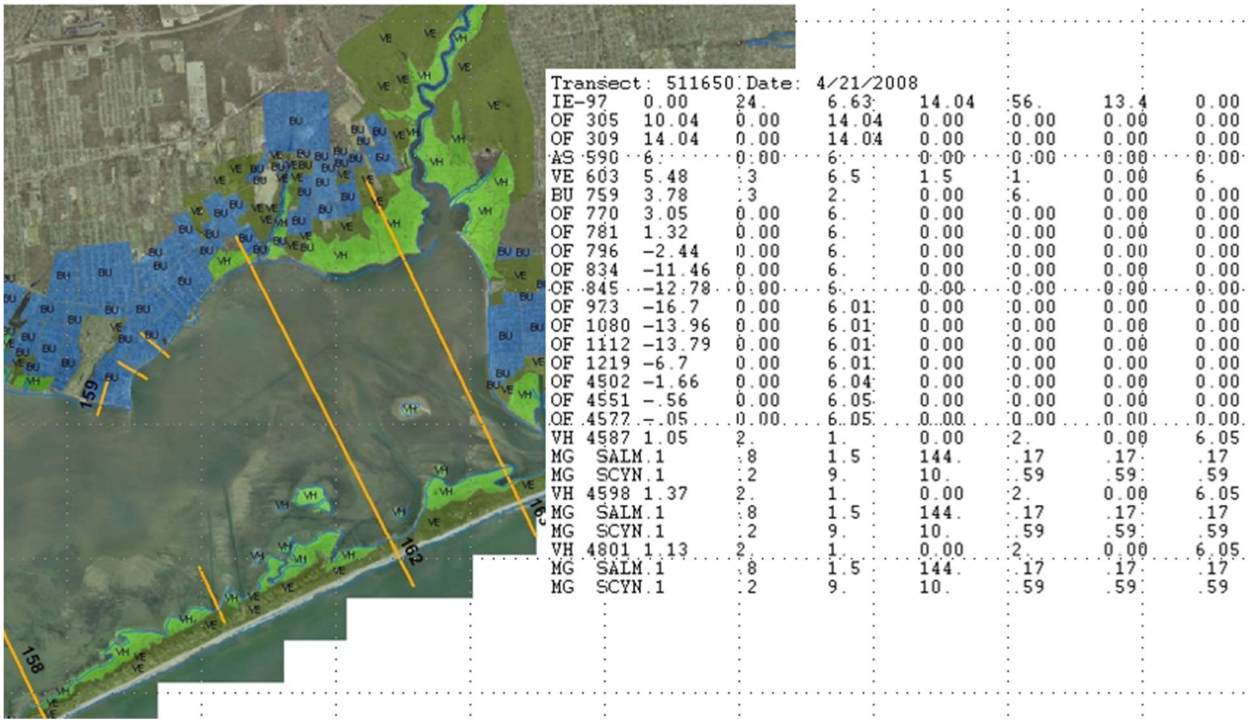
Figure 11. Schematic for wind profile transition across different terrains.

A real-world case can illustrate the difficulty of determining the appropriate roughness length (z_0) and drag coefficient to use when reduced wind speeds are applied in hydrodynamic models. The takeaway of the presentation is: (1) wind speeds decrease significantly from sea to land, influencing storm surge and wave modeling accuracy, (2) transition methods (ASCE 7-22 vs. ESDU) differ, particularly in whether they apply to gust or mean wind speeds, (3) hydrodynamic modelers must carefully consider terrain exposure, displacement height, and drag coefficients to improve prediction reliability.

2.11. Talk 11: Wave Height Analysis For Flood Insurance Studies (WHAFIS) by Jeff Gangai, Dewberry

Jeff Gangai spoke about the WHAFIS (Wave Height Analysis for Flood Insurance Studies) model. This has been FEMA's standard method to model the overland propagation of waves for Flood Insurance Rate Maps (FIRMs) since 1980. WHAFIS is a 1D transect model that represents wave growth by wind, transformation by varying depth, and dissipation by obstructions, breaking, against structures, or from vegetation (Figure 12). WHAFIS outputs the controlling wave heights and wave crest elevations for use in defining zones and Base Flood Elevations on FEMA FIRMs. WHAFIS is very quick to run on any modern computer and can be used by engineering and planning professionals directly. WHAFIS uses detailed land cover and terrain inputs directly and can use eroded profiles. Recent extensions allow for use of the 500-year inundation conditions as well as the 100 year storm. The latest version also allows for user input wind speeds.

Because WHAFIS is a 1D transect model, results need to be interpolated in between transects to reach all areas. There have been attempts to model overland waves in 2D and match to WHAFIS, but these are not yet completely successful. For all models including WHAFIS, measured data for overland waves is needed to validate and to improve model performance and accuracy.



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OF 309   14.04   0.00    14.04   0.00    0.00    0.00    0.00
AS 590   6.      0.00    6.      0.00    0.00    0.00    0.00
VE 603   5.48    .3      6.5     1.5     1.      0.00    6.
BU 759   3.78    .3      2.      0.00    6.      0.00    0.00
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OF 1112 -13.79   0.00    6.01    0.00    0.00    0.00    0.00
OF 1219 -6.7     0.00    6.01    0.00    0.00    0.00    0.00
OF 4502 -1.66    0.00    6.04    0.00    0.00    0.00    0.00
OF 4551 -.56     0.00    6.05    0.00    0.00    0.00    0.00
OF 4577 -.05     0.00    6.05    0.00    0.00    0.00    0.00
VH 4587 1.05     2.      1.      0.00    2.      0.00    6.05
MG  SALM.1       .8      1.5     144.    .17     .17     .17
MG  SCYN.1       .2      9.      10.     .59     .59     .59
VH 4598 1.37     2.      1.      0.00    2.      0.00    6.05
MG  SALM.1       .8      1.5     144.    .17     .17     .17
MG  SCYN.1       .2      9.      10.     .59     .59     .59
VH 4801 1.13     2.      1.      0.00    2.      0.00    6.05
MG  SALM.1       .8      1.5     144.    .17     .17     .17
MG  SCYN.1       .2      9.      10.     .59     .59     .59
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Figure 12. Example of WHAFIS carding inputs.

3. Breakout Sessions

Two, 90-minute breakout sessions were conducted in the afternoon to discuss (1) research needs for modeling and measurements in the context of overland flow in the built environment and (2) laboratory studies that can be used to benchmark the development of numerical models. The workshop participants were divided among three tables. Each table was assigned a scribe to take notes and to share the table discussion with the entire group. In addition to the general discussion, each table was instructed to consider actionable items that could yield advancements in overland flow.

3.1. Breakout Session 1: Research needs for modeling and measurements

Discussion Summary from Table 1

This table identified two main priorities for what is needed in modeling overland flow in built environments. First, there is a need for higher accuracy, low-cost models. Multiple approaches were discussed including physics-based AI, statistical but physics-aware methods, surrogate modeling, and subgrid methods. The table identified that there is a need to better predict forces and loads on structural components, especially those exposed to multiple hazards such as wind, waves, currents, surge, and rainfall. Second, this table discussed the need for a central database with geospatial data that is tied to mesh and other input generators. This database could be used to create inputs to hydrodynamic models such as elevations, bathymetry, land cover, and building inventories. This database could also be used to house observation data to be used in validating numerical models.

This table additionally discussed what can be done with existing tools. Four priorities were identified: (1) scour, (2) understanding uncertainty, (3) predicting runup during storm events, and (4) better consideration of cascading consequences. In particular, robust scour and runup predictions are lacking in guidance documents such as ASCE 7-22, leading to challenges in coastal design and construction. Regarding scour, the group identified that there are currently many models that consider scour (XBeach, Delft3D, FUNWAVE, etc.). The group discussed that scour could be considered in the design of structures and that hazard maps with scour could be created. Regarding uncertainty, this table discussed the propagation of uncertainty from the hazard to structural response and a need to compare existing models. There was also a need to consider uncertainty in models regarding population growth and urbanization. The discussion of uncertainty led to a discussion of how to communicate uncertainty to the public. Regarding runup, this table identified that wave runup could be considered in structural design and that existing models could do a better job of reporting the computed runup during simulations. Regarding cascading consequences, the table discussed that existing tools could better quantify cascading consequences such as scour leading to pipe failure or debris generation/transport.

Actionable Items:

The action items identified from this table are:

1. Develop a centralized database with geospatial datasets that are tied to input generators for numerical models.

2. Develop scour maps to be included in structural design.
3. Evaluate uncertainty in existing models through a cross-model comparison.

Discussion Summary from Table 2

The discussion in this group focused on modeling of overland wave and current forces on structures from individual structure scales up to community-scales.

At the individual structure scale, the table identified that there could be better collaboration between structural and coastal engineers to identify what exactly is needed when designing buildings to withstand wave forces. For example, are statistical properties of wave heights (mean, max, significant wave height, etc.) sufficient or are time series necessary? Additionally, the statistics of wave heights and current velocities over the built environment are not well quantified for reliability analysis. This is further complicated when considering repeat hurricane events in a region. The table also identified that it is difficult from a structural engineering perspective to model gradual damage or fatigue. This includes damage accumulation within an event due to repeated wave loads and during the service life of a building, where it sees multiple such events. Further, there is a need for high-resolution models of structural response with two-way coupling of fluid-structure interaction, rather than assuming that the structure is fixed/constant.

At the community scale, the discussion began with identifying that there is a need for models to more accurately capture wave reflection on structures, and subsequently a need to better predict wave forces on structures, including both horizontal and uplift forces. Related to wave forces, this table discussed that improved fragility curves accounting for surge, wave, and currents could be developed. The table also discussed that there is a need to identify how sophisticated models need to be in order to capture wave forces on structures at community scales. For example, are phase-averaged models, long-wave resolving models, or short-wave resolving models necessary? This table also discussed that current models of morphology and sediment transport near buildings need to be validated and improved.

There was consensus at this table that better data is needed to validate overland flow through the built environment. There is a need to have instrumentation in place before landfall of a hurricane rather than only examining high water marks afterward. There was consensus that videos tend to be better than sensors, although videos cannot adequately capture current velocity. The videos would also show the evolution of damage through the built environment, which cannot be captured well in post-disaster damage surveys. This discussion also extended to using existing camera infrastructure (e.g., doorbell cameras) to obtain data that is geographically distributed.

Actionable Items:

1. The action items identified from this table are:
2. Evaluate existing models to identify how sophisticated they need to be in order to capture wave impacts on structures, e.g., phase averaging vs. resolving.

3. Make use of present observation techniques including improved image processing to extract wave heights as well as crowdsourced data (e.g., doorbell cameras).
4. Develop digital twin frameworks that can be easily updated as more data becomes available.
5. Better communication between structural and coastal engineers to identify what is needed for structural design.

Discussion Summary from Table 3

There was a general agreement that the models are doing fairly well in terms of estimating the water level (surge). However, the discussion at Table 3 focused on a need to pull all the relevant overland flow models together to get a better understanding of what they are doing and where the gaps are with respect to waves and currents. This ‘pulling together’ of the models could be accomplished through a state-of-the-art review paper and/or by conducting a modeling exercise with a common boundary condition. Some of the relevant numerical models were (in no particular order): ADCIRC+Swan, XBeach, XBeach-nonhydrostatic, Delft3D, Boussinesq models such as Funwave (Fully Nonlinear Waves) and COULWAVE, reduced complexity models such as SFINCS, solvers for the nonlinear shallow water wave equations, and time-averaged models such as WHAFIS. It was noted that there can be a difficulty in conducting purely numerical modeling exercises with individual modelers ‘going their own way’, limiting the usefulness of model comparisons. Therefore, it was suggested that if such an approach were taken that there be clear guide rails on the boundary conditions and minimum prescription of the outputs, for example, estimates of free surface, velocity, and waves at given output locations. There was a discussion about the appropriate location and scale of such a modeling exercise. For example, it was thought that the domain could encompass the entirety of Estero Island with particular attention paid to a few areas on the island that would represent moderate to high density of buildings or areas where there were significant changes in land use such as vegetation, open areas, dense buildings and so on. This action item would leverage existing work already completed for Hurricane Ian by the research community, for example ADCIRC model runs for the NOPP (National Oceanographic Partnership Program) project would be readily available to supply the boundary conditions.

There was a discussion about the limitation of data that would be useful for potentially benchmarking the models. As a ‘sub-action item’ to support the modeling activity, it was suggested that existing observations such as the Max Olson video (and perhaps other survivor videos) could be used to give estimates of wave condition and velocity at a given location. It was thought that this could be accomplished, for example, by a graduate student within a few months. With regard to the state-of-the-art review, this was deemed as a useful exercise and potentially ‘low hanging fruit’ that could set the stage for a future model-comparison work. It was suggested that the review could develop a comprehensive table listing the models, theoretical framework, inputs/outputs, example use cases for overland flow, verification and validation, and any other relevant information.

Actionable Items

There were three main action items from this breakout session:

1. State-of-the-art review paper on overland flow
2. Quantification of wave height, period, and surface velocity from Max Olson video to support future model-model comparison study
3. Model-model comparison study on overland flow for a fixed domain (e.g., Estero Island)

Action items (AI) 1 and 2 were deemed to be easier than (3). AI-1, 2 could be completed within 1 year with relatively low financial support. AI-1 would require a small contribution from a larger number of researchers with expertise on each sub-class of model, and AI-2 would require a large contribution from a single researcher. AI-3 would take considerably longer, require support (funding) at least for the person leading the effort, and would take potentially 1-2 years to complete.

3.2. Breakout Session 2: Laboratory benchmark studies

Prior to the start of Breakout Session 2, Dr. Cox gave a 10-minute presentation on the use of physical models to study surge/wave in the built environment. The presentation focused on the length scales that are typically associated with projects ranging from the largest scales of 1:25 to 1:200 scale to study multiple buildings at a community (or local) level, to 1:3 to 1:10 for studying isolated buildings at the parcel level, to 1:3 to 1:1 (prototype) for studying structural elements at prototype scale (Figure 13).

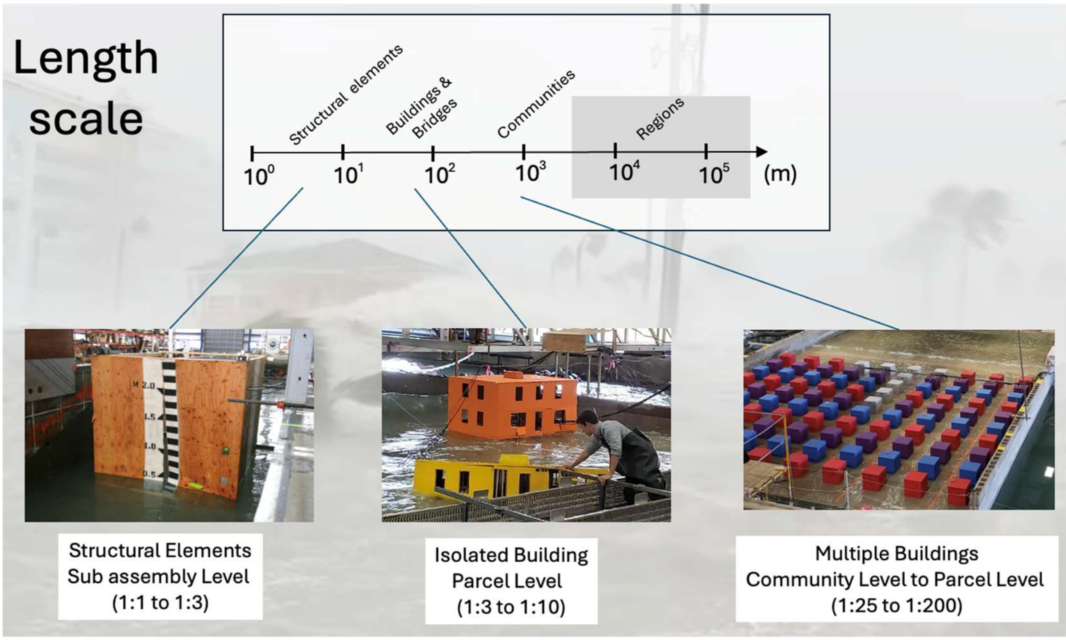
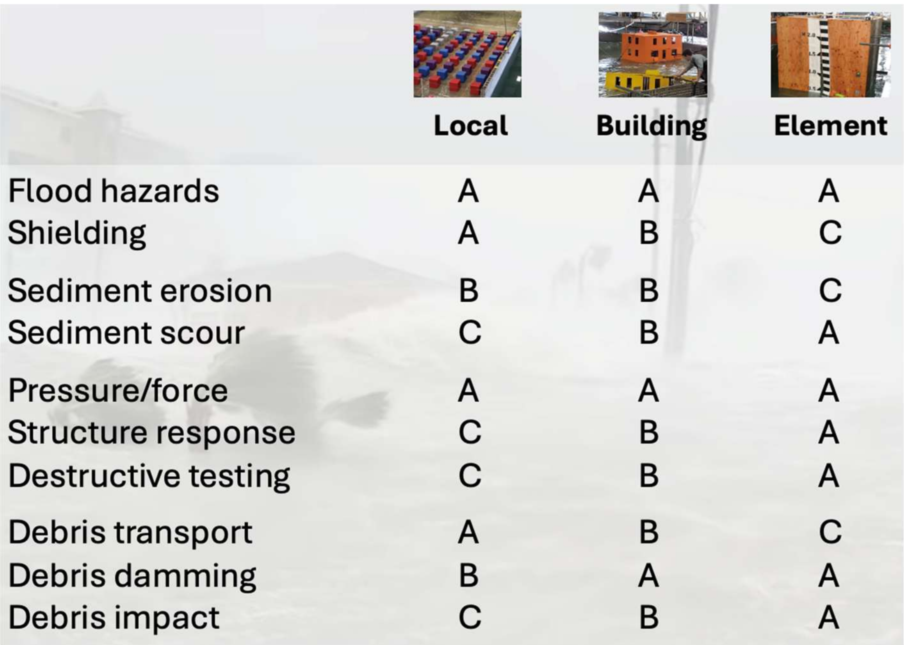


Figure 13. Different lengths scales considered for different types of laboratory experiments.

In general, the local scale (1:25 to 1:200) is well-suited for studying the hazard (surge, waves and currents), sheltering and shielding, hydrodynamic pressure, and debris transport. But this scale is less well-suited for other phenomena such as sediment scour or destructive testing. As the geometric scale decreases, the ability to reliably study some of these phenomena change. Figure 14 presents a summary opinion of our ability to model certain processes in a physical laboratory. These capabilities should be considered when designing experiments to benchmark numerical models.



	Local	Building	Element
Flood hazards	A	A	A
Shielding	A	B	C
Sediment erosion	B	B	C
Sediment scour	C	B	A
Pressure/force	A	A	A
Structure response	C	B	A
Destructive testing	C	B	A
Debris transport	A	B	C
Debris damming	B	A	A
Debris impact	C	B	A

Figure 14. Our ability to model different physical phenomena varies depending on the geometric scale considered for laboratory experiments.

The following sections contain summaries from the table discussion with attention to the actionable items.

Discussion Summary from Table 1

The discussion in this group began with what hazards would be useful to have a full-scale benchmark study. The group decided that full-scale benchmark studies considering multi-hazard events from wind, rain, surge, and wave hazards would be very useful. When focusing on surge and waves, the group proposed that currents, debris, and scour should be investigated at full-scale. Some other aspects to focus on included structural integrity and resilience of weathering and degraded components from previous storms.

The conversation then turned to including the natural environment and analyzing natural and built environment interactions. Proposed areas to study this interaction included moveable beds, flexible vegetation, dunes, and flood protection systems of various designs. The usefulness of video captured during extreme weather events was brought up and the group decided that capturing the corresponding strains, forces, pressures, and displacements to the video were vital to benchmark physical complexities that occur with fluid structure interaction during extreme weather events.

Another area that could be explored is the impact of interior components, such as furniture, on structural failure. The discussion concluded with a summary of which processes were most important to capture. The first of the most important processes to capture were the multi-hazard processes (wind, rain, surge, waves, scour, sedimentation). Next, the importance of system-level feedback across landscape types was emphasized. Another important process to capture included the hydrological impact of coastal protection features across various scales. The importance of modeling flow variables from subgrid corrections and closure schemes at the "neighborhood" scale was also stressed. Finally, understanding the uplift forces on buildings was included in these important processes to capture.

Actionable Items:

1. Full-Scale, multi-hazard experiment
2. Flow variables at the "neighborhood" scale to validate subgrid corrections
3. Natural and built environment interactions during extreme weather events

Discussion Summary from Table 2

The discussion in this group covered 5 topics: (1) connections between numerical and laboratory modeling, (2) fluid-structure interaction, (3) scour, (4) waves, and (5) debris.

Regarding connections between numerical and laboratory modeling, the group identified that there is a need to identify what is missing in numerical models that can be captured through lab experiments. The usefulness of numerical modeling for testing different laboratory experiment configurations as a cost-effective means was discussed. This can occur after the numerical model is validated with experimental model results. Laboratory work could also be more tightly merged with numerical modeling approaching hybrid simulation as is done in structural engineering. Geographically distributed experiments were discussed, where, for example, one experiment is occurring in the wave basin at O.H. Hinsdale Wave Research Laboratory simultaneously with another experiment occurring in the wave flume. Sensors in both the wave basin and flume would communicate with each other and experiments could be performed at different scales.

Regarding fluid-structure interactions, the group identified that there is a need to better quantify uplift forces on structures when water can completely flow underneath an elevated building. The discussion of uplift forces extended to overhanging structures such as carports. The group also identified a need to test structural connections since many buildings in Fort Myers beach were washed away due to poor connections. Laboratory experiments could also be performed to test the extent that the first row of houses block waves. This could be compared to wave attenuation through nature-based features or alternative coastal engineering structures such as a seawall or breakwaters. The discussion also included the need for using different scaling methods within an experiment such as the use of Froude scaling for hydrodynamic loads and mass/Cauchy scaling for debris impact loads.

Regarding scour, the group discussed scour and the need to test how different configurations of structural/geotechnical properties lead to failure. Further, there is a need to test time-dependent scour rather than under steady flow conditions.

Regarding waves, the group discussed that there is a need to better understand how wave spectra evolve and are represented in overland conditions. This is expanded to include how waves propagate and vary at community scales through the built environment.

Regarding debris, the group discussed that debris could be better represented in laboratory experiments. Currently, there are no ways to systematically account for debris in laboratory experiments. The need to have more “deterministic” debris in laboratory experiments or statistically describe debris through probabilistic distributions was discussed. The usefulness of laboratory experiments in determining the mechanisms of structural failure was discussed and how this contrasts with field work, where only post-event observations can be made. For example, in the lab, one could observe the extent that debris vs. wave impacts cause structural failure.

Actionable Items:

1. Identify what is missing in numerical models that could be captured through laboratory work.
2. Laboratory experiments of uplift forces on structures - both elevated structures and overhanging structural members.
3. Identify ways to systematically account for debris in laboratory settings (probabilistic distributions, deterministic approaches to introduce debris).

Discussion Summary from Table 3

During this breakout session, the group focused on experiments that would provide valuable insights into fundamental mechanisms related to fluid structure interaction. Pat Lynett proposed a study into turbulence and mixing of an elevated structure to better understand the turbulence signature at and around the structure. The group agreed that it was important to understand this interaction at the individual structure level. Rick Luettich then suggested an experiment running waves with two elevated structures and exploring the wave characteristics between the structures. Some valuable insights from this study could be the impact of the separation of the two structures on the wave characteristics, specifically momentum lost between the front and back of the structures. Increasing the scope of experiments, the group discussed an experiment utilizing a model of a community to explore wave propagation and dissipation through the built environment. Rick Luettich asked what the setup of the community would look like, Pat Lynett and Dan Cox approximated a 5x5 or 4x4 setup. However, Dan Cox mentioned that it would be more valuable to have more rows of structures because the storm surge from Hurricane Ian extended approximately 300 m from the shoreline. Pat Lynett commented that this experiment could be used to validate Erick Velasco’s Delft3D model, specifically looking at velocities on the back side of the structures. Pat Lynett proposed a study more focused on solely wave characteristics, specifically the non-linear transfer of wave groups in spatially variant currents. The discussion turned to what was needed on the structural side related to building design codes. Pat Lynett asked what design codes were in place related to wave properties, Dan Cox explained that ASCE 7-22 recently started considering these properties and mainly focused on the velocity of the waves. The session concluded with some suggestions from Rick Luettich on looking into the impact of imposing no-slip conditions in models such as ADCIRC, which generally assumes free-slip conditions. Rick said that a preliminary experiment into flow through a narrow inlet showed significant differences with no-slip conditions versus free-slip.

Actionable Items:

1. Study of turbulence signatures of flow through and around an elevated structure.
2. Study focusing on the impact of a gap between two elevated structures on wave characteristics from the front to the back of each structure.
3. Study exploring storm surge and overland flow through the built environment using a community of structures, focusing on velocity around structures

4. Summary

This one-day workshop convened twenty-six experts on landfalling hurricanes to discuss the overland flow of surge, waves and currents in the built environment. Twenty attended in-person, and six were on-line. Eleven invited talks were presented and discussed to explore the state of the art of numerical modeling of overland through a series of invited talks. After the invited talks, two breakout sessions were held to discuss (1) Research needs for modeling and measurements in the context of overland flow in the built environment and (2) Laboratory studies that can be used to benchmark the development of numerical models. Participants were asked to consider actionable items that could yield advancements in overland flow. The following actionable items are identified from this workshop:

1. State-of-the-art review paper – This review paper could be prepared relatively quickly (within 12 months) and could be written by the collective effort of several of the experts who attended this workshop. A key component of this manuscript could be a large table listing open-source models ranging in complexity from time-averaged models such as WHAFIS to highly resolved models such as OpenFOAM. The table could include (a) model formulations, (b) inputs/outputs, (c) pros & cons, (d) verification and validation, (e) and references to use cases.
2. Inter-model comparison – This comparison would enable researchers to better understand 'what is missing' in our ability to predict overland currents and waves in the built environment. The recommendation is to form a small group to scope out the requirements of this comparison. For example, the group would identify:
    a. the testbed domain, for example a section of Fort Myers Beach
    b. the storm condition at the seaward boundary conditions, for example Hurricane Ian surge and waves at the seaward boundary from existing work
    c. the treatment of the built environment pre- and post-Hurricane Ian (e.g, building footprints, elevations, and likelihood of failure)
    d. the locations overland to predict the waves and currents

    The group would present their proposal to the larger working group for 'buy-in'. The group would be responsible for data-sharing (providing the model grids, forcing conditions, building footprints). The International Conference on Coastal Engineering (ICCE), May 18-22, 2026, in Galveston Texas was seen as a good venue for sharing progress and results.
3. Scoping study for laboratory validation – A large physical model would enable detailed validation for numerical models. Like the Inter-model comparison, a reasonable first step is to convene a small group to scope out the requirements of such an effort. For example, the group would identify:
    a. The overall objectives of the study. There are likely to be several objectives, some of which are complementary and some of which may be in competition

due to differences, for example, in geometric scale. The group should narrow the scope to complimentary objectives

b. The appropriate geometric scale, considering the objectives, capabilities of laboratory facilities, and costs
c. An overall experimental approach, building off previously successful model validation studies

The group would present their proposal to a larger working group for feedback. This activity could be accomplished by the end of Q4 2025.

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[1] Amini, M., D. Cox, A. Barbosa, S. Appleton Figueira (2024). " An integrated Pre and Post Storm Dataset for Hurricane Ian (2022)", in Virtual Damage Assessment and First-floor Elevation Estimation: Application to Fort Myers Beach, Florida and Hurricane Ian (2022). DesignSafe-CI. https://doi.org/10.17603/ds2-c1g8-qy41

[2] Cox, D., M. Amini, D. Roueche, D. Sanderson, A. Meselhe, D. Slinn (2025). Hurricane Ian Workshop Series, DesignSafe-CI. https://doi.org/10.17603/ds2-y4va-fw72

[3] American Society of Civil Engineers. (2022). ASCE 7-22: Minimum Design Loads and Associated Criteria for Buildings and Other Structures. American Society of Civil Engineers, Reston, VA.

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Appendix A. Meeting Agenda

8:00 (30 min) Intro (check-in, self intros, goals/agenda)

8:30 (100 min) Invited talks, 20 min each including questions

Talk 1: *Flood Hazards: Large to Local Scales,* Rick Luettich, University of North Carolina

Talk 2: *ADCIRC Developments for Overland Flows affected by (a) Small-Scale Pathways and Barriers, and (b) Coastal Erosion,* Casey Dietrich, North Carolina State University

Talk 3: *ADCIRC Developments for Overland Flows and Thoughts for Future Efforts,* Matt Bilskie, University of Georgia

Talk 4: *Modeling Hurricane Waves through the Built Environment,* Don Slinn, National Institute of Standards and Technology

Talk 5: *Waves and the Built Environment with XBeach,* Dylan Sanderson, Johns Hopkins University and National Institute of Standards and Technology

10:10 (20 min) Break

10:30 (120 min) Invited talks, 20 min each including questions

Talk 6 Andrew Kennedy, University of Notre Dame: Wave-Current-Debris Loading During Storm Inundation

Talk 7: *Some Thoughts on Coastal Wave Modeling in the Context of Structural Loading* Pat Lynett, University of Southern California

Talk 8: *Numerical model simulation of flood impacts,* Jim Kaihatu, Texas A&M University

Talk 9: *Hx Ian Building-aware Modeling Using Deflt3D-FM,* Erick Velasco-Reyes, Oregon State University

12:30 (30 min) Lunch

1:00 (40 min) Invited talks, 20 min each including questions

Talk 10: *Sea-Land Transition of Wind Speeds,* Peter Vickery, Vickery Consulting

Talk 11: Jeff Gangai / Dewberry. Wave Height Analysis For Flood Insurance Studies (WHAFIS)

1:40 (80 min) Breakout Session 1, Research needs for modeling and measurements

3:00 (90 min) Breakout Session 2, Laboratory benchmark studies

4:20 (30 min) Wrap up

5:00 Adjourn

Appendix B. Participant List

Table B-1. Participant List

First	Last	Affiliation	Role	Email
Karim	Abdelwahab	National Institute of Standards and Technology	attendee	karim.abdelwahab@nist.gov
Mehrshad	Amini	University of Rhode Island	attendee	mehrshad.amini@uri.edu
Matt	Bilskie	University of Georgia	presenter	mbilskie@uga.edu
Tanya	Brown-Giammanco	National Institute of Standards and Technology	attendee	tanya.brown-giammanco@nist.gov
Joel	Cline	National Institute of Standards and Technology	attendee (online)	joel.cline@nist.gov
Daniel	Cox	Oregon State University	co-organizer	dtc@oregonstate.edu
Casey	Dietrich	North Carolina State University	presenter	jcdietrich@ncsu.edu
Jeff	Gangai	Dewberry	presenter	JGangai@Dewberry.com
Adi	Gupta	University of Georgia	attendee	adi.gupta@uga.edu
Betsy	Hicks	Federal Emergency Management Agency	attendee (online)	betsy.hicks@fema.dhs.gov
Keenan	Hubbard	Oregon State University	attendee	hubbakee@oregonstate.edu
John	Ingargiola	Federal Emergency Management Agency	attendee (online)	John.Ingargiola@fema.dhs.gov
Chris	Jones	Jones Consulting	attendee (online)	chris.jones@earthlink.net
Jim	Kaihatu	Texas A&M University	presenter	jkaihatu@civil.tamu.edu
Sabarethinam	Kameshwar	Louisiana State University	attendee	skameshwar1@lsu.edu
Andrew	Kennedy	University of Notre Dame	presenter	andrew.b.kennedy.117@nd.edu
Marc	Levitan	National Institute of Standards and Technology	attendee (online)	marc.levitan@nist.gov
Pedro	Lomonaco	Oregon State University	attendee	Pedro.Lomonaco@oregonstate.edu
Rick	Luettich	University of North Carolina	presenter	rick_luettich@unc.edu

Pat	Lynett	University of Southern California	presenter	lynett@usc.edu
Norberto	Nadal	United States Army Corps of Engineers	attendee (online)	Norberto.C.Nadal-Caraballo@usace.army.mil
Dylan	Sanderson	Johns Hopkins University/NIST	presenter	sandersondylan@gmail.com
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