Community-Engaged Flood Modeling to Evaluate Pathways toward Sea-Level Rise Resilience

Thomas Thelen[1], Katherine Anarde[1], Casey Dietrich[1], Max Cawley[3], Miyuki Hino[2]

4th International Workshop on Waves, Storm Surges, and Coastal Hazards – September 25, 2025

1 NC STATE UNIVERSITY

2 THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

3 MUSEUM of LIFE + SCIENCE

SUNNY DAY FLOODING PROJECT

(Photo credit: Coastal Observer app)

Coastal flooding is occurring more frequently outside of extreme storm and wave events

New York City, New York


Vegadeo, Spain


San Francisco, California


Plaza del Ayuntamiento
Santander, Spain


Cork, Ireland

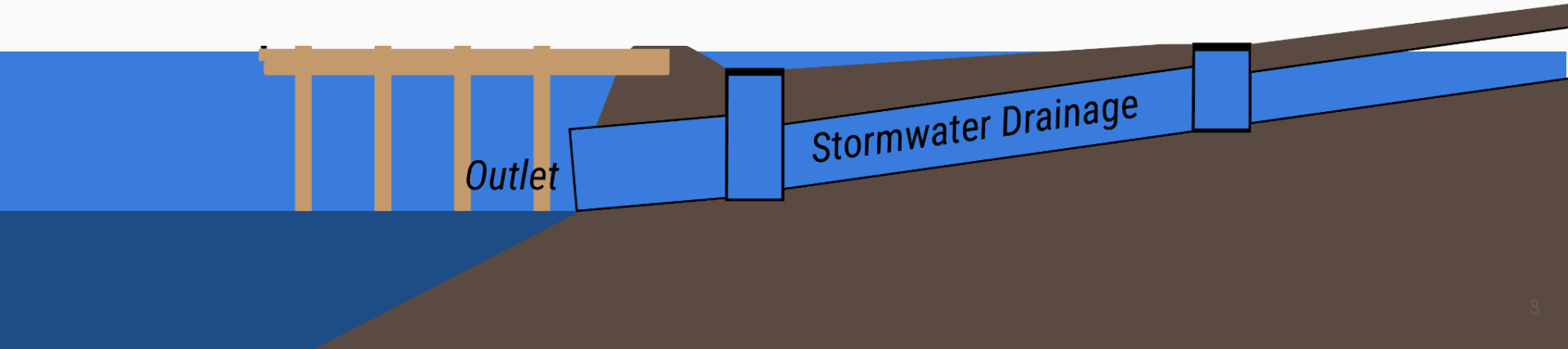
(top left: NY Sea Grant
bottom left: me walking home from the Workshop on Monday,
bottom right: RTE,
top right: Business Insider,
top center: La Nueva Espana)

Gap #1: How to model **multi-driver** coastal flooding at relevant resolutions?

*Drivers of **chronic flooding***

Ocean-scale flooding drivers:

- Tides (Hague et al., 2023)
- Wind setup (Coz et al., 2021)



Gap #1: How to model **multi-driver** coastal flooding at relevant resolutions?

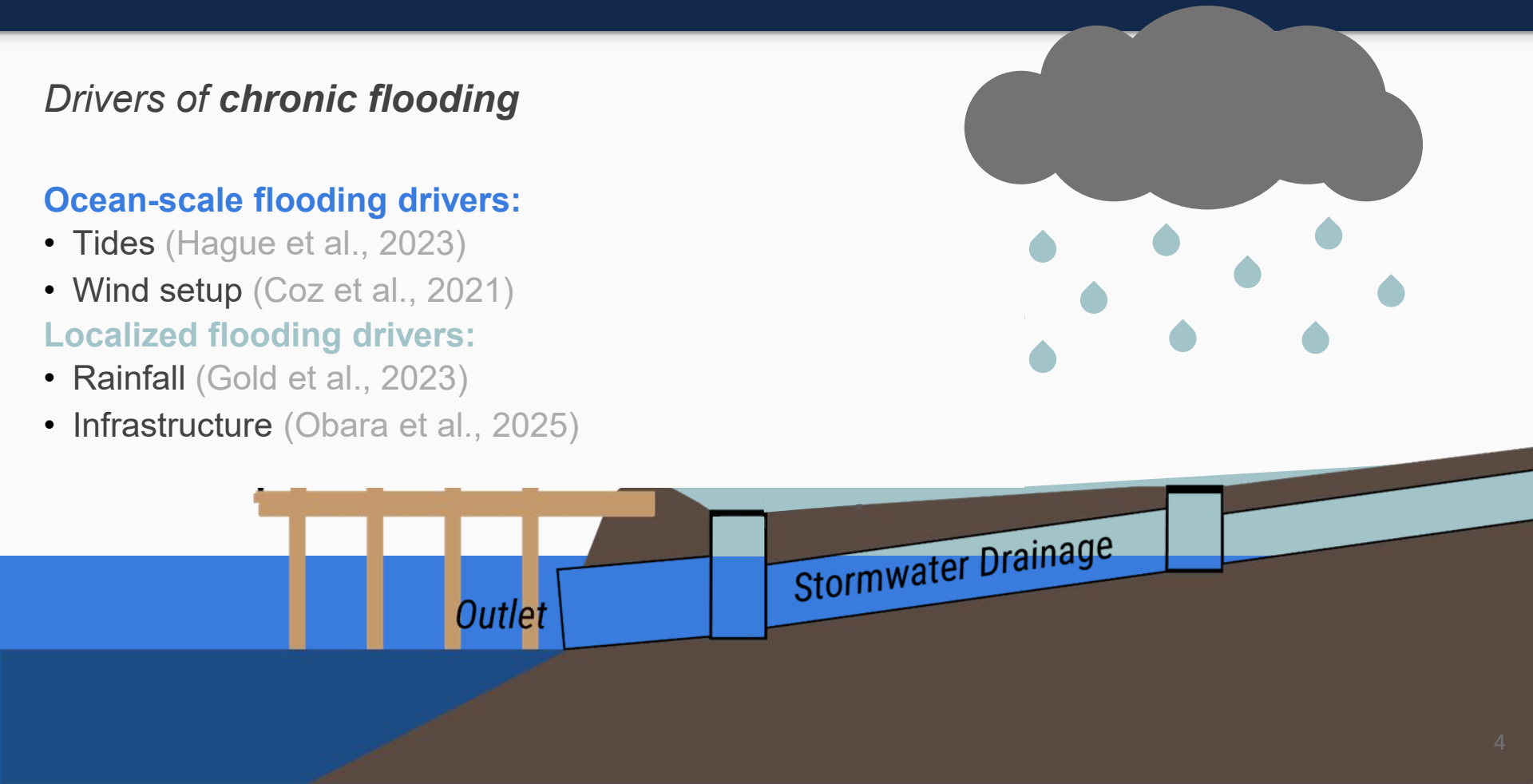
*Drivers of **chronic flooding***

Ocean-scale flooding drivers:

- Tides (Hague et al., 2023)
- Wind setup (Coz et al., 2021)

Localized flooding drivers:

- Rainfall (Gold et al., 2023)
- Infrastructure (Obara et al., 2025)



Gap #1: How to model **multi-driver** coastal flooding at relevant resolutions?

*Drivers of **chronic flooding***

Ocean-scale flooding drivers:
- Tides (Hague et al., 2023)
- Wind setup (Coz et al., 2021)

Localized flooding drivers:
- Rainfall (Gold et al., 2023)
- Infrastructure (Obara et al., 2025)

Sea-level rise (Sweet et al., 2022)

Spatial scale: several city blocks (Mydlarz et al., 2024)
Temporal scale: minutes to hours (O'Donnell et al., 2024)

*Coastal flooding driven by **rainfall at high tide** in Carolina Beach, North Carolina (Source: Sunny Day Flooding Project camera)*

Gap #2: How to test the effectiveness (present & future), acceptability of adaptations?

Lesson learned from storm surge adaptation projects:
involve community members in strategy selection
(Rasmussen et al., 2023)

OPEN ACCESS | Technical Papers | Nov 22, 2022

Check for updates

Coastal Defense Megaprojects in an Era of Sea-Level Rise: Politically Feasible Strategies or Army Corps Fantasies?

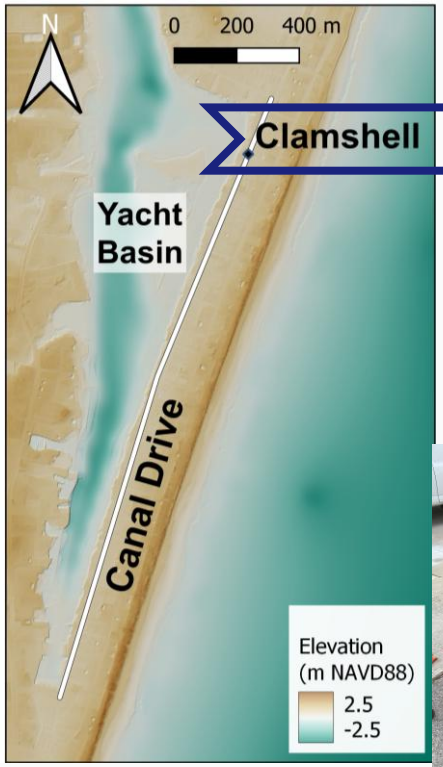
This article has a reply. VIEW THE REPLY

Authors: D. J. Rasmussen, Robert E. Kopp, and Michael Oppenheimer | AUTHOR AFFILIATIONS

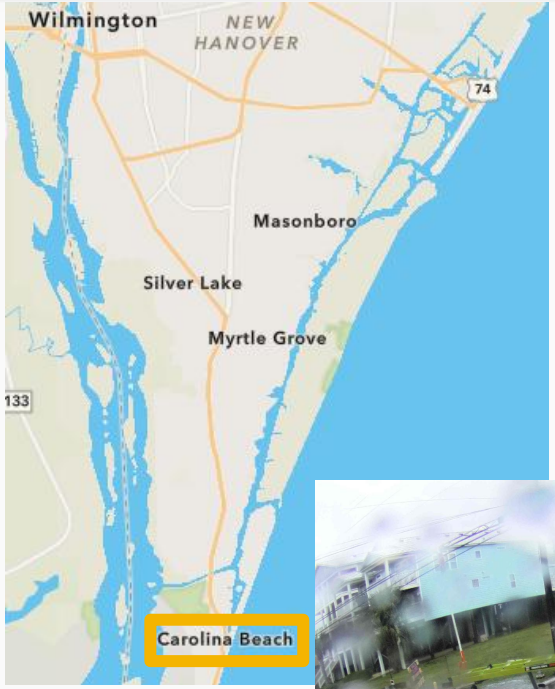
Miami-Dade County Rejected An Army Corps Plan To Fight Storm Surge — Here's What The Corps Says Is Up Next

WLRN 91.3 FM | By Jenny Staletovich
Published September 2, 2021 at 2:52 PM EDT

Carolina Beach, North Carolina, USA: overland flooding & impaired stormwater networks



Sensor data: Carolina Beach experiences **40 to 65 floods yearly** outside of extreme storms



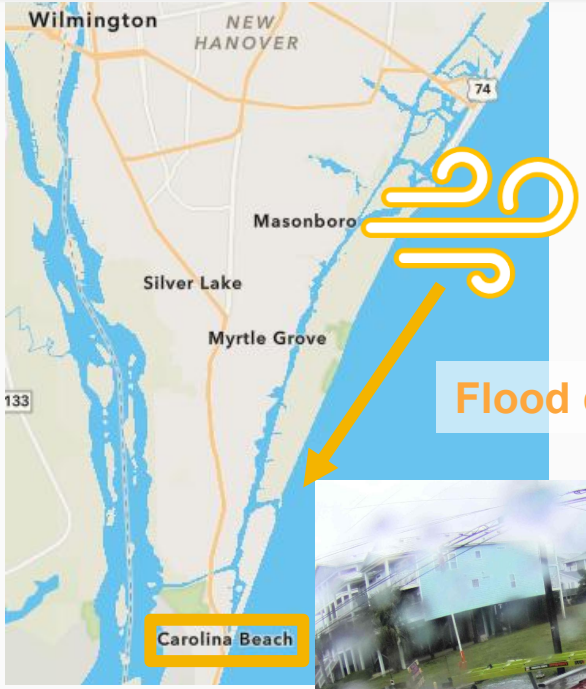
Check out real-time flood sensor data here

Scan Me

Floods* outside of extreme storms
April 2022 to April 2023: **43 floods**
May 2023 to April 2024: **64 floods**
May 2024 to April 2025: **51 floods**
(Thelen et al., 2024; Hino et al., 2025)

*flood = any amount of water on the road

Sensor data: **Wind** and **rain** compound with tides to exacerbate flooding in Carolina Beach



One-third of measured floods in Carolina Beach occurred during tidal forecasts below the community's threshold for flood monitoring (Thelen et al., 2024)

Flood driver: wind

Check out real-time flood sensor data here

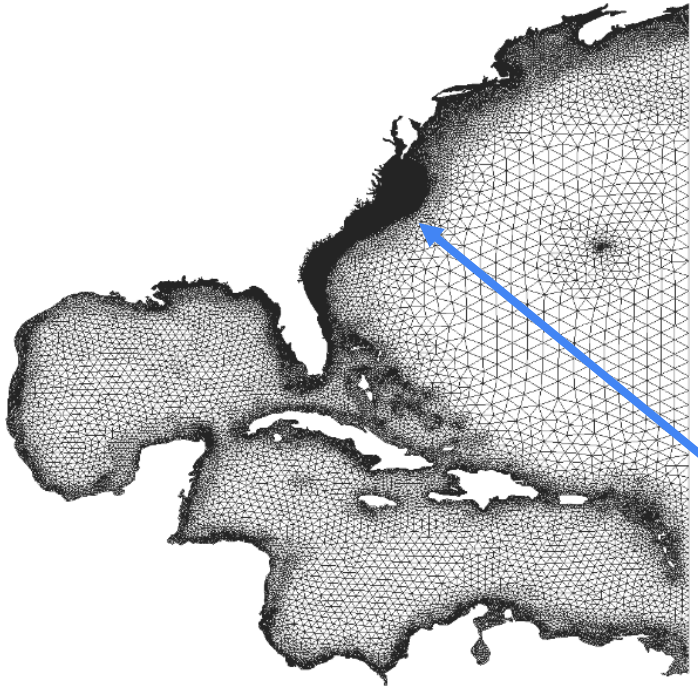
Scan Me

Floods* outside of extreme storms
April 2022 to April 2023: **43 floods**
May 2023 to April 2024: **64 floods**
May 2024 to April 2025: **51 floods**
(Thelen et al., 2024; Hino et al., 2025)

*flood = any amount of water on the road

A coupled **hydrodynamic** and stormwater model to simulate coastal flooding

ADCIRC: ocean-scale hydrodynamics



(Luettich and Blanton, 2008)

Model domain:
Western Atlantic

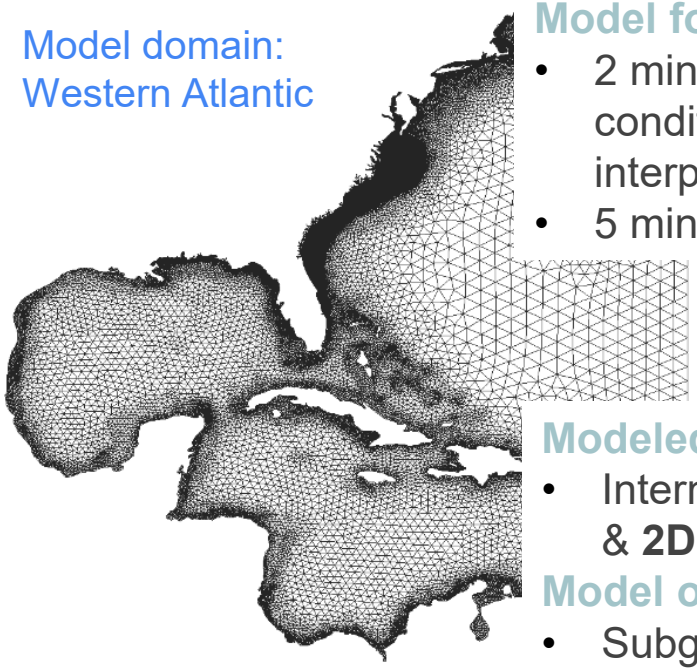
Model forcings:

- **Tidal constituents** at open ocean boundary
- 3 hr, 12 km interval **wind and pressure** fields
- **Sea-level rise** from domain-wide water level increase

A coupled hydrodynamic and **stormwater** model to simulate coastal flooding

ADCIRC: ocean-scale hydrodynamics

Model domain:
Western Atlantic



(Luettich and Blanton, 2008)

Model forcings:

- 2 min. **water level** boundary conditions (**BCs**) interpolated from ADCIRC
- 5 min. interval **rain-on-grid**

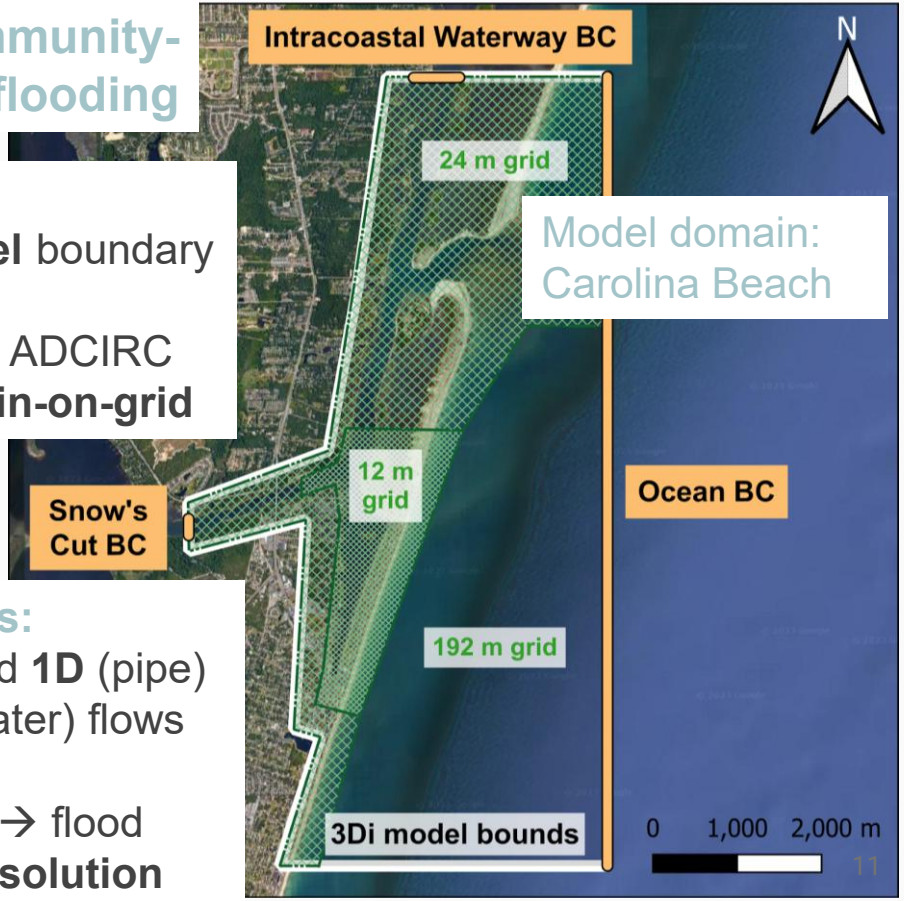
Modeled processes:

- Internally coupled **1D** (pipe) & **2D** (surface water) flows

Model output:

- Subgrid method → flood depths at **1 m resolution**

3Di: community-scale flooding



Knowledge gaps

1. Model of multi-driver coastal flooding

ELSEVIER

Water Research

Available online 28 August 2024, 122339

In Press, Journal Pre-proof What's this?

Wind and rain compound with tides to cause frequent and unexpected coastal floods

Thomas Thelen [1], Katherine Anarde [1], Joel Casey Dietrich [1], Miyuki Hino [2 3]

Flood modeling paper →

Knowledge gaps

1. ✓ Model of multi-driver coastal flooding
2. Framework for testing effectiveness, acceptability of chronic flooding adaptations

Canal Drive flooding woes due to handful of properties. A proposed solution? Expensive bulkheads

PORTCITYDAILY
WILMINGTON, NC

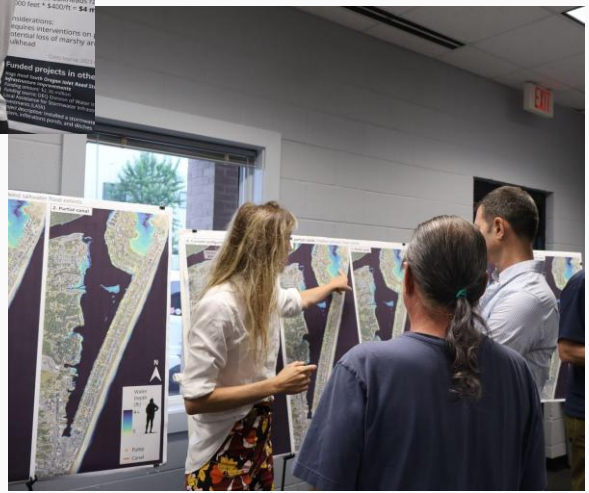
Private problem, public nuisance? Carolina Beach committee pinpoints 9 properties causing flooding on Canal

By Johanna F. Still June 29, 2021

Norfolk, VA

Envisioning Flood Resilience in Carolina Beach community workshop series

We engaged *~15 residents* to identify flood resilience **strategies preferred by the community**, and **test how effective** these strategies might be in mitigating flooding now and in the future



Identify strategies → model at present-day sea levels → model at future sea levels

Workshop #1: June 2024
- What strategies?
- Where?

Long list of potential strategies

Workshop #2: November 2024
- Effectiveness at present-day sea levels?
- Effectiveness against different drivers (tides/wind vs. rain)?

Short list of potential strategies

Workshop #3: February 2025
- Effectiveness at future sea levels?
- Feasibility?

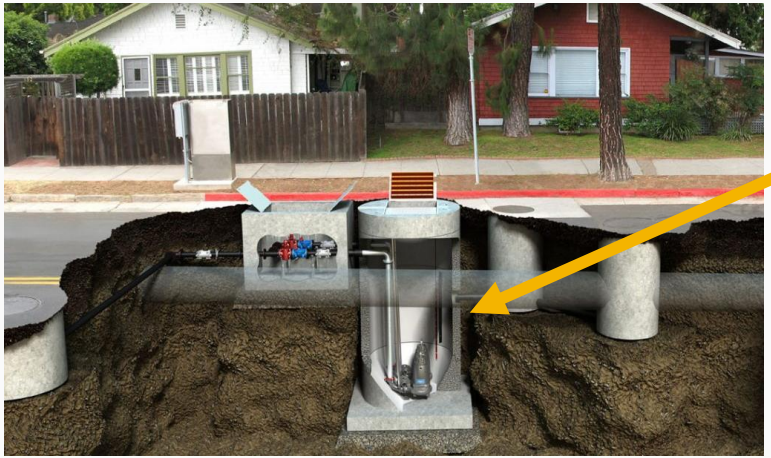
Preferred strategies and associated next steps

Workshop #4: May 2025
- Reflection, next steps
- Report back to broader community

Flood resilience strategies selected by participants for modeling

Modeled strategies

- *Minimum bulkhead elevation*
- Pumps
- *Min. bulkhead elevation + pumps*
- Movable flood barrier
- Drainage canal



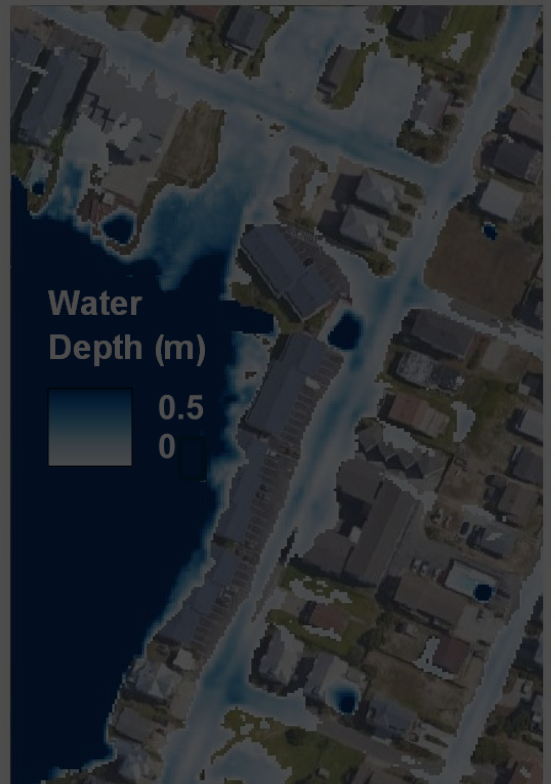
Pump

Bulkhead

(left: Romtect
right: Southern NC Marine)

1) With bulkheads, present-day flooding from rain at high tide > 2050 flooding without rain

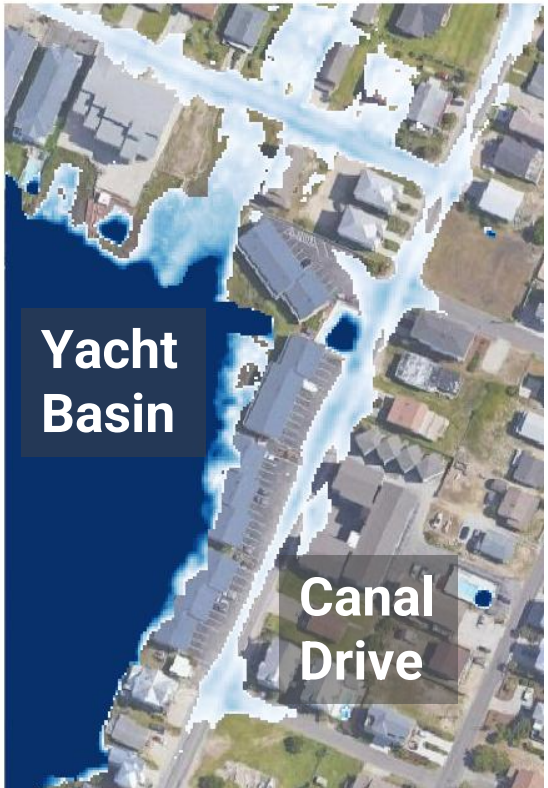
Tides, wind, ***rain***
Present-day sea levels
Minimum bulkhead elev.



January 22, 2023
hindcast flood

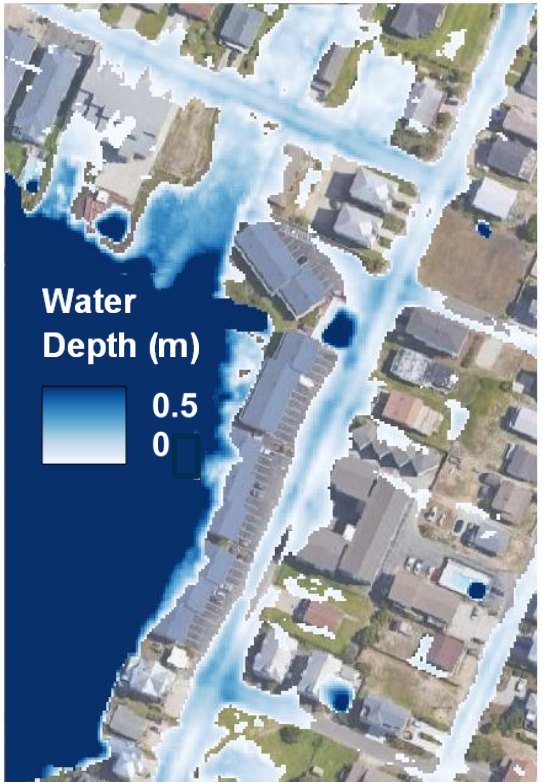
Tides & wind
2050 sea levels
Minimum bulkhead elev.

(int. high projections – Sweet et al. 2022)



1) With bulkheads, present-day flooding from rain at high tide > 2050 flooding without rain

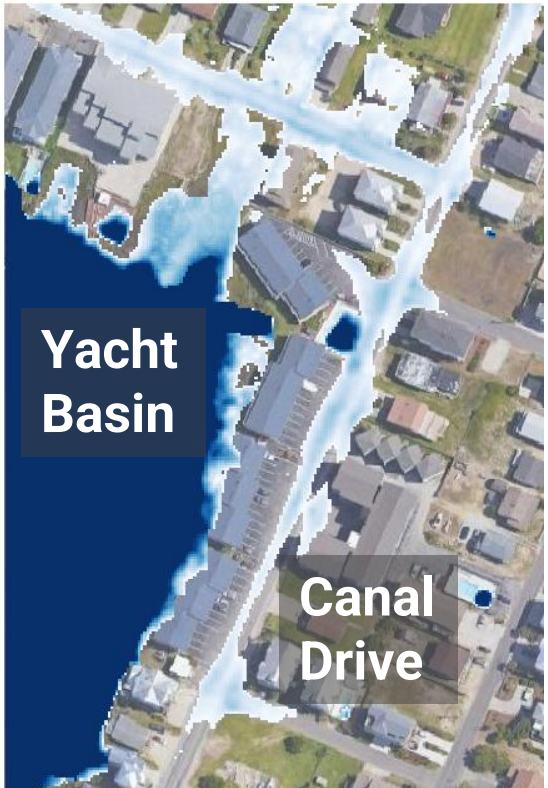
Tides, wind, ***rain***
Present-day sea levels
Minimum bulkhead elev.



January 22, 2023
hindcast flood

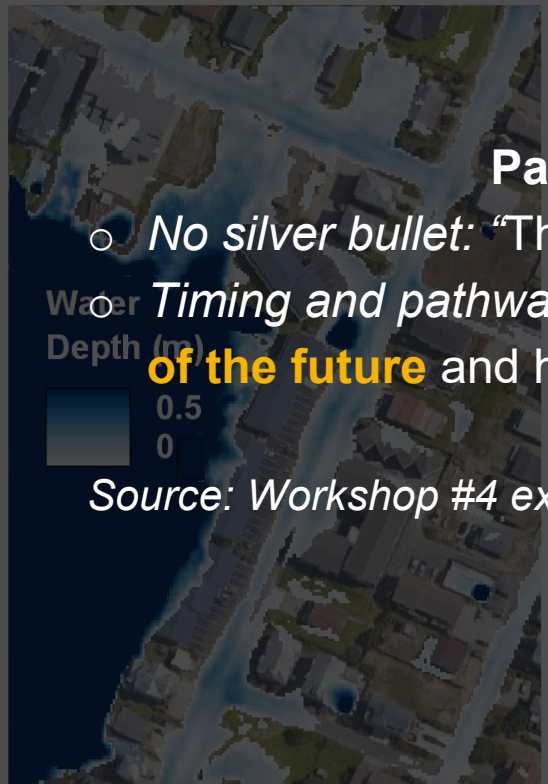
Tides & wind
2050 sea levels
Minimum bulkhead elev.

(int. high projections – Sweet et al. 2022)

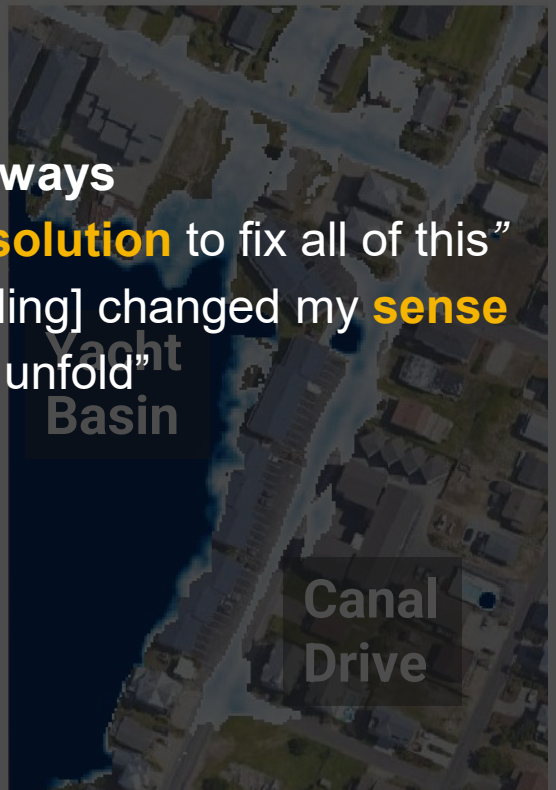


Modeling at future sea levels informed time horizons to target for adaptation

Tides, wind, ***rain***
Present-day sea levels
Minimum bulkhead elev.



Tides & wind
2050 sea levels
Minimum bulkhead elev.

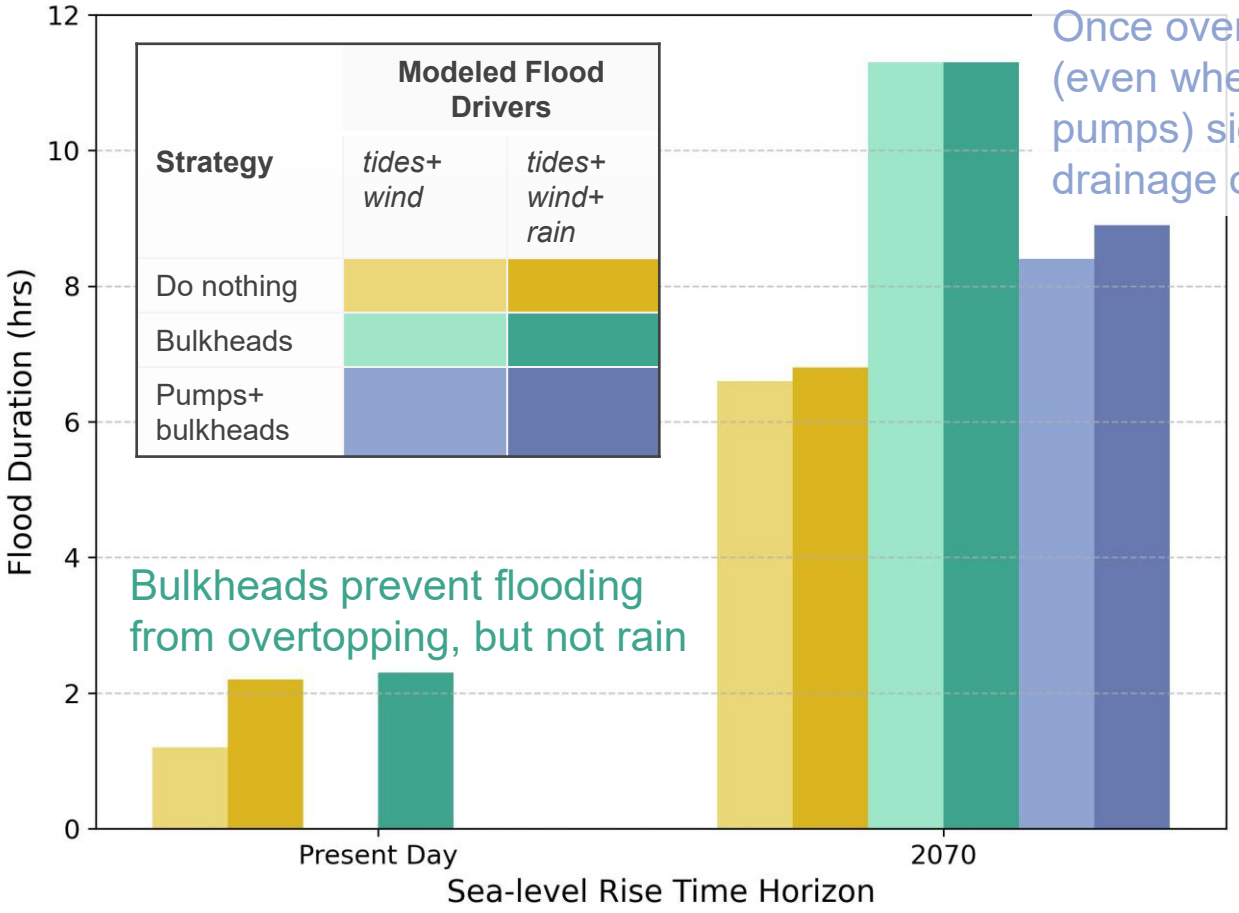


Participant takeaways

- *No silver bullet:* "There is **no one solution** to fix all of this"
- *Timing and pathways:* "[The modeling] changed my **sense of the future** and how things may unfold"

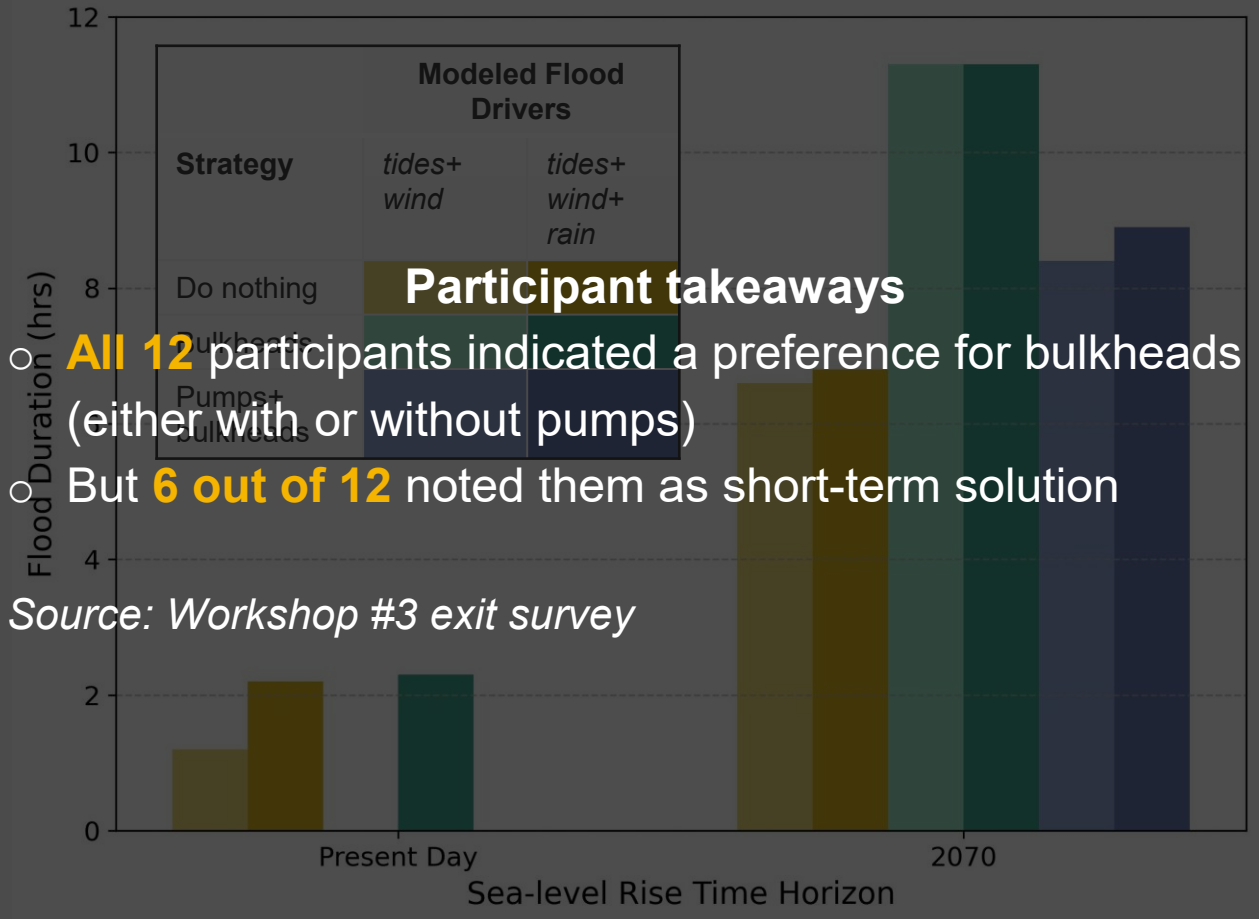
Source: Workshop #4 exit interviews

2) Higher bulkheads block return flow, increasing flood duration → *maladaptive at future sea levels*



(int. high projections – Sweet et al. 2022)

Participants weighed present-day functionality/feasibility vs. future maladaptive outcomes



Participant takeaways

- **All 12** participants indicated a preference for bulkheads (either with or without pumps)
- But **6 out of 12** noted them as short-term solution

Source: Workshop #3 exit survey

Tailored models, validated with local data, engage residents in adaptation conversations

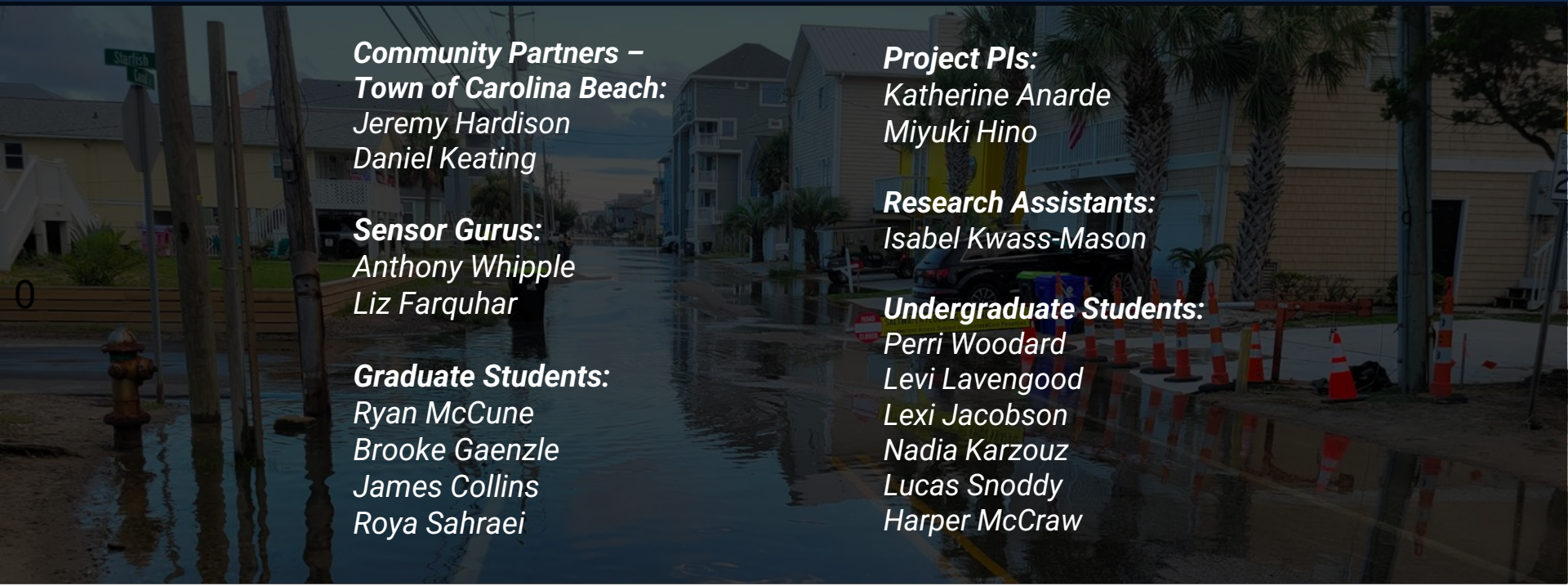
Physical science takeaways: *effectiveness of SLR adaptation strategies*

1) *Today*: raising shoreline elevations (e.g., bulkheads or seawalls) keeps out marine flood drivers but **does not protect** against compound events
2) *Future sea levels*: raised shorelines become **maladaptive** by trapping floodwaters (marine and compound) & increasing flood duration

Social science takeaways: *perceptions of SLR adaptation strategies*

1) Modeling a range of future sea-levels helped participants **select time horizons** that they most value for adaptation decisions
2) The perceived ease of implementation to address immediate flooding issues **outweighed** potential maladaptive outcomes at future sea levels

Project Partners and Funders



Community Partners – Town of Carolina Beach:
Jeremy Hardison
Daniel Keating

Sensor Gurus:
Anthony Whipple
Liz Farquhar

Graduate Students:
Ryan McCune
Brooke Gaenzle
James Collins
Roya Sahraei

Project PIs:
Katherine Anarde
Miyuki Hino

Research Assistants:
Isabel Kwass-Mason

Undergraduate Students:
Perri Woodard
Levi Lavengood
Lexi Jacobson
Nadia Karzouz
Lucas Snoddy
Harper McCraw

NC STATE UNIVERSITY

SUNNY DAY FLOODING PROJECT

NOAA NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION U.S. DEPARTMENT OF COMMERCE

NSF

SOUTHEAST Climate Adaptation Science Center

Sea Grant NORTH CAROLINA

COASTAL RESILIENCE CENTER
A U.S. Department of Homeland Security Center of Excellence

Thanks for your attention! Questions?

ththelen@ncsu.edu

linkedin.com/in/ththelen

Graduating **January 2026**

Next steps: post-doc or researcher position

CV linked here →

Let's talk!

Flood modeling paper →

Two papers in prep:

1. How coastal residents perceive hazards from chronic flooding
2. Takeaways from the workshops and adaptation modeling

Extra slides

Gap #1: How to model **multi-driver** coastal flooding at relevant resolutions?

*Drivers of **chronic flooding***

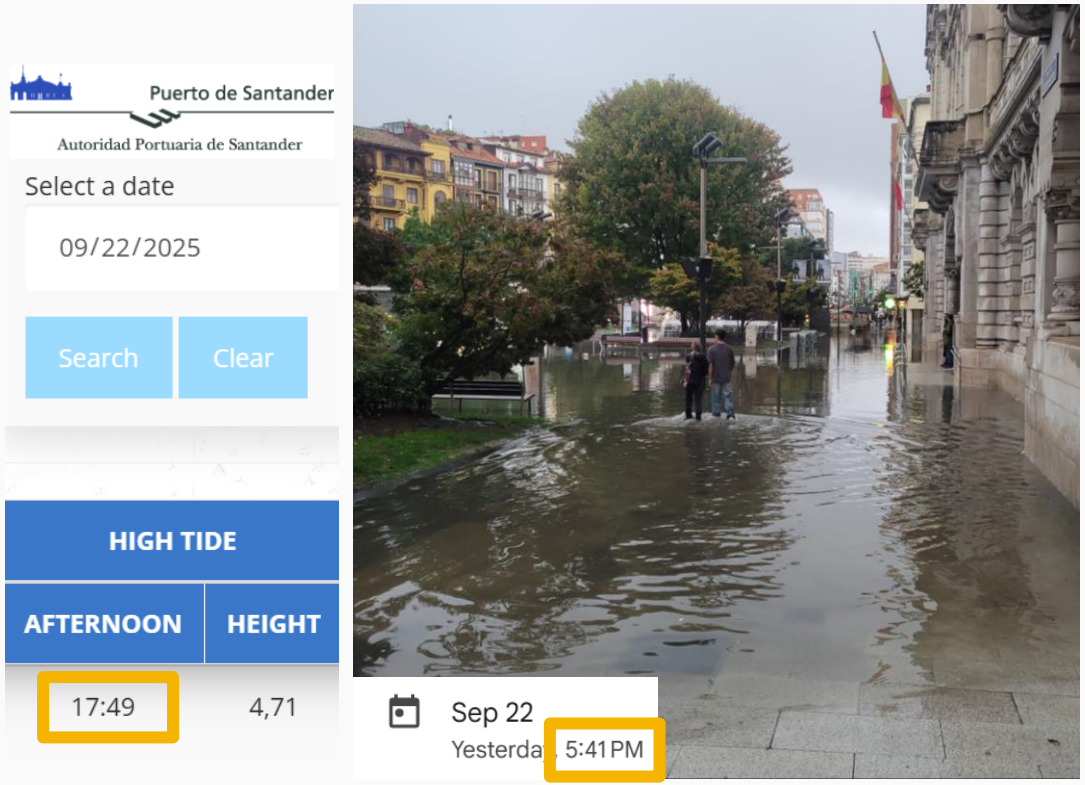
Ocean-scale flooding drivers:
- Tides (Hague et al., 2023)
- Wind setup (Coz et al., 2021)

Localized flooding drivers:
- Rainfall (Gold et al., 2023)
- Infrastructure (Obara et al., 2025)

Sea-level rise (Sweet et al., 2022)

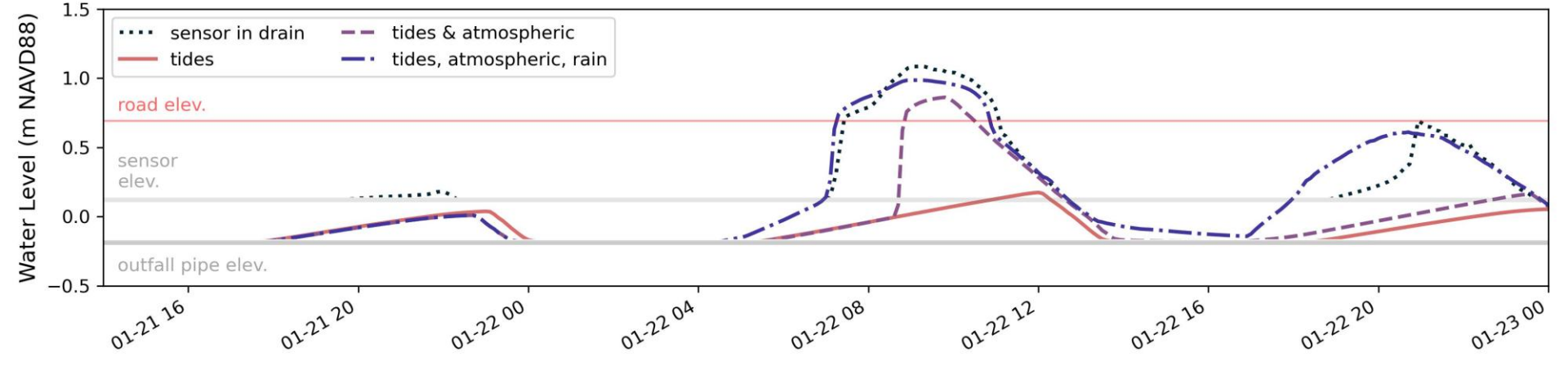
Spatial scale: several city blocks (Mydlarz et al., 2024)

Temporal scale: minutes to hours (O'Donnell et al., 2024)



*Coastal flooding driven by **rainfall at high tide** in Plaza del Ayuntamiento, Santander (Source: my walk home from the Workshop on Monday)*

Model reproduces flooding only after addition of atmospheric effects and rain



Gap #1: How to model **multi-driver** coastal flooding at relevant resolutions?

*Drivers of **chronic flooding***

Ocean-scale flooding drivers:
- Tides (Hague et al., 2023)
- Wind setup (Coz et al., 2021)

Localized flooding drivers:
- Rainfall (Gold et al., 2023)
- Infrastructure (Obara et al., 2025)

Sea-level rise (Sweet et al., 2022)

Spatial scale: several city blocks (Mydlarz et al., 2024)
Temporal scale: minutes to hours (O'Donnell et al., 2024)

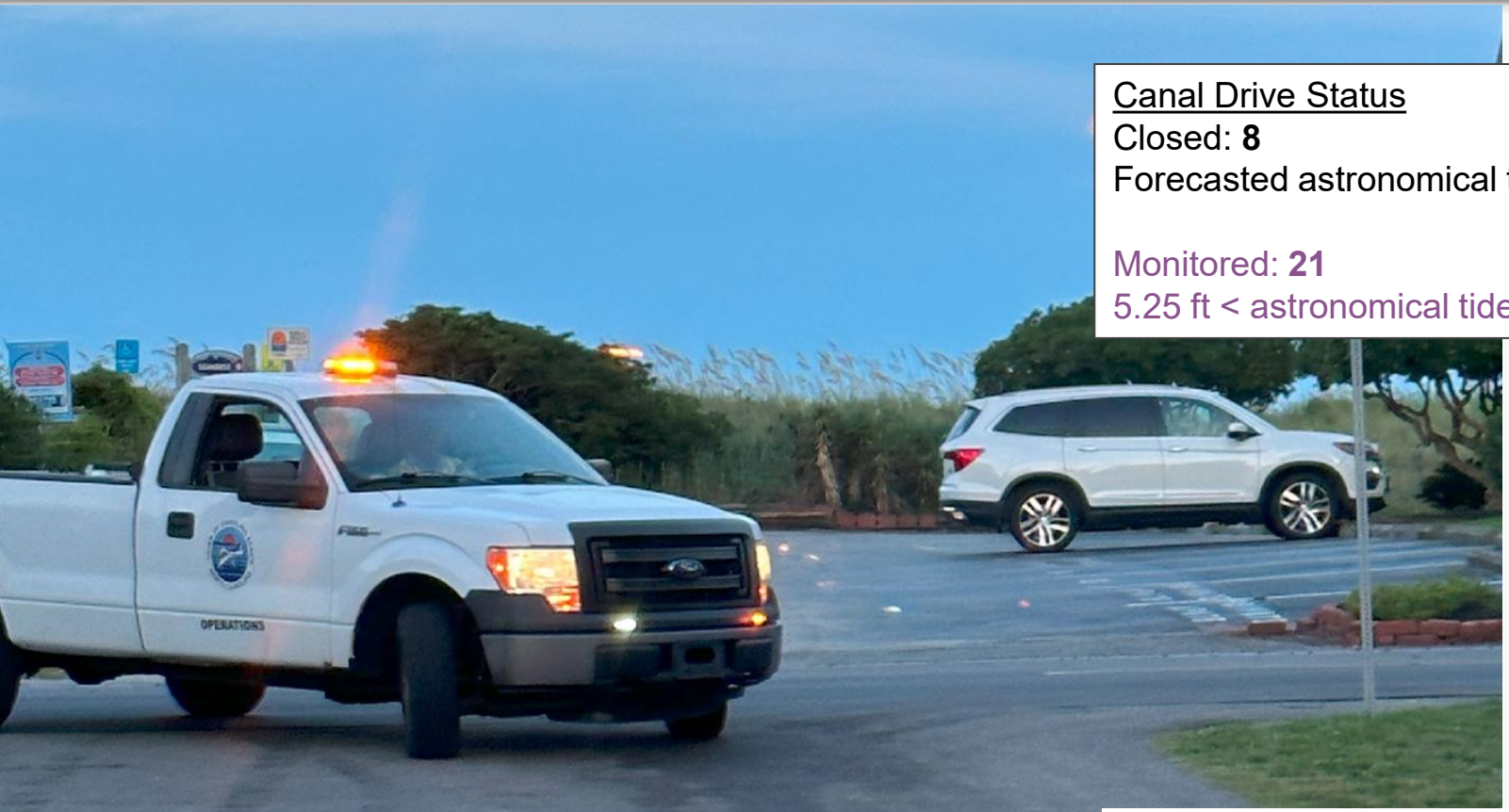
*Coastal flooding driven by **rainfall at high tide** in Carolina Beach, North Carolina (Source: Sunny Day Flooding Project camera)*

20% of floods occurred at forecasted tides above the threshold for closing Canal Dr.

Canal Drive Status
Closed: **8**
Forecasted astronomical tide > 6 ft

Data from April 2022 to April 2023

An additional 50% of floods occurred at tides above the threshold for monitoring Canal Dr.



Canal Drive Status
Closed: **8**
Forecasted astronomical tide > 6 ft

Monitored: **21**
5.25 ft < astronomical tide < 6 ft

Data from April 2022 to April 2023

30% of floods were “unexpected” based on the tidal threshold

Canal Drive Status

Closed: **8**

Forecasted astronomical tide > 6 ft

Monitored: **21**

5.25 ft < astronomical tide < 6 ft

Not monitored: **14**

Forecasted astronomical tide < 5.25 ft

Data from April 2022 to April 2023

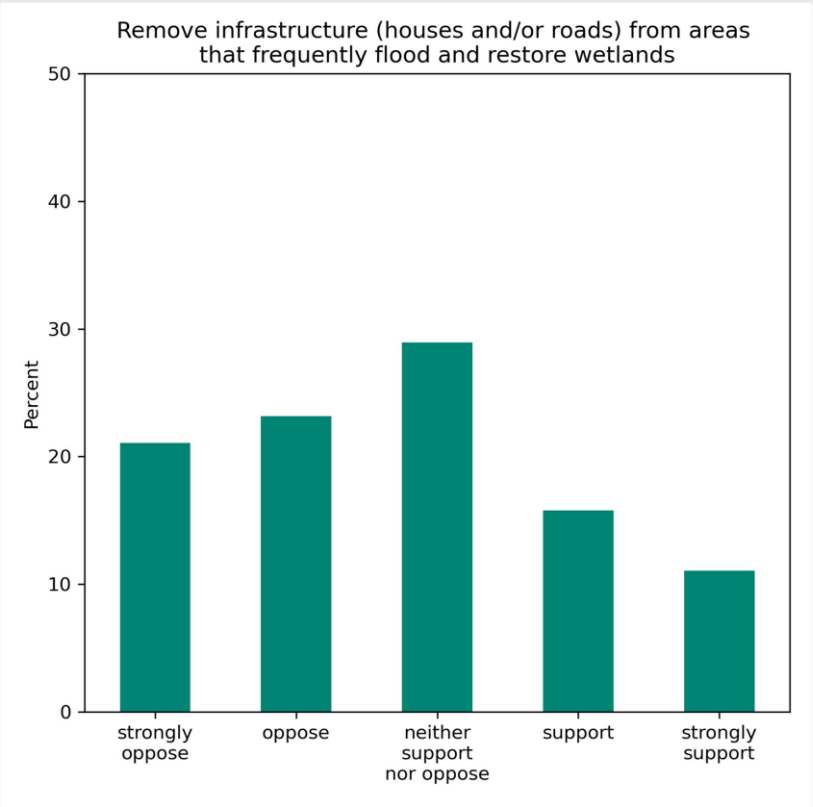
Jan. 22, 2023: if we modeled **tides only**, water would not have reached Canal Dr.

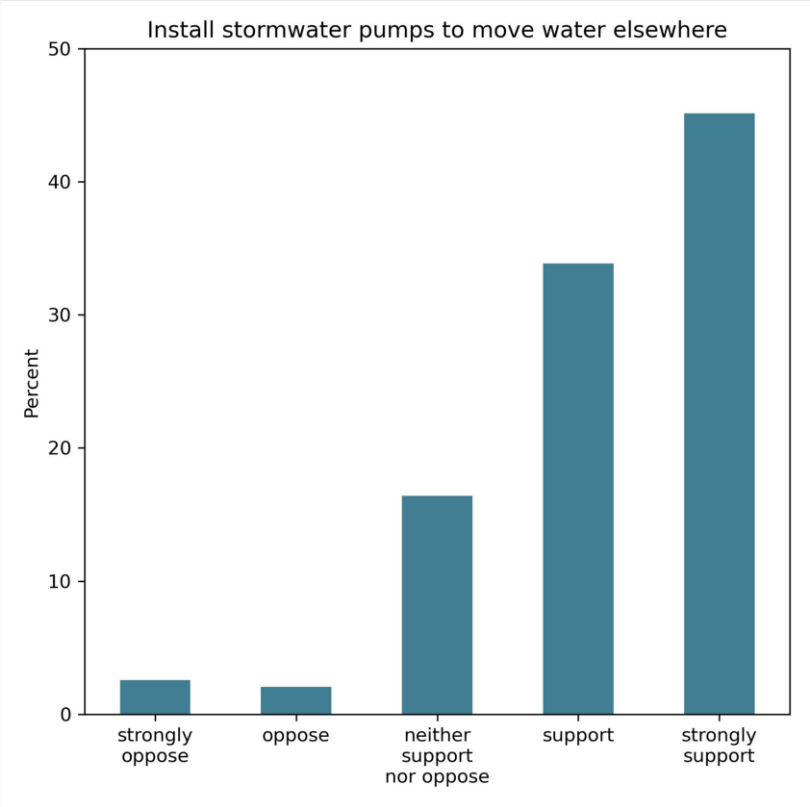
Jan. 22, 2023: when we add **wind** to the model, flooding reaches Canal Dr.

A survey to understand chronic flooding impacts and preferred adaptations

Flooding survey mailer

Survey results show a preference for adapting in place





But what adaptation strategies will be effective in mitigating flooding, and over what timescales?

Workshops content e.g.: What might sea-level rise look like on Canal Drive? **2022 to 2050-2070**

We expect *this much* SLR **by:**	**2030**	**2040**	**2050**	**2070**	**2100**
30 cm			Worst case	Best case	

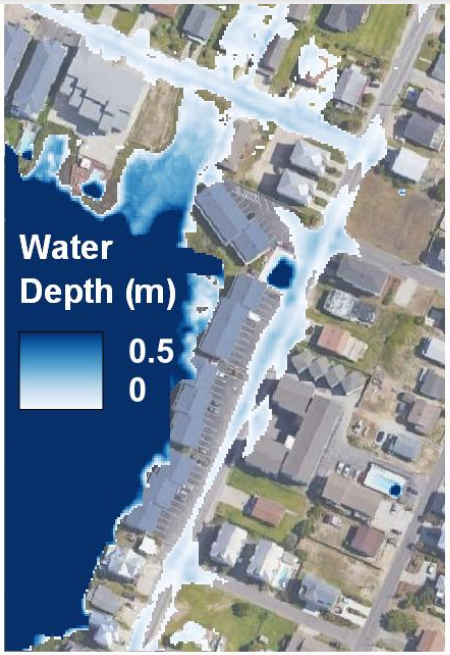
Baseline: 2022 flood + *30 cm* = 2050 to 2070 flood

Workshops content e.g.: What might sea-level rise look like on Canal Drive? **2022 to 2070-2100**

We expect *this much* SLR **by:**	**2030**	**2040**	**2050**	**2070**	**2100**
61 cm				Worst case	Best case

Baseline: 2022 flood + *61 cm* = 2070 to 2100 flood

Even at present day sea levels, raised shorelines do not mitigate compound high bayside water level and rain-driven flooding



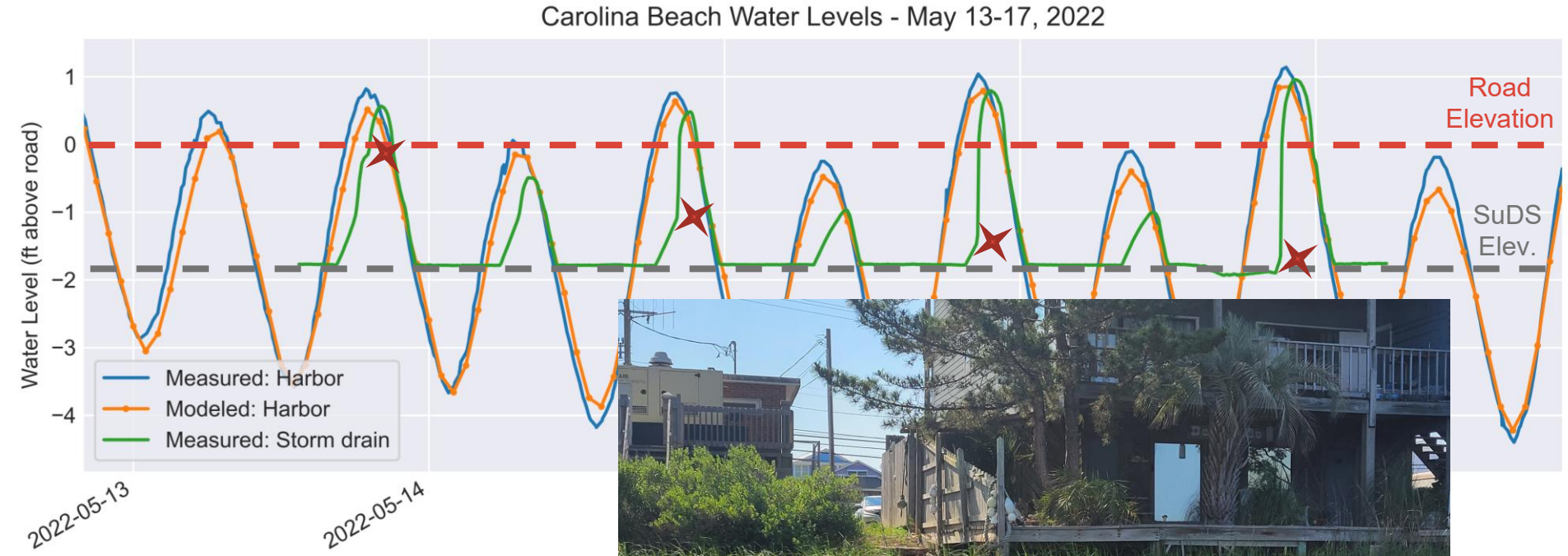
Tides & atmospheric
Present-day sea levels

Tides & atmospheric
Present-day sea levels
Higher bulkheads

*Tides, atmospheric, **rain***
Present-day sea levels
Higher bulkheads

Tides & atmospheric
2050 sea levels
Higher bulkheads

Duckbill valves distort the tidal signal in the stormwater network.



Drain fills from road

Wave setup is not a significant driver of back-bay flooding in Carolina Beach

We find that water levels in the Yacht Basin differ by less than 0.01 m between SWAN+ADCIRC and ADCIRC simulations run on the same mesh with the same wind forcing. Therefore, we conclude that wave setup is not a substantial driver of chronic flooding in Carolina Beach.