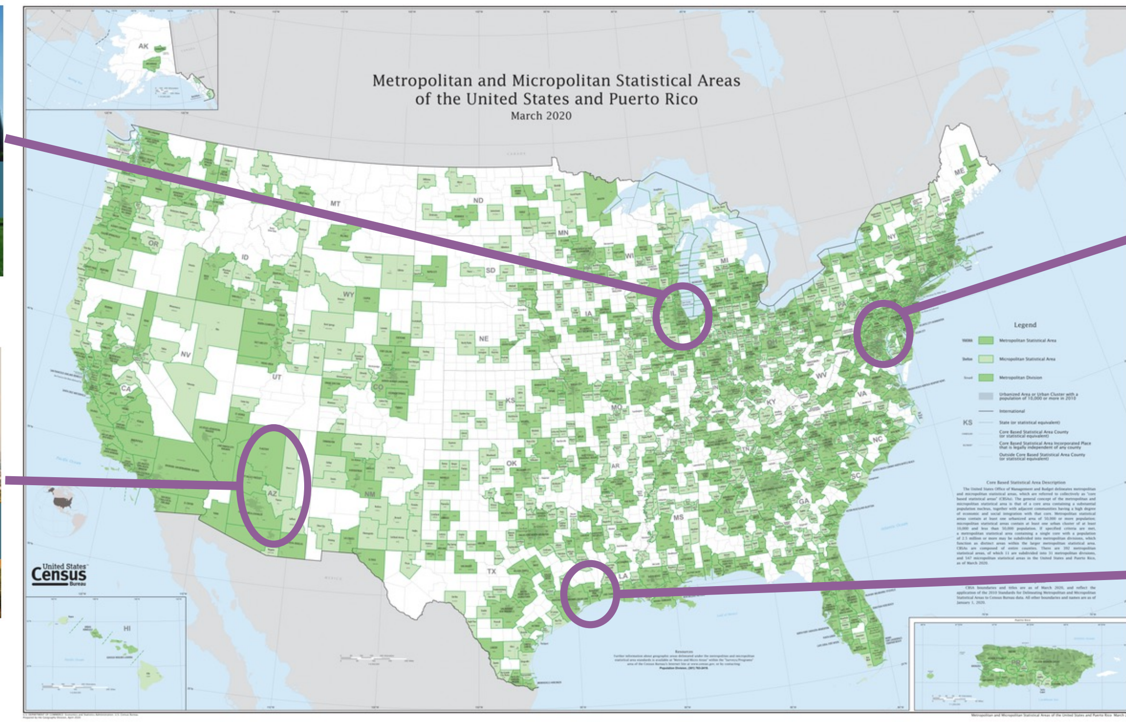
Predicting the impacts of tomorrow's storms on tomorrow's cities

Flood frequency analysis under changing Storms, Land Use, and Infrastructure

Ethan Coon
Oak Ridge National Laboratory

SETx URBAN IFL

Urban Integrated Field Laboratories are a DOE BER effort to "advance the science underpinning our understanding of the predictability of ***urban systems and interactions with the climate system***, and to provide the knowledge and information necessary to ***inform equitable climate and energy solutions*** that can ***strengthen community-scale resilience across urban landscapes***."



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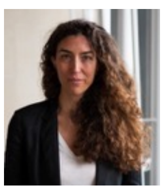
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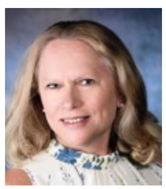
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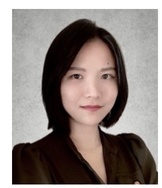
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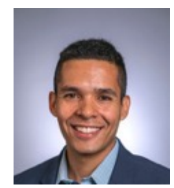
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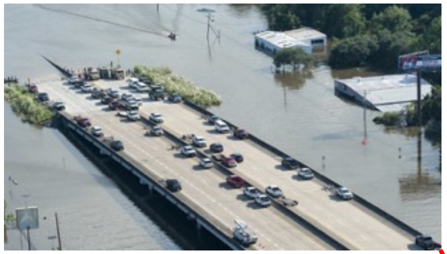
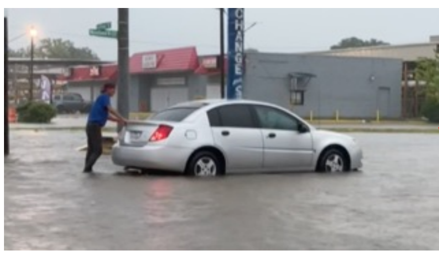
Motivation & Key Questions



Harvey, 8/31/2017

Imelda, 9/17/2019



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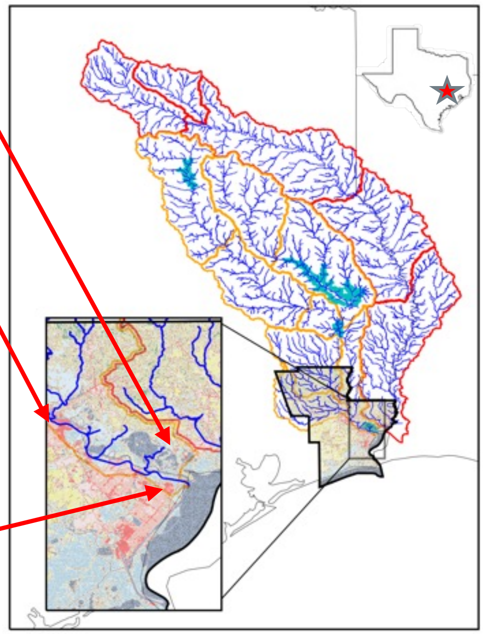

- How do spatial patterns of land use, including heterogeneity in imperviousness and water infrastructure, control spatial patterns of flooding?
- How will changes in land use affect hydrologic variability in flooding events under future climate scenarios?
- What is the role and function of nature-based and traditional infrastructure in reducing the impacts of flooding across urban regions?

SETx experiences each of *coastal (storm surge)*, *fluvial (riverine)*, and *pluvial (rain on pavement)* flooding, making it hydrologically complex region.

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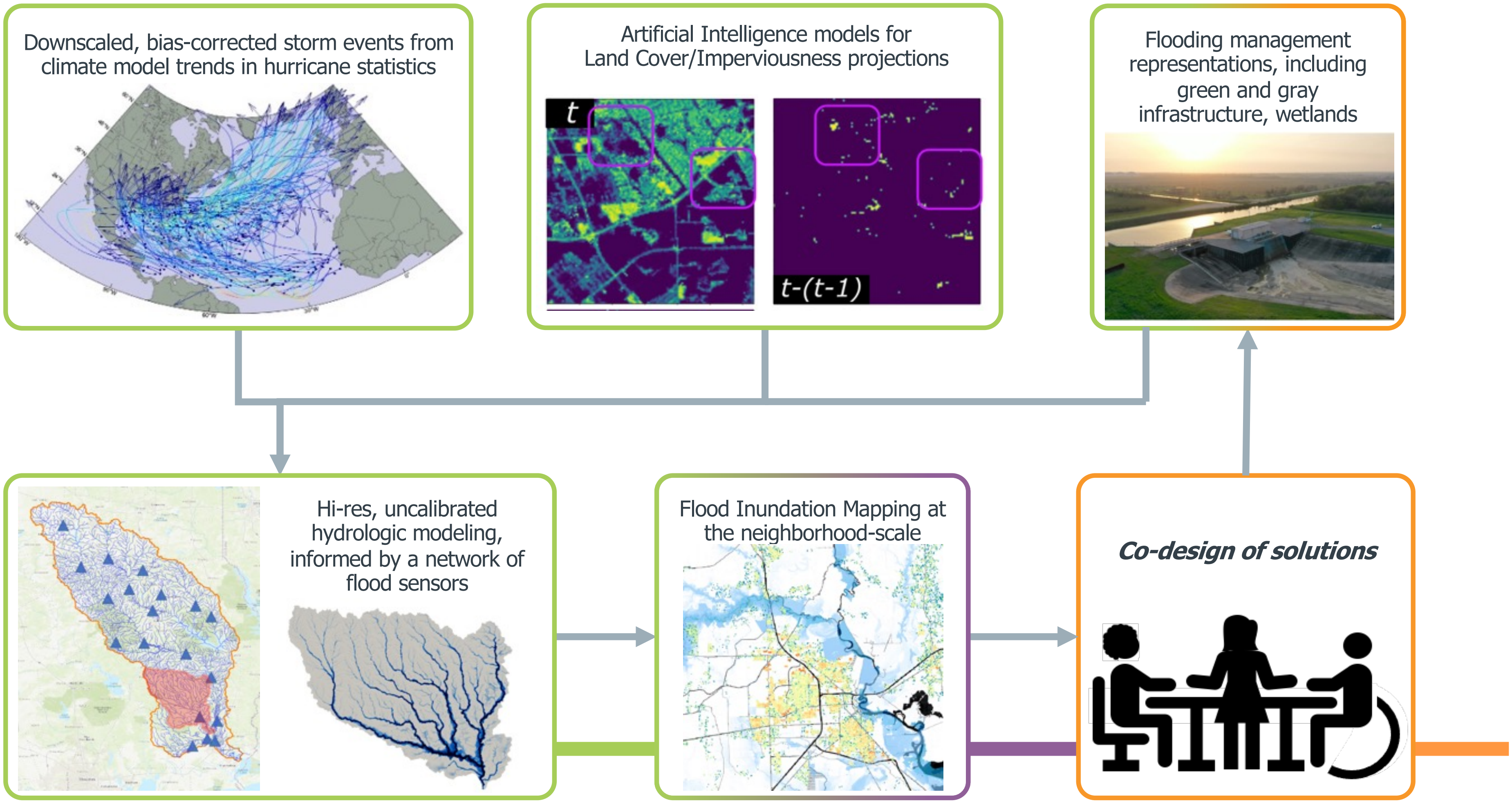
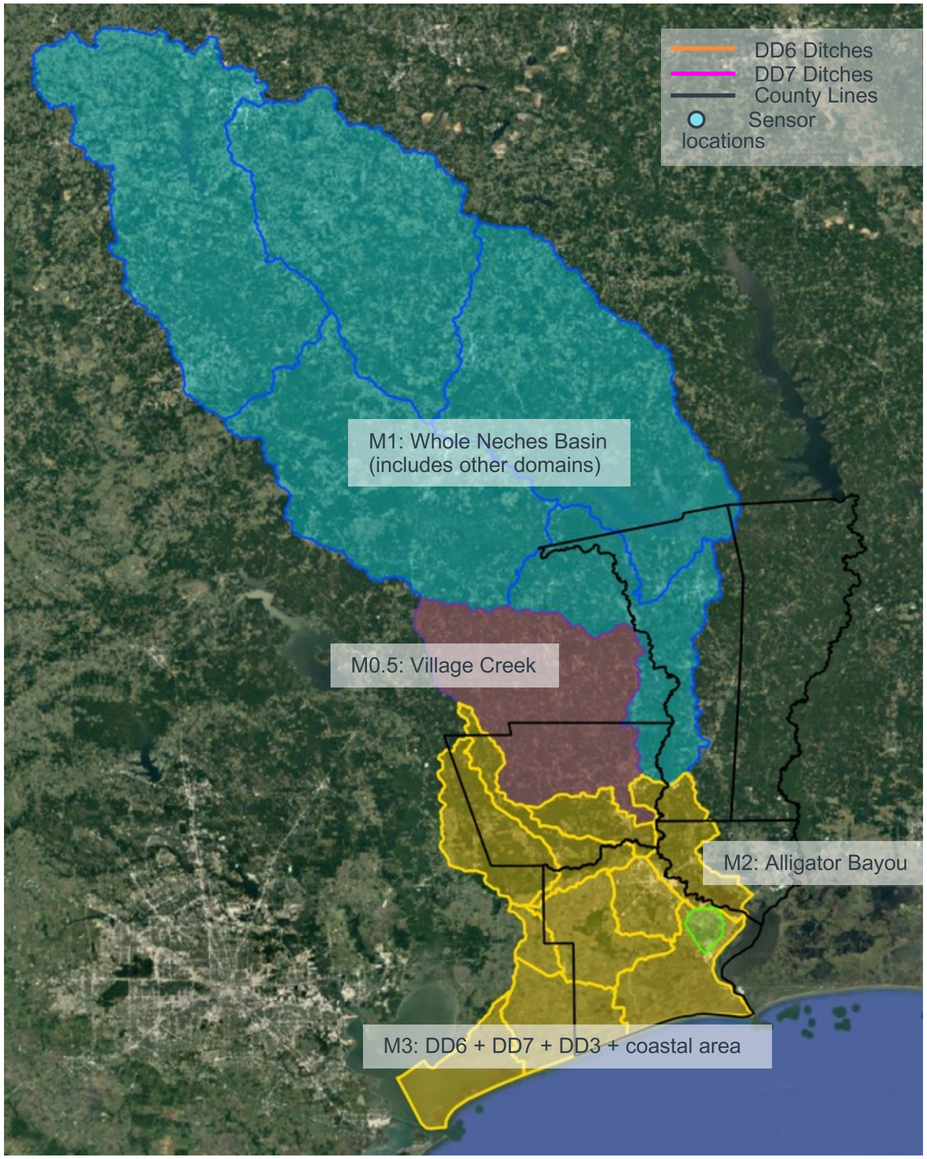
Images courtesy Beaumont-area news

Informing decisions on water





ATS Hydrology Simulation Campaigns

M0.5: Village Creek (med spatial res.)

- Understand ET, Runoff, and Infiltration partitioning (long-term vs. event scale)
- Quantify the role of subsurface flow (different seasons, long-term vs. event scale)
- Quantify the effects of impervious surface area on hydrological response

M1: Whole Neches Basin (low spatial res.)

- Evaluate the ATS Integrated hydrology model to reproduce river flow (input to high res. model study-focus area in yellow)
- Implement the reservoir operation model (new capability from DOE-sponsored Exasheds project)
- Identify additional field data needs and sensor locations for calibrations

M2: Alligator Bayou (high spatial res.)

- Meticulous curation and integration of stream/ditch line datasets from NHD, county/DD7, and students' theses
- Developing and evaluating modeling strategies for:
  - Ditches and Canals
  - Detention ponds
  - Levees
  - Pump stations
  - Impervious surfaces
- Developing workflows to synthesize available datasets and prepare ATS inputs

M3: SETx Urban Area (high spatial res.)

- Co-design area that integrates all aspects of compound flooding
- Driven using upstream data from M1
- Provide input to Flood Inundation Mapping

Robust flood predictions under future climate/land cover

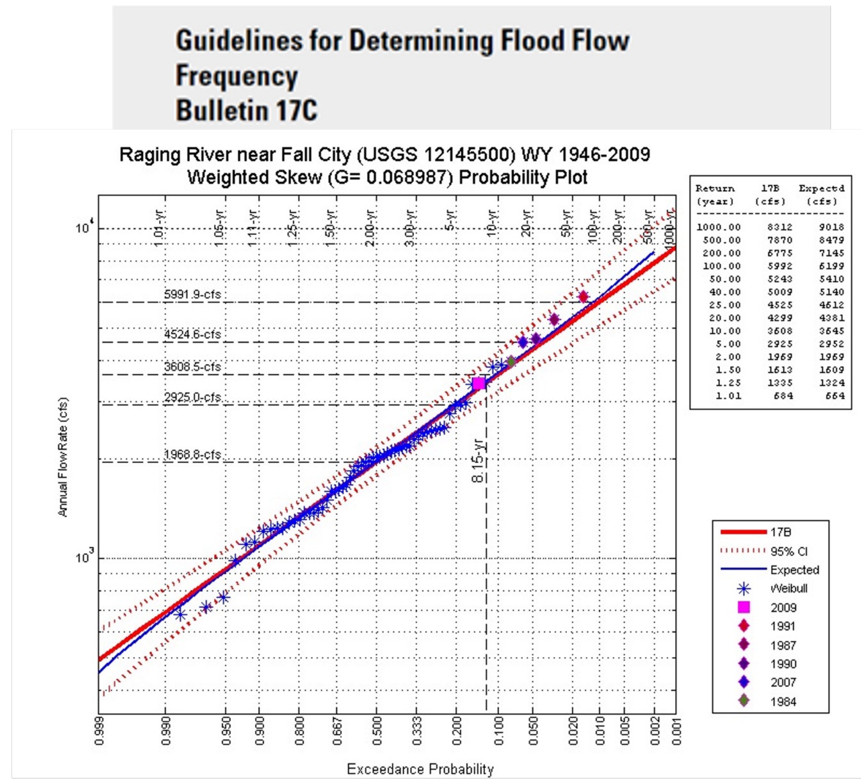
Flood frequency analysis is the standard tool for characterizing flood risk

- Probabilistic methodology (e.g. ”100 year storm”)
- Traditionally done by analyzing precipitation intensity-duration-frequency curves and empirical gage ratings curves.
- Relies on synthetic catalogs of events to generate sufficient data

Parameterized/empirical models are often used to turn precipitation into riverine runoff

Studying flooding in future conditions cannot rely on existing curves and data

- Changing climate precipitation patterns
- Different land cover, infrastructure patterns



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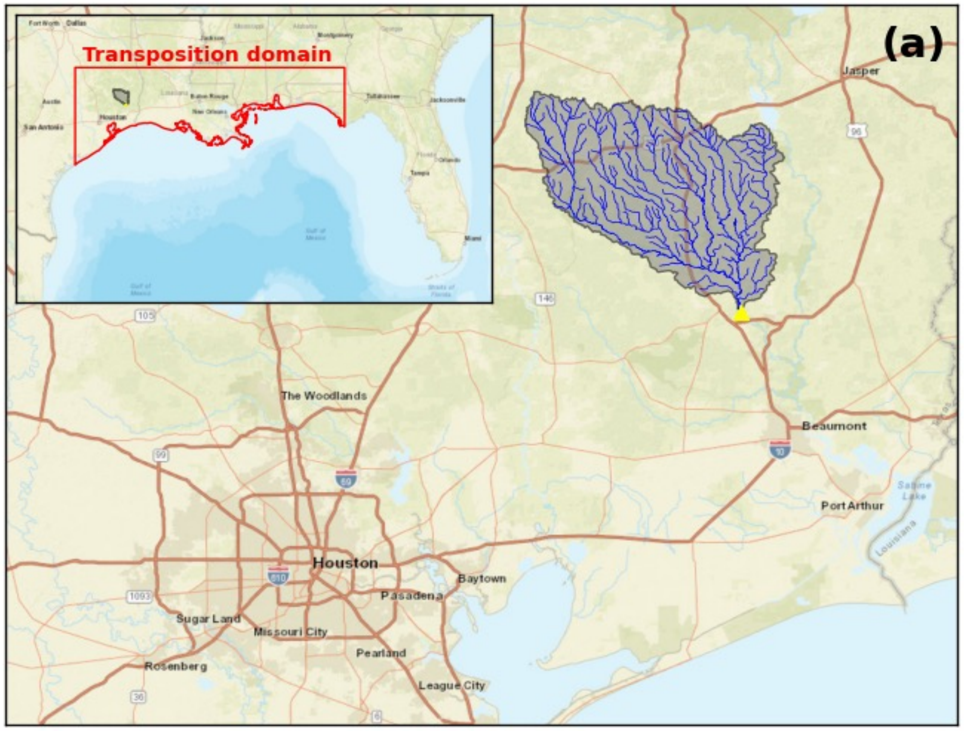
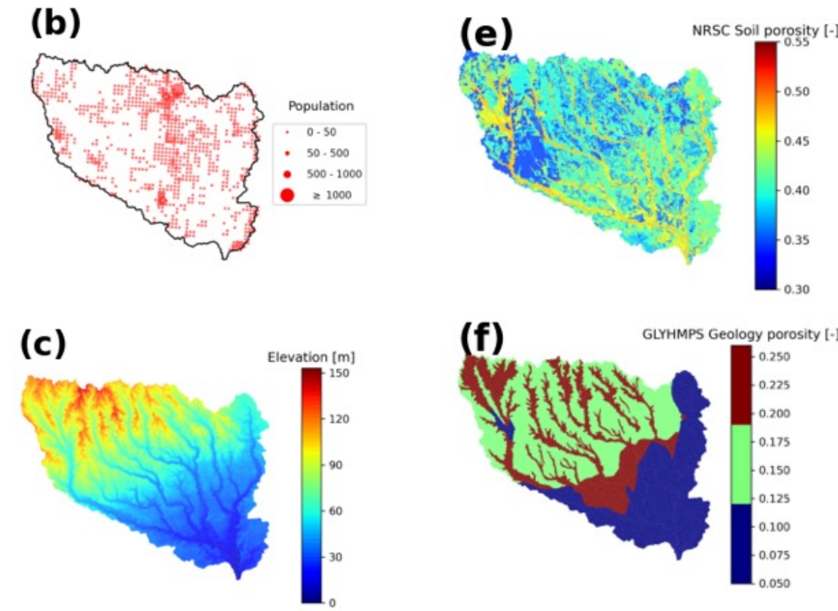
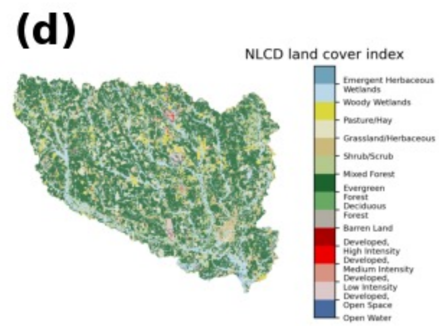
Southeast Texas UIFL



Village Creek Basin, upstream of
Beaumont & Port Arthur, TX





a. Domain
b. Population
c. Elevation (DEM)
d. NLCD (Land Cover)
e. NRCS Soils
f. GLHYMPS Geologic layer

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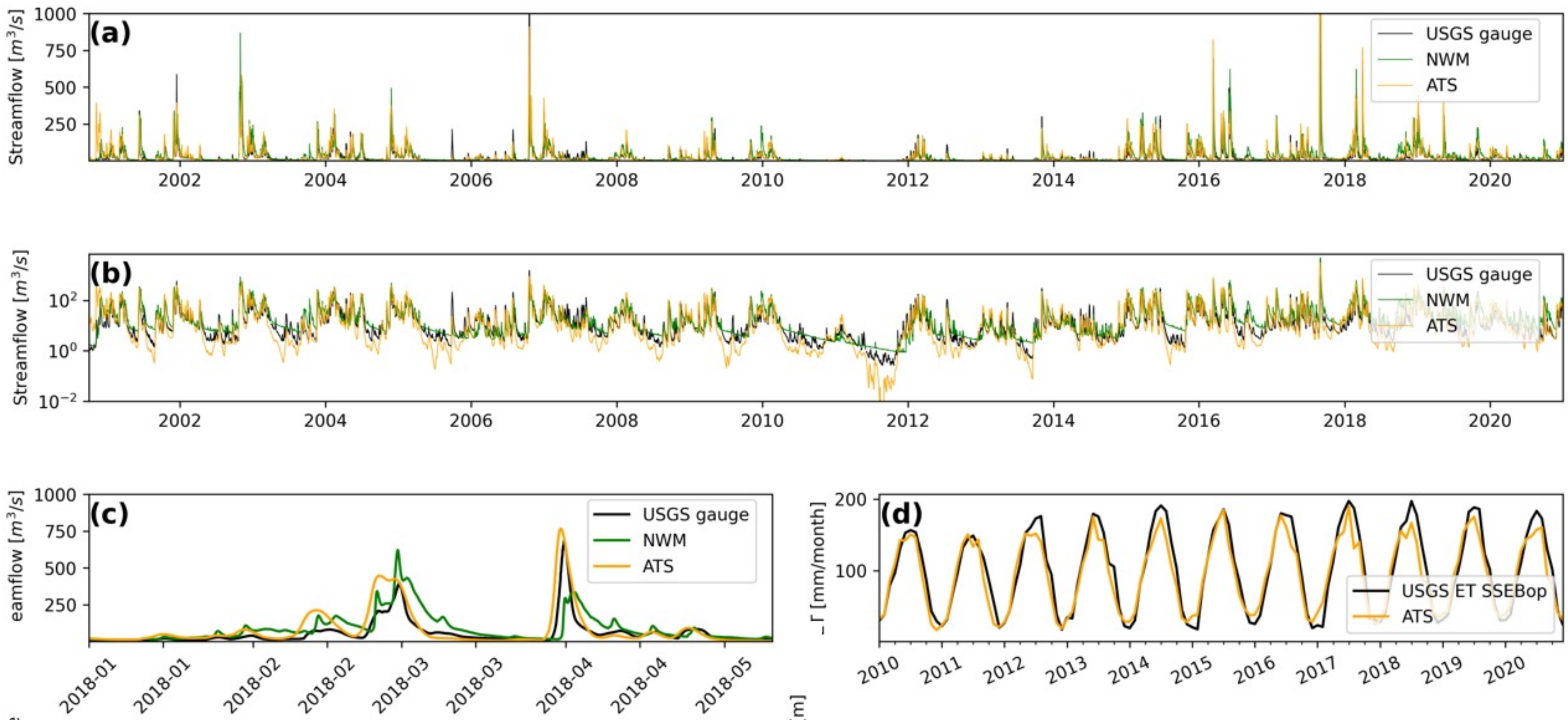
Perez et al, J. Hydrology 2024

Evaluating ATS for Flooding and Peak Flows



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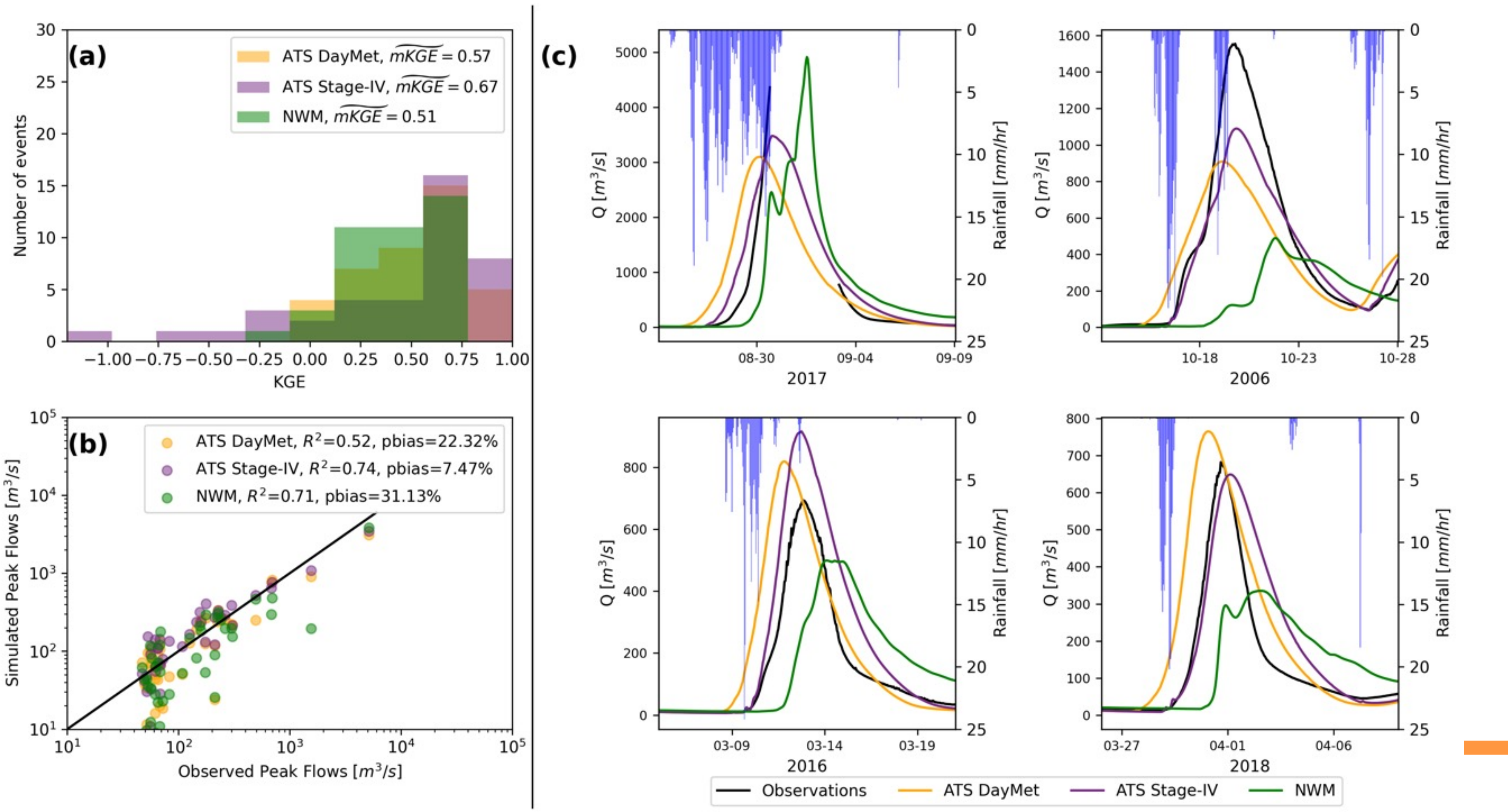
Perez et al, J. Hydrology 2024

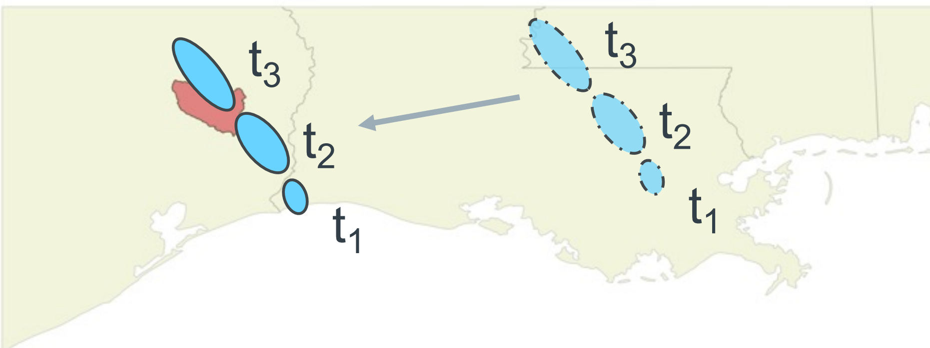
Evaluating ATS for Flooding and Peak Flows

Perez et al, J. Hydrology 2024

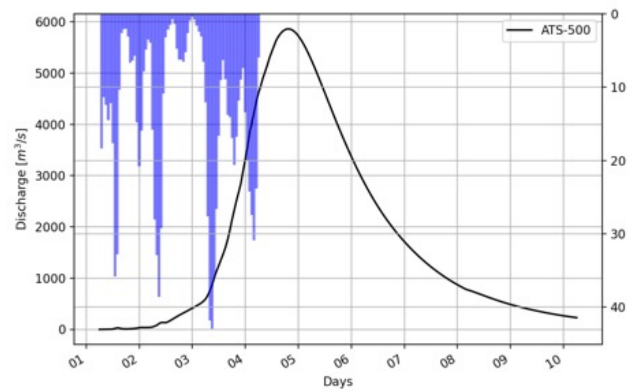


Flood Frequency Analysis under Future Conditions

Stochastic Storm Transposition



Physical Hydrological Model



Studying flooding in future conditions cannot rely on existing empirical relations

- Changing climate through models
- Changing land cover through ML
- Scenarios of infrastructure change

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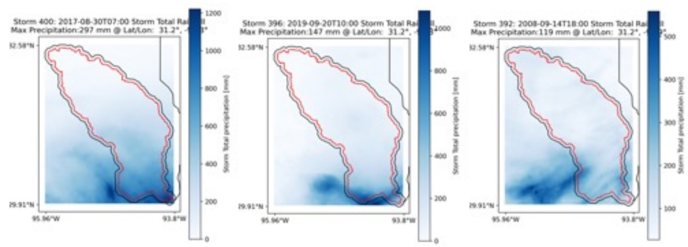
Stochastic Storm Transposition for robust statistics of Rainfall Events

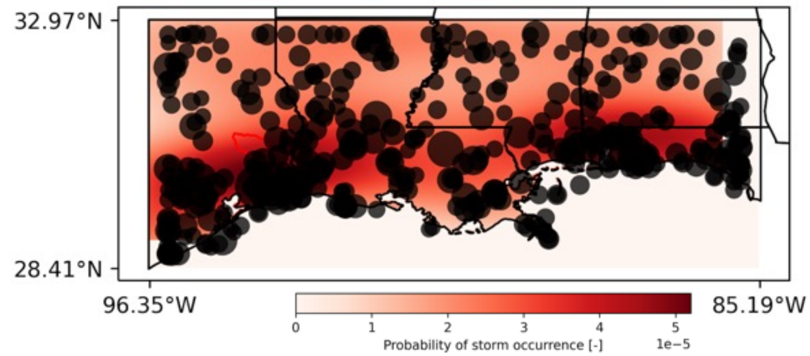
SST is a strategy to create a large synthetic rainfall dataset (e.g., 10,000 storm events) that are consistent with a given climate scenario.

Identification and characterization of the most extreme rainfall events (in **observations** or in **downscaled climate projects**)

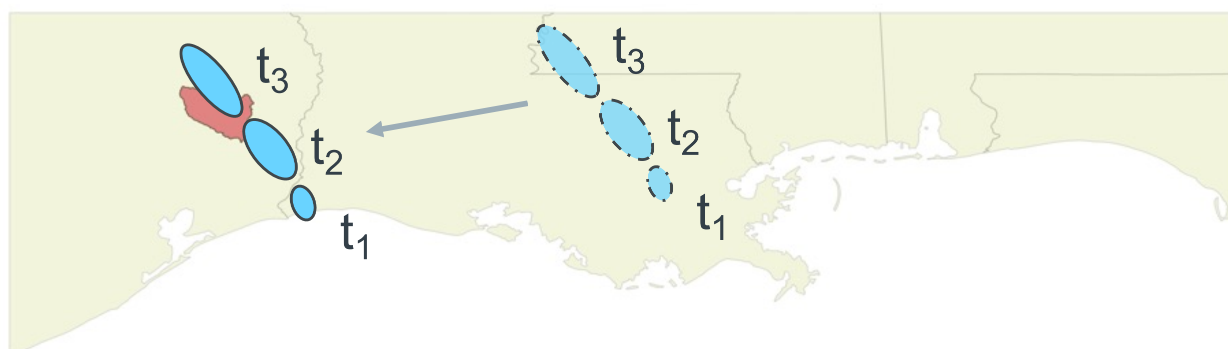
Harvey Imelda Ike



Identify the transposition domain over which events are homogeneous



Generation of 10,000 **synthetic** storm events and posterior statistics by transposing events throughout the domain



RAINY DAY

Wright, D.B., et al (2020)

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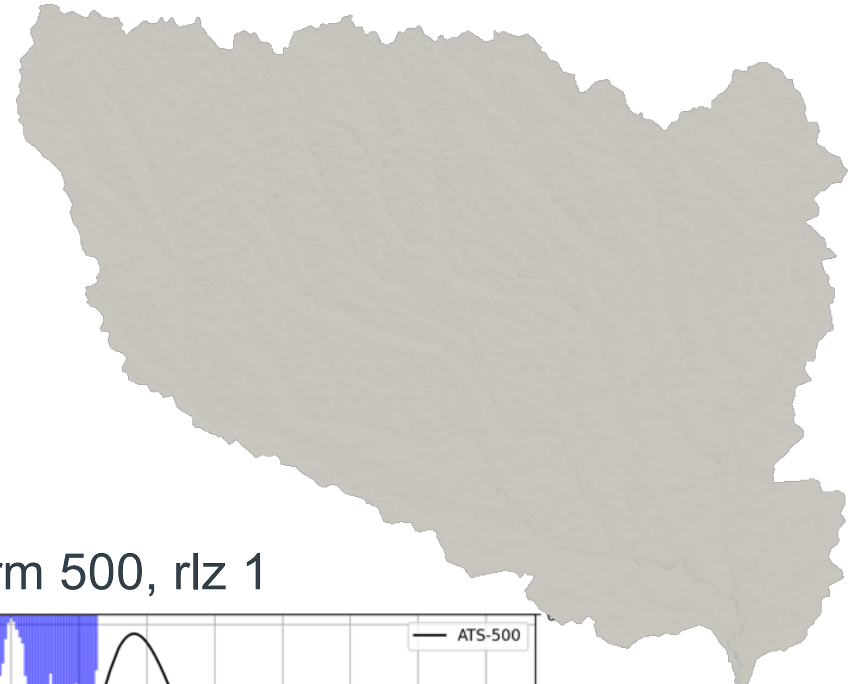
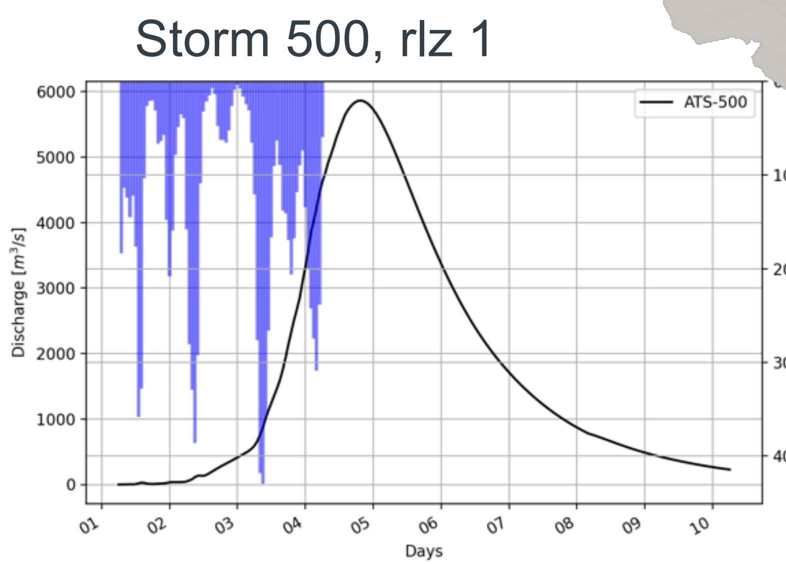
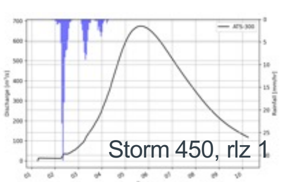
Flood Frequency Analysis

- Generated catalog via SST for current climate based on Stage-IV precipitation data
- Antecedent soil conditions selected randomly from long-time (10 year) simulation; current-day land cover
- Simulated 5,000 events using ATS (~40K node-hours on NERSC via ALCC)
- *Perez et al J. Hydrology 2024*







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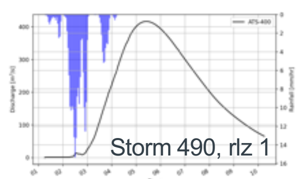

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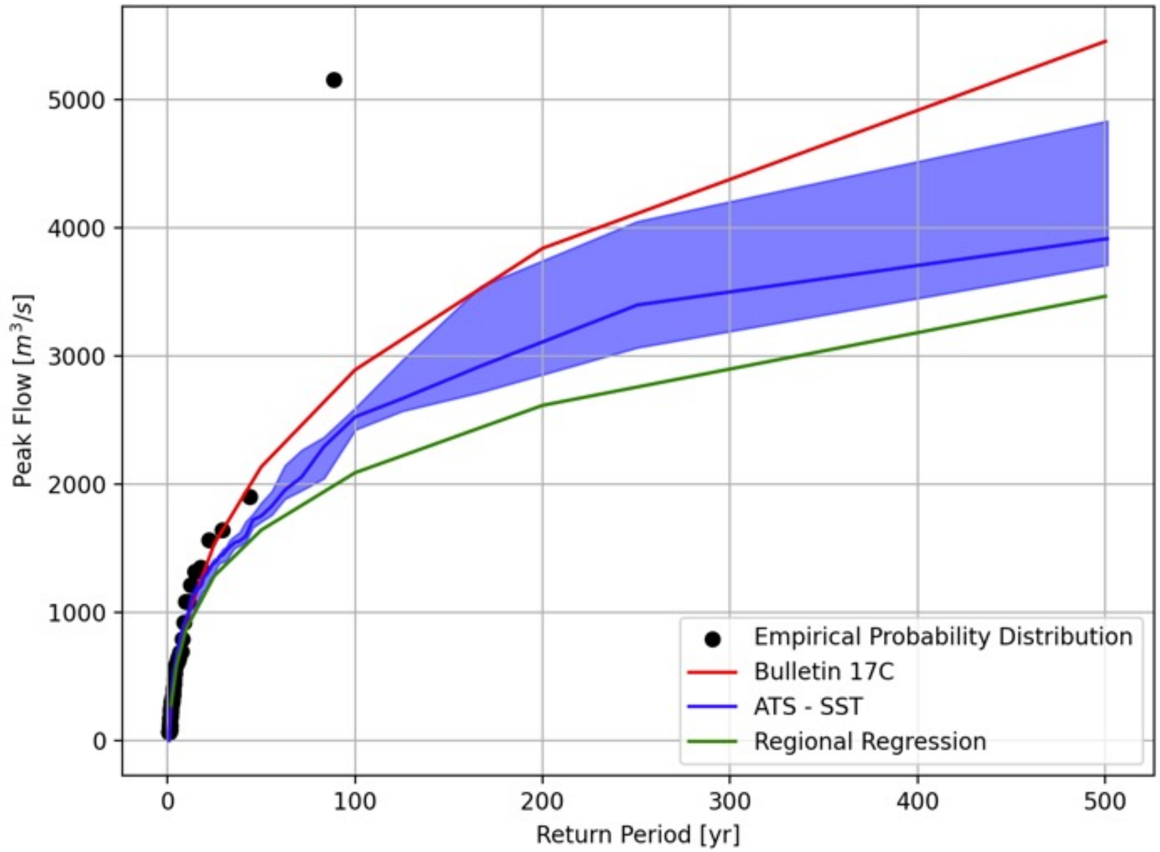
Flood Frequency Analysis



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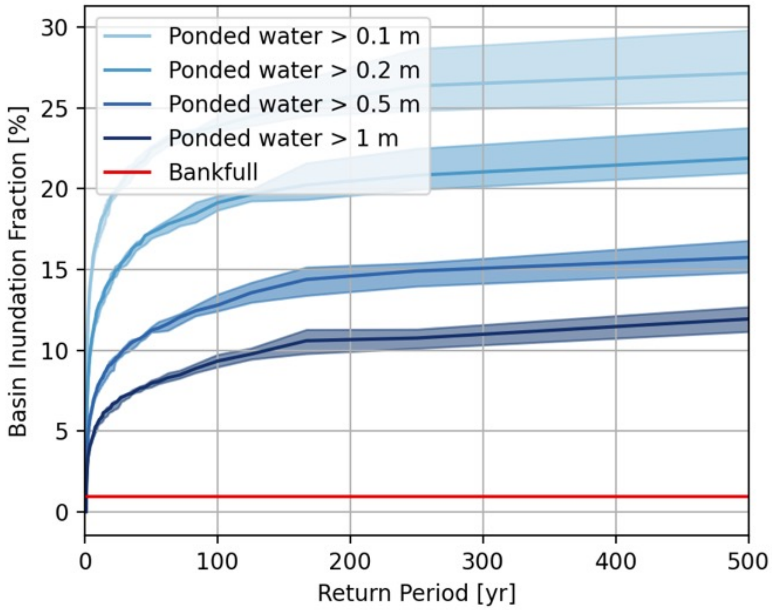
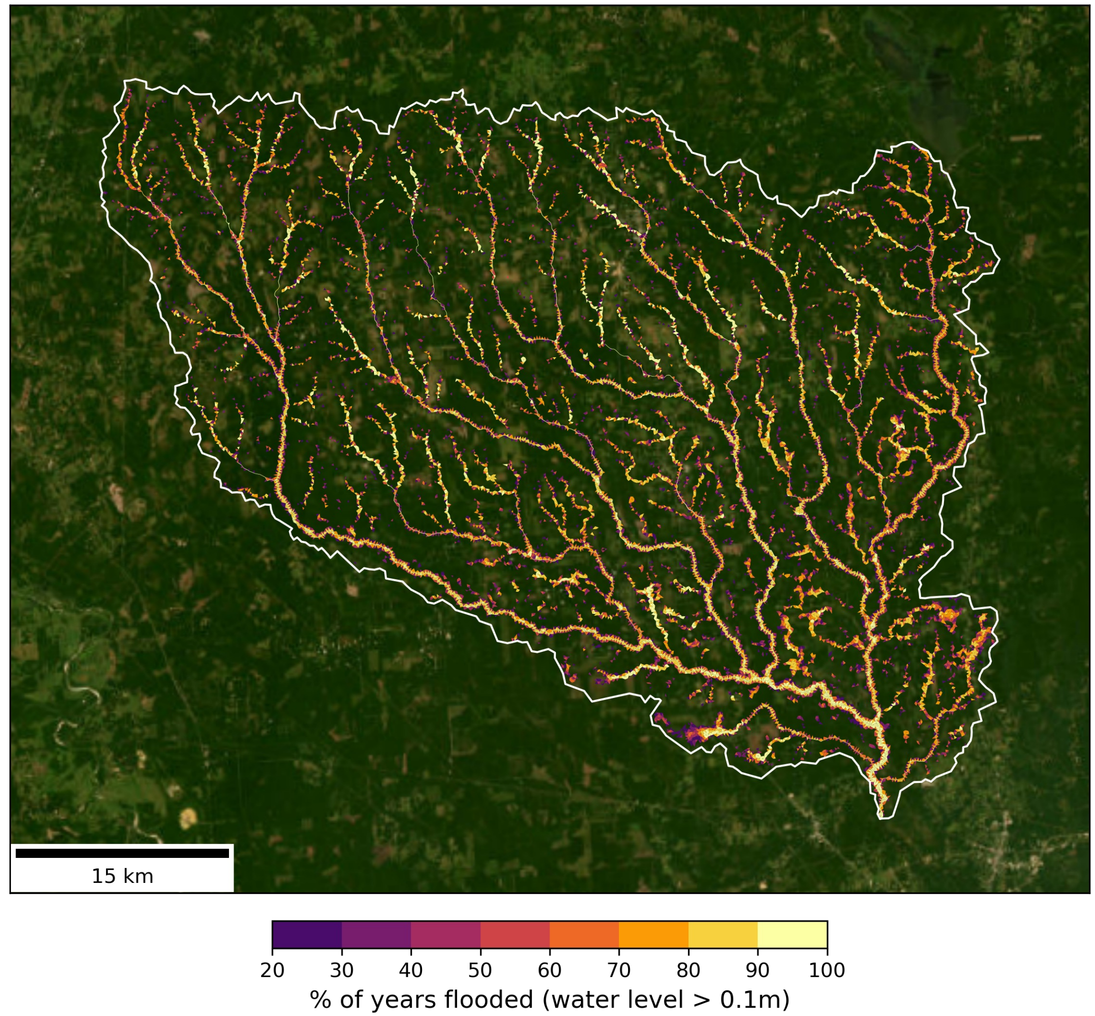
Perez et al, J. Hydrology 2024

Flood Frequency Analysis





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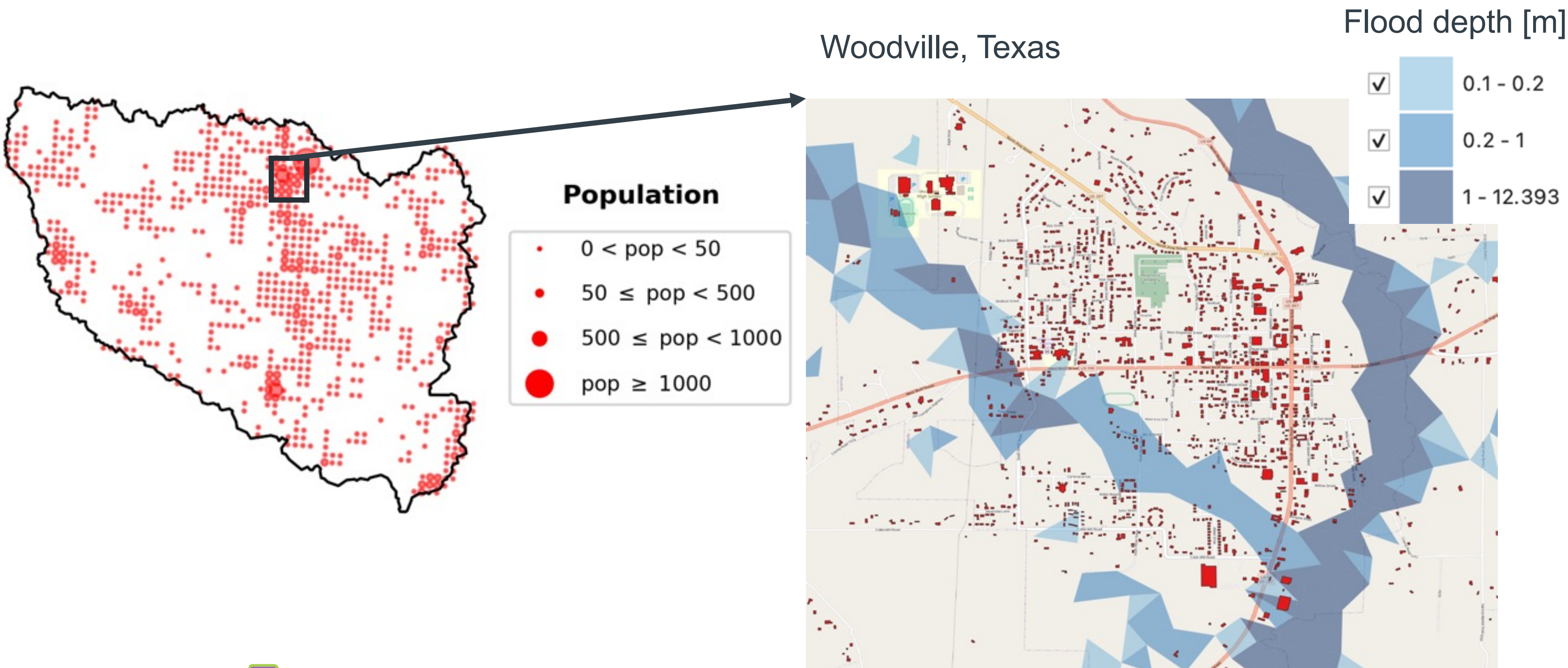

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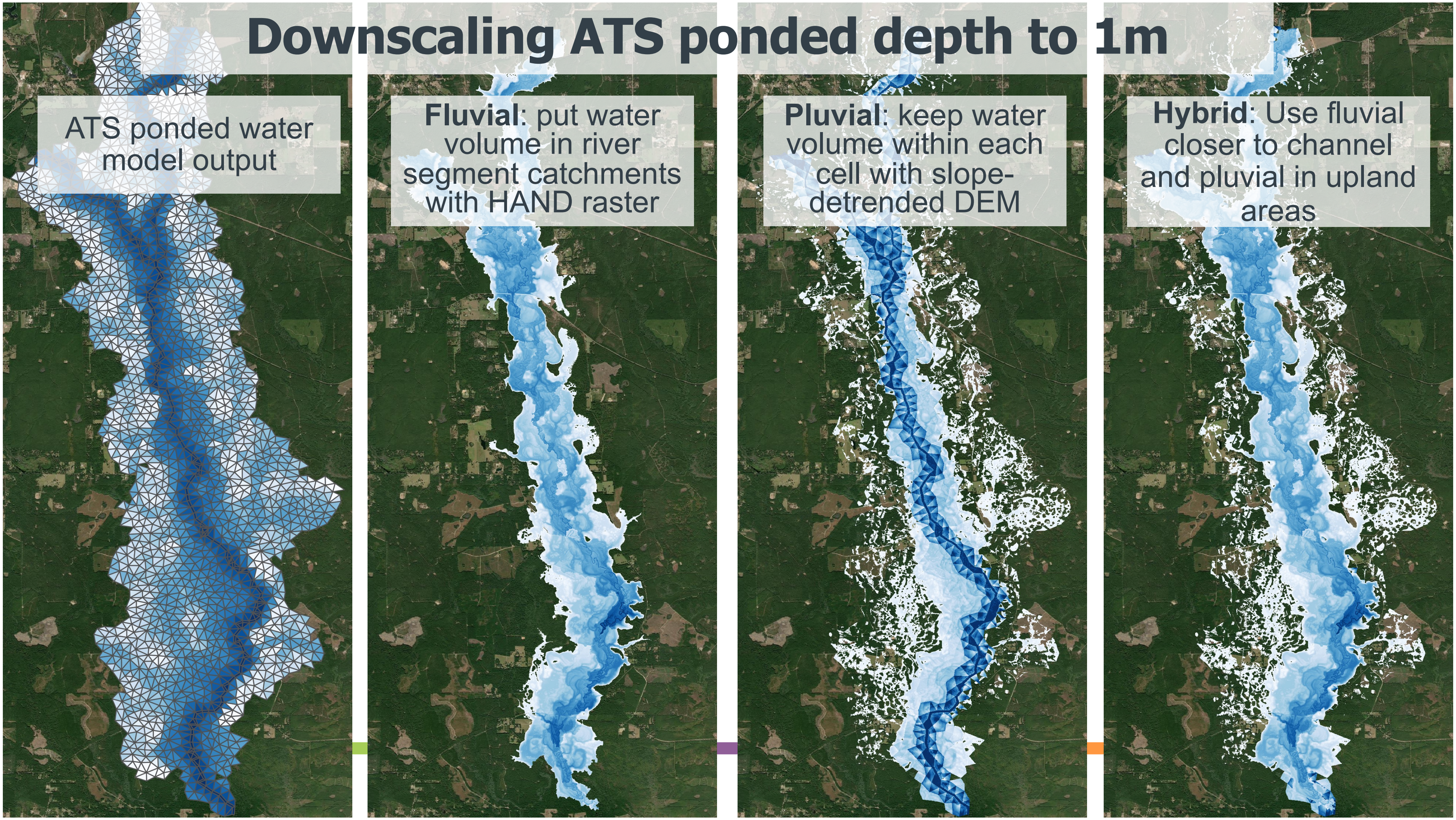
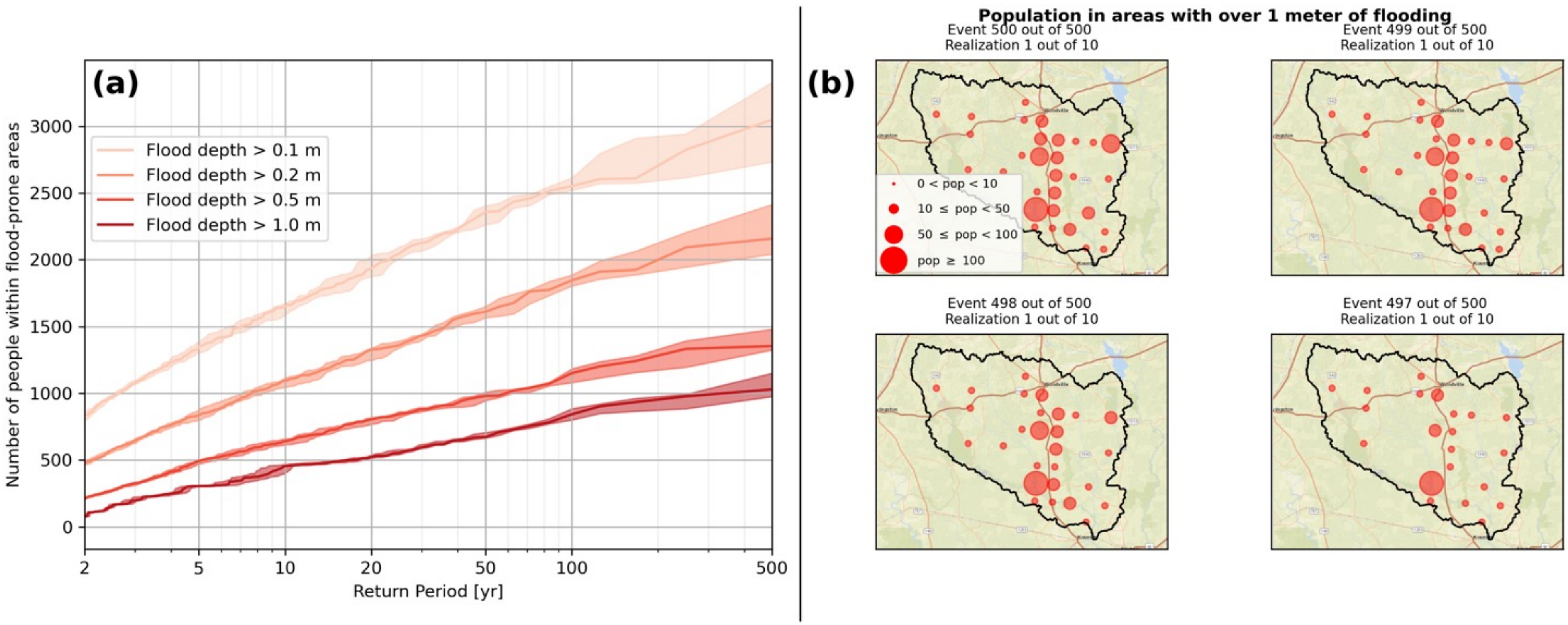
Downscaling ATS ponded depth to 1m



Perez Mesa et al, J. Hydrology 2024



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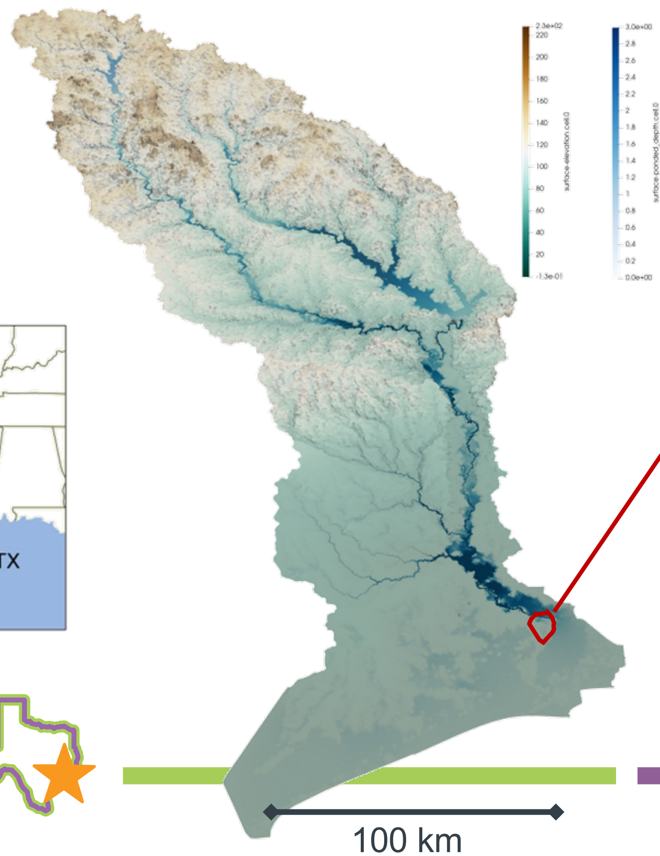
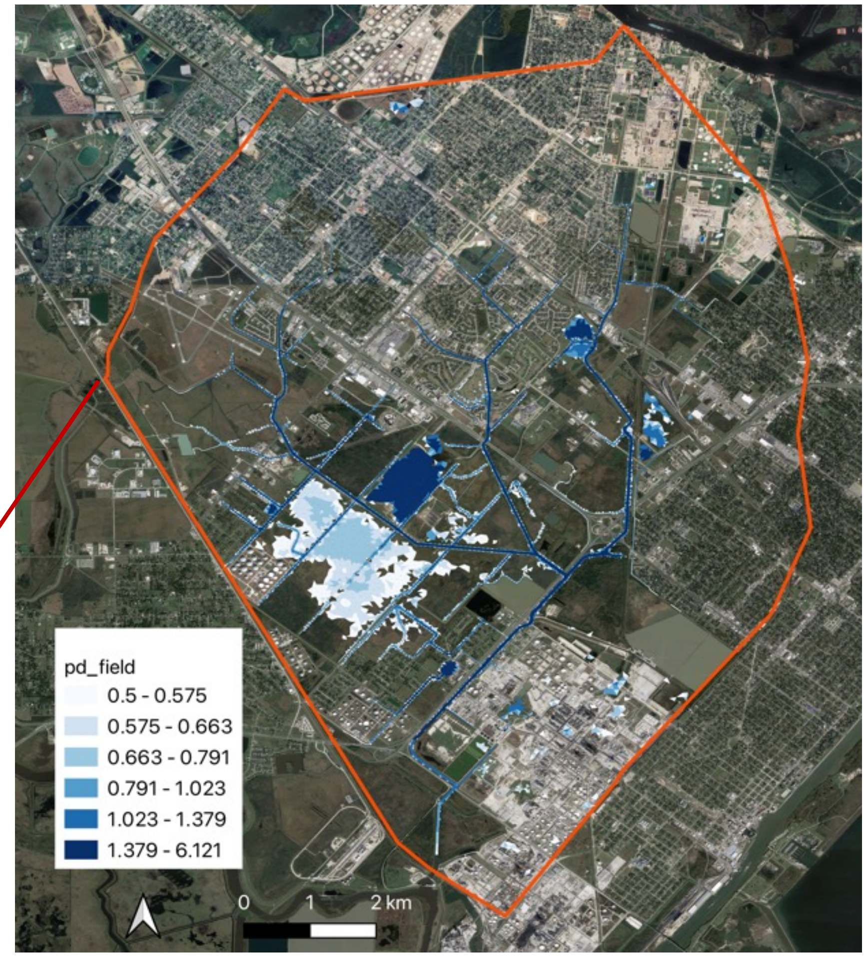
Urban hydrology and stormwater infrastructure





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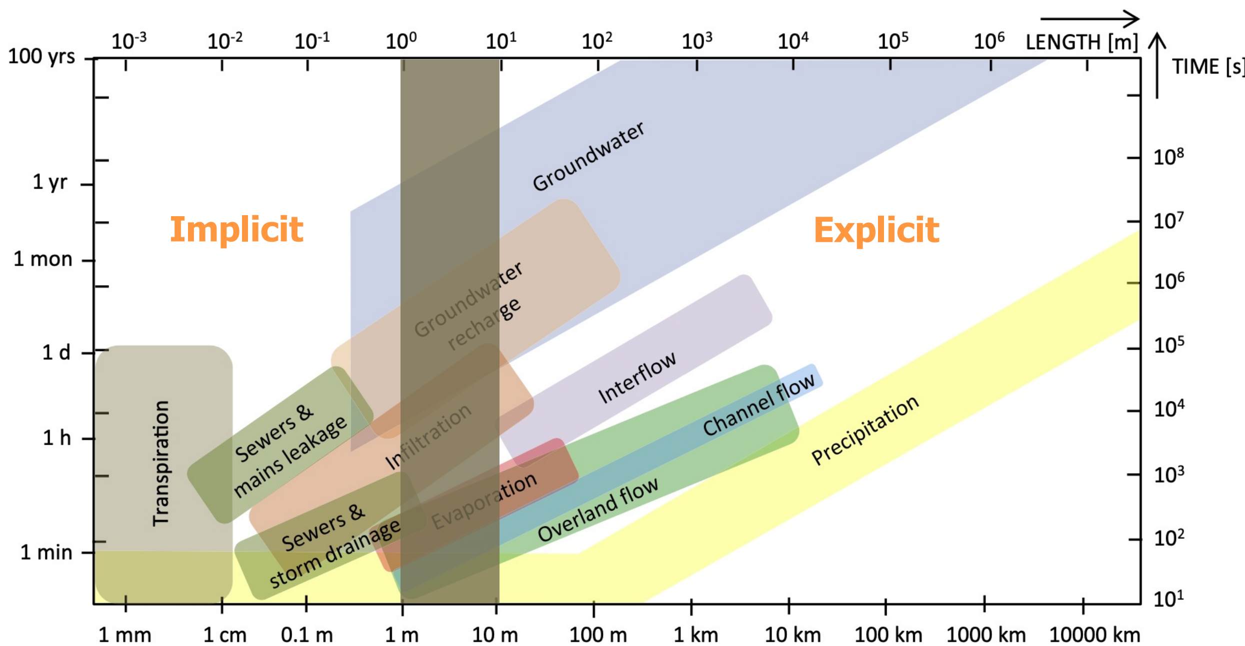
Representing stormwater infrastructure

Relevant processes scales and their representation
(existing or planned) in ATS



(Modified from Salvadore et al. 2015)

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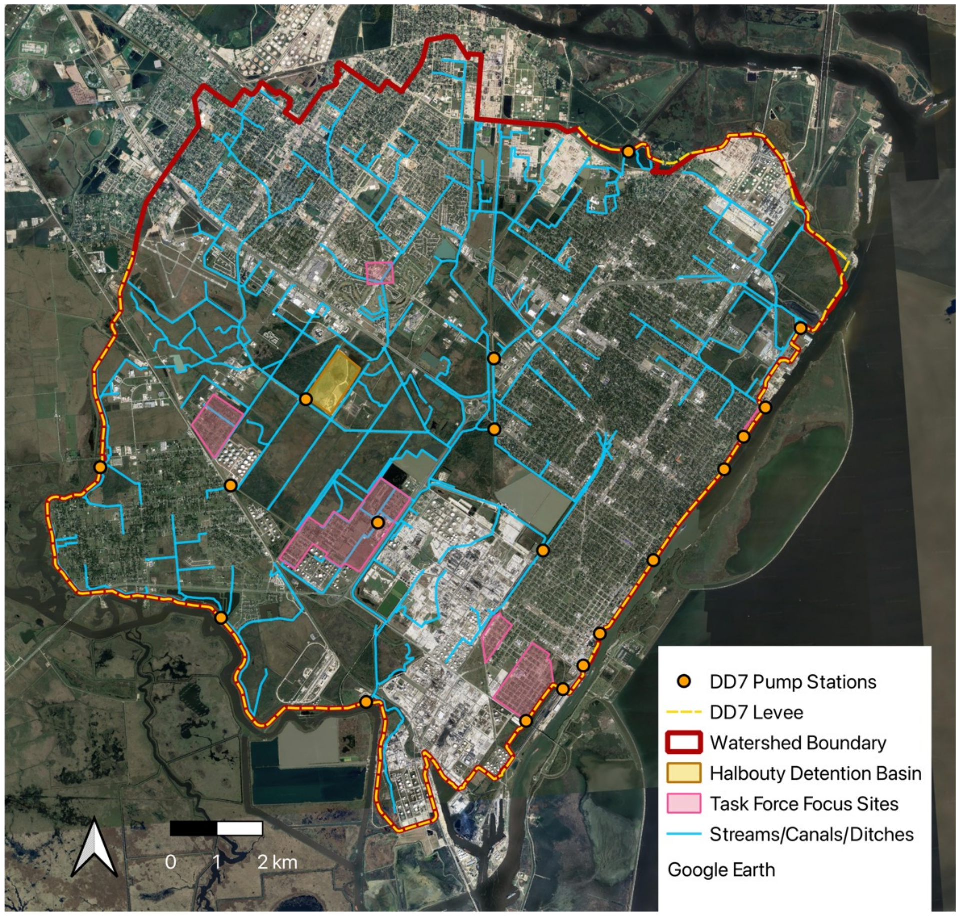
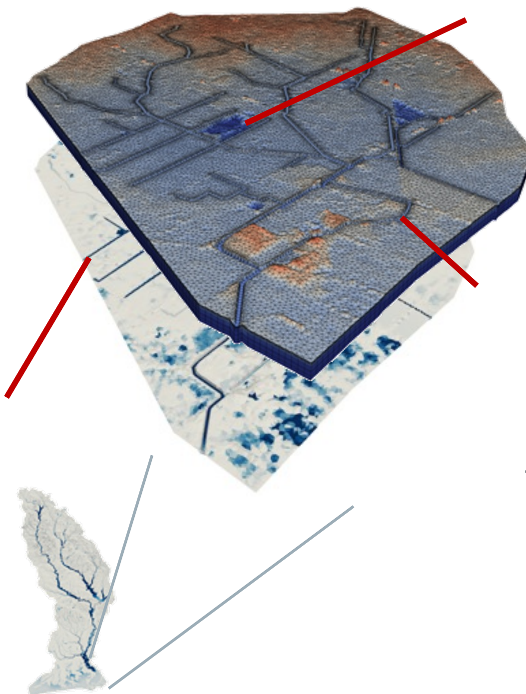
Representing stormwater infrastructure: explicit features



Representing stormwater infrastructure: explicit features

Rely on accurate representation of topography, land-surface depressions, streams, drainage canals, and other stormwater infrastructure for reliable riverine and pluvial flooding patterns, based on preliminary USGS 3DHP data.

Demonstration Model: Alligator Bayou (~106 km^2)



Detention ponds built into topography; gates opened/closed by simple rules

Streams and canals are burnt into mesh using special quad elements based on mapped flowlines

Explicit representation of canals critical for reliable inundation patterns

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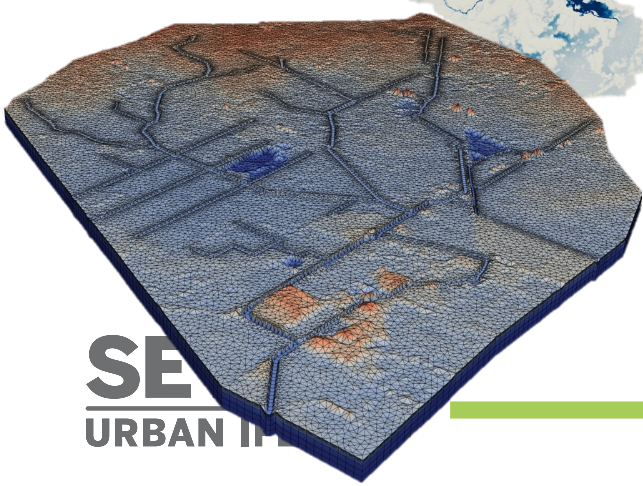
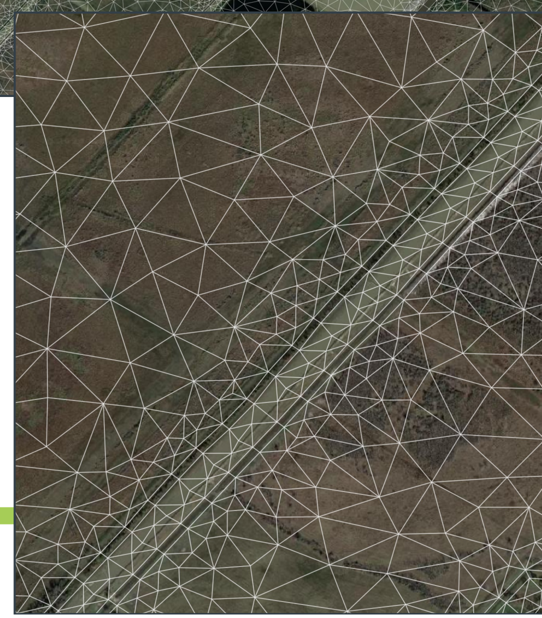
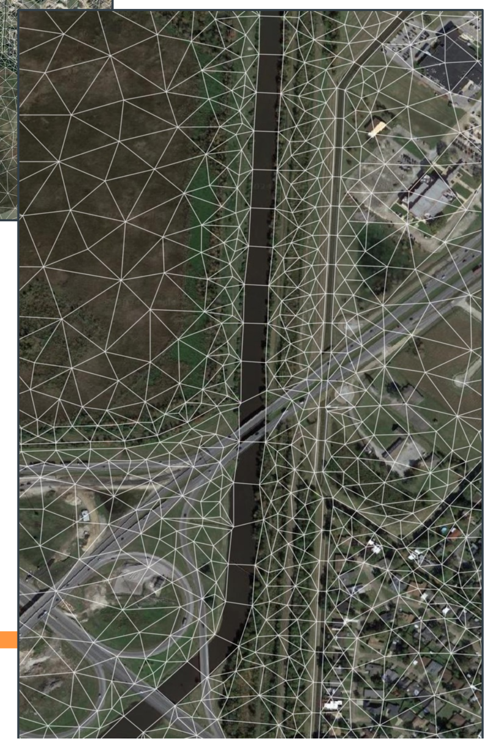
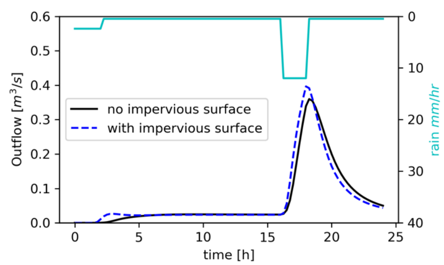


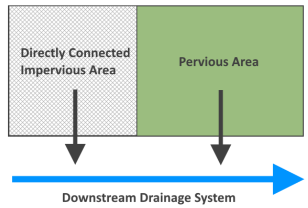




Impervious Surfaces

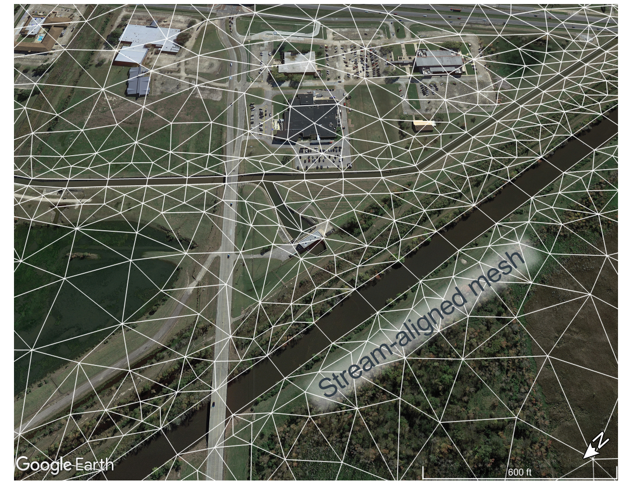
Impervious surfaces connected to the drainage system are modeled to simulate rainfall interception and flow routing. The figure illustrates an increase in peak flow and an earlier peak in the storm hydrograph due to the addition of impervious surfaces.

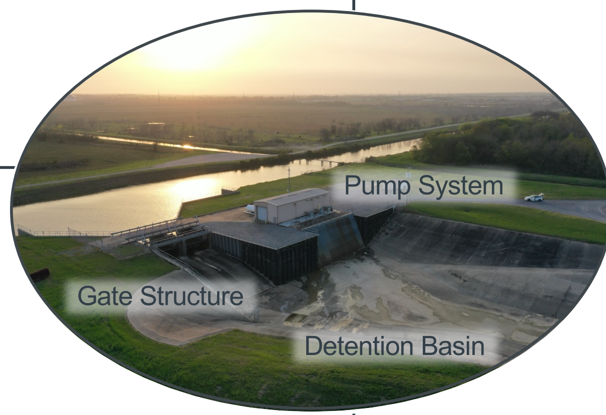




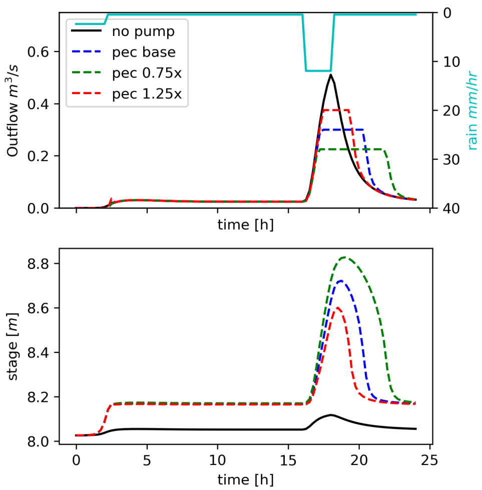
Drainage Canals

Drainage canals and ditches are resolved in watershed-scale models using stream-aligned mixed-polyhedral mesh. Figure shows mesh for urban watershed with canals.





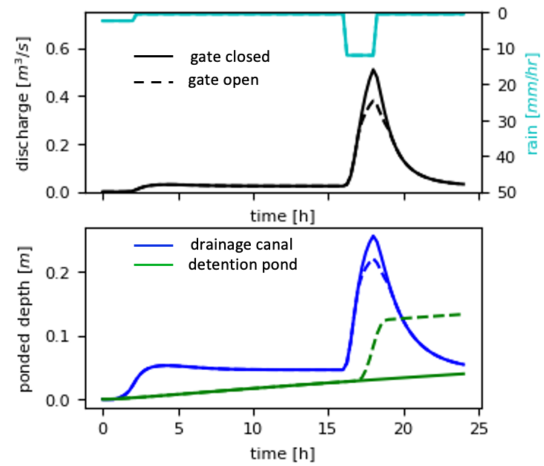
Stage-based Pump



A stage-based pump model has been implemented in the ATS. The figure presents a comparison across multiple efficiency curves, highlighting their influence on both peak flow and water stage levels.

Gate Structures

Gate structure model based on flow-curves implemented in ATS. Figure shows reduction in peak flow and stage as water is diverted from drainage canal into detention basin during a storm event.



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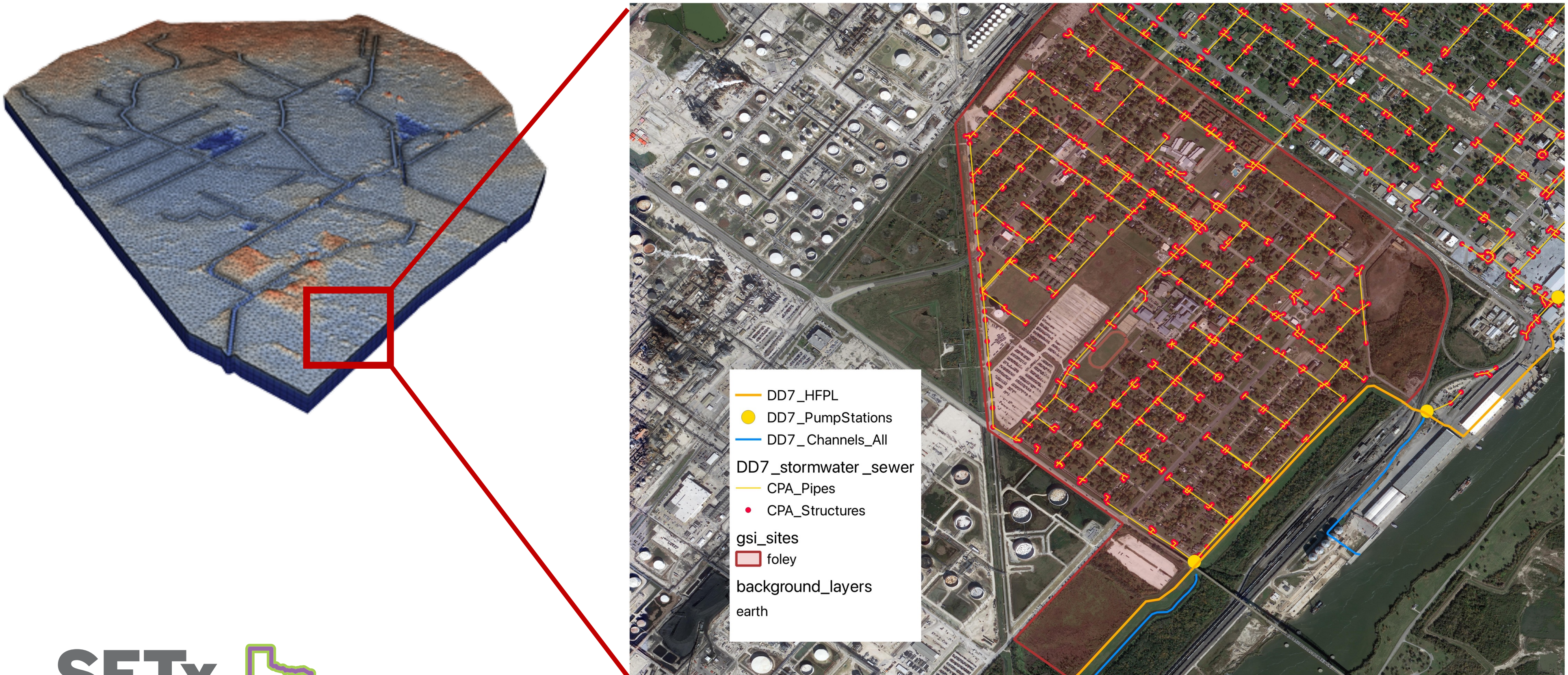
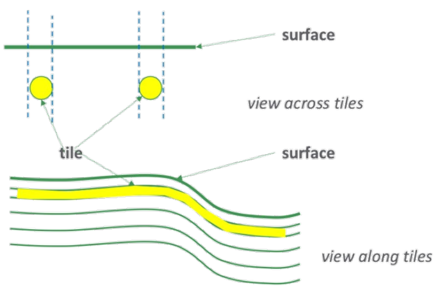
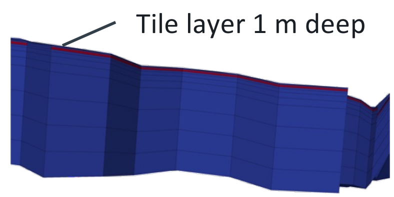
Representing stormwater infrastructure: implicit features

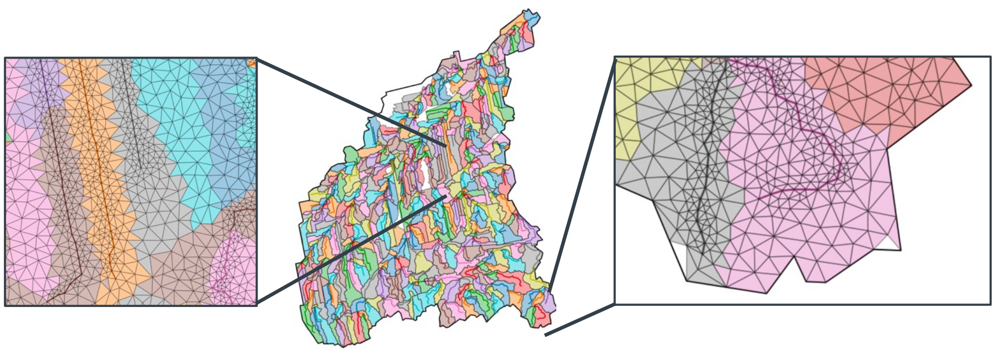


Tile Drains

Catchment-based subsurface sinks







Hooghoudt’s drainage model for tile-water flux

Storm Drains

- Non-local connections of paired source (canal) and sink (stormwater drain)
- Stormwater runoff is integrated and moved to connected drainage canal or pump station sump.
- Limits on flow rate set by pipe specifications.

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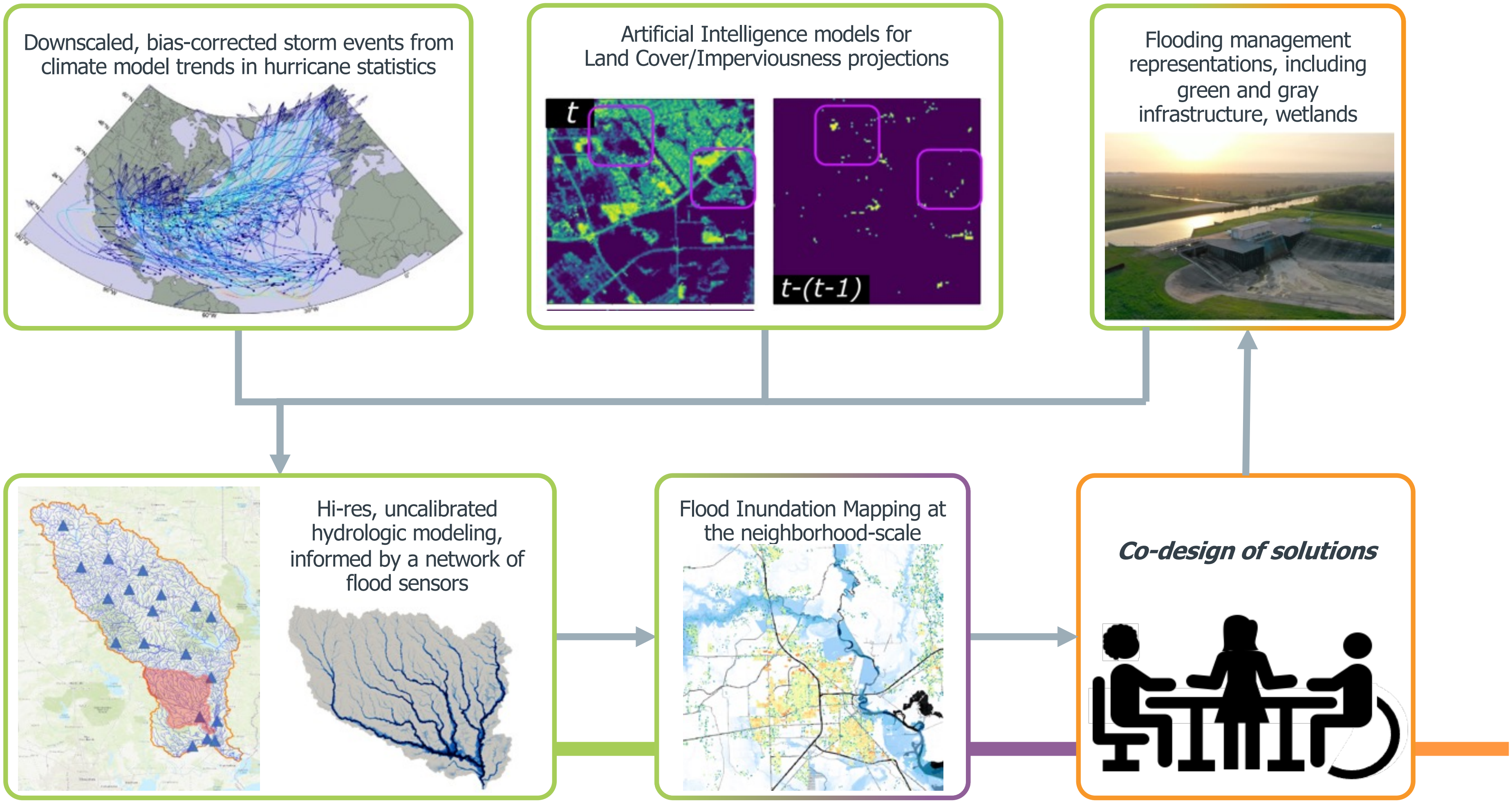
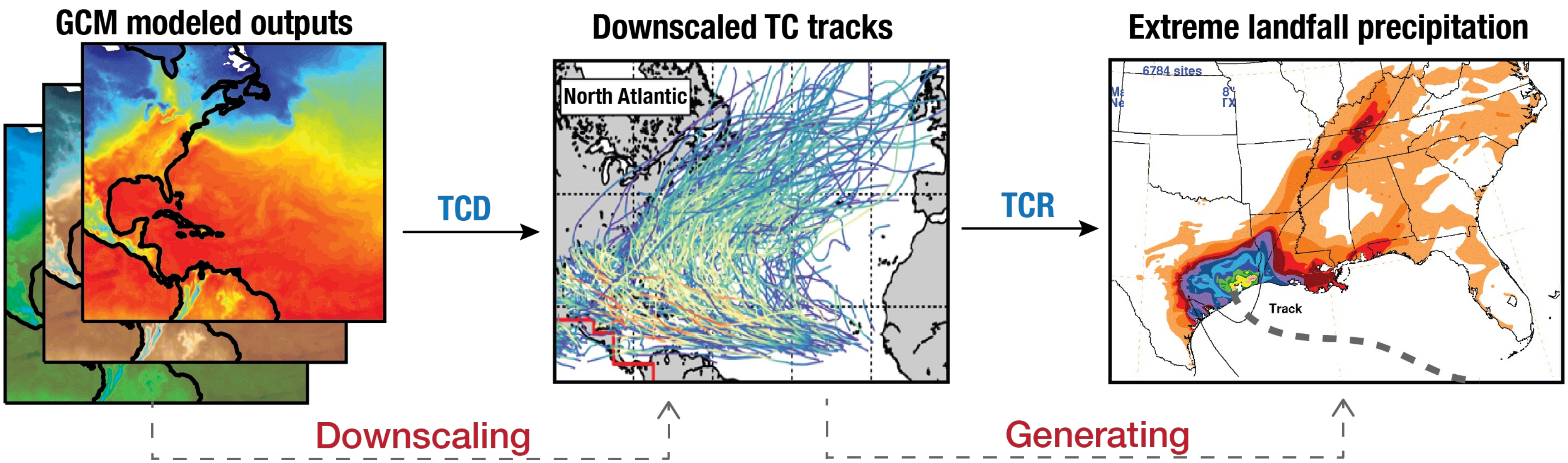
Informing decisions on water



Climate Forcing: statistically robust storm analysis



Downscale global climate models to detect storm events tracks, then leverage existing rainfall generation methods to form storm catalogs consistent with climate projections.

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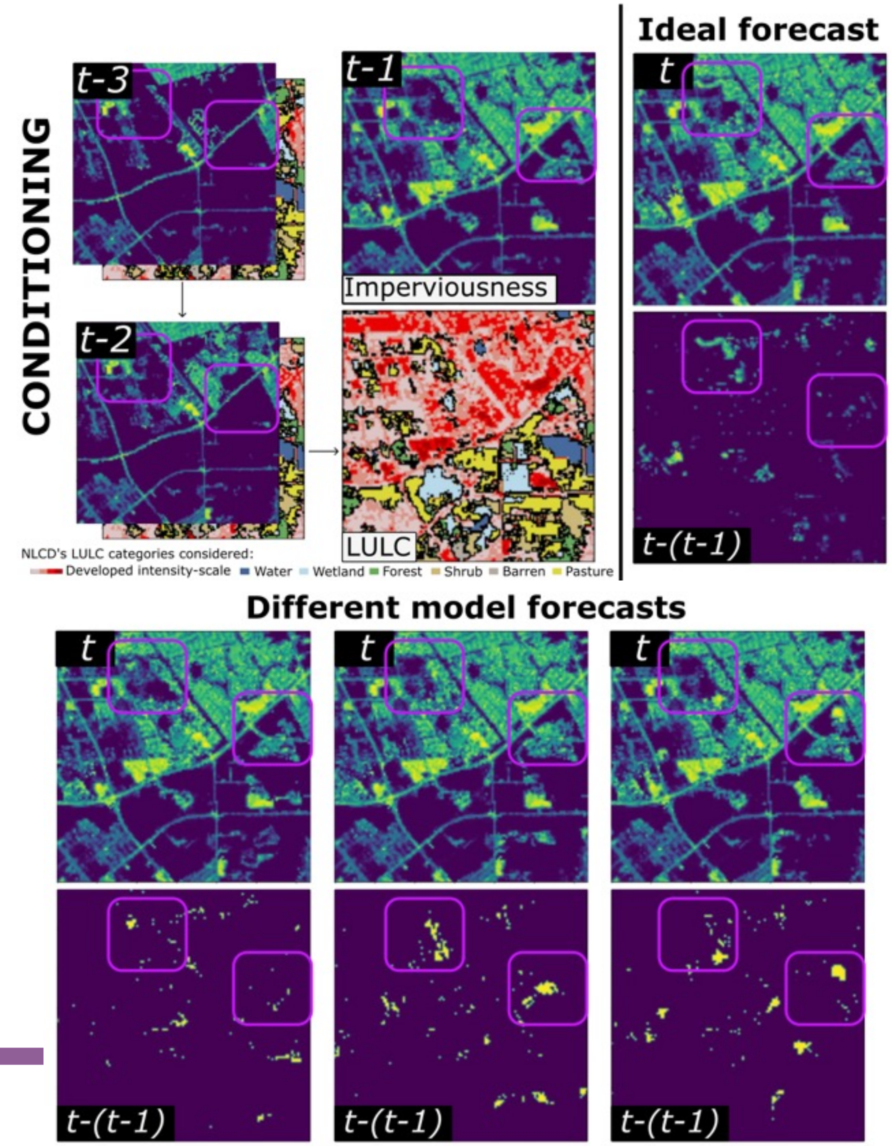
Phong Le, *https://github.com/levuvietphong/pyTCR*

Land-Use Land-Cover forecasting using generative AI

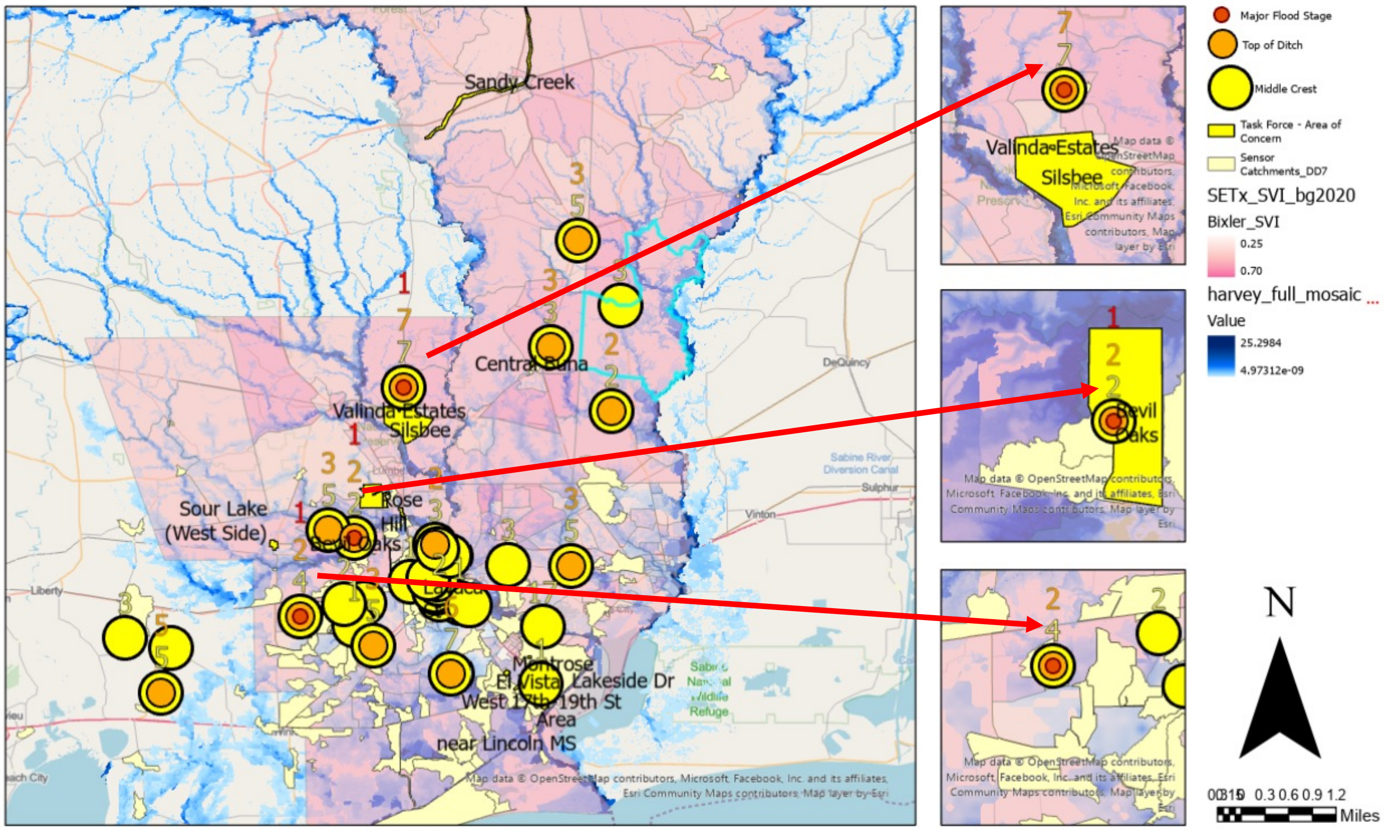
- Experiment: forecast imperviousness change
- Method:
  - Diffusion-based model conditioned on historical imperviousness and LULC maps
- Dataset:
  - National Land Cover Database (NLCD) – 30m/pixel

areas with significant imperviousness increase over the years

Qualitative assessment:
Model projections also present more change in these areas, suggesting that correct spatiotemporal patterns are being learned



SETx Flood Control District Sensor Network



- A low-cost sensor network (>200 sensors) was augmented with additional sensors, providing high resolution inundation data.
- Recently flooded areas include areas of concern identified by the Codesign team and Technical Task Force
- Data to be used to evaluate models of flooding

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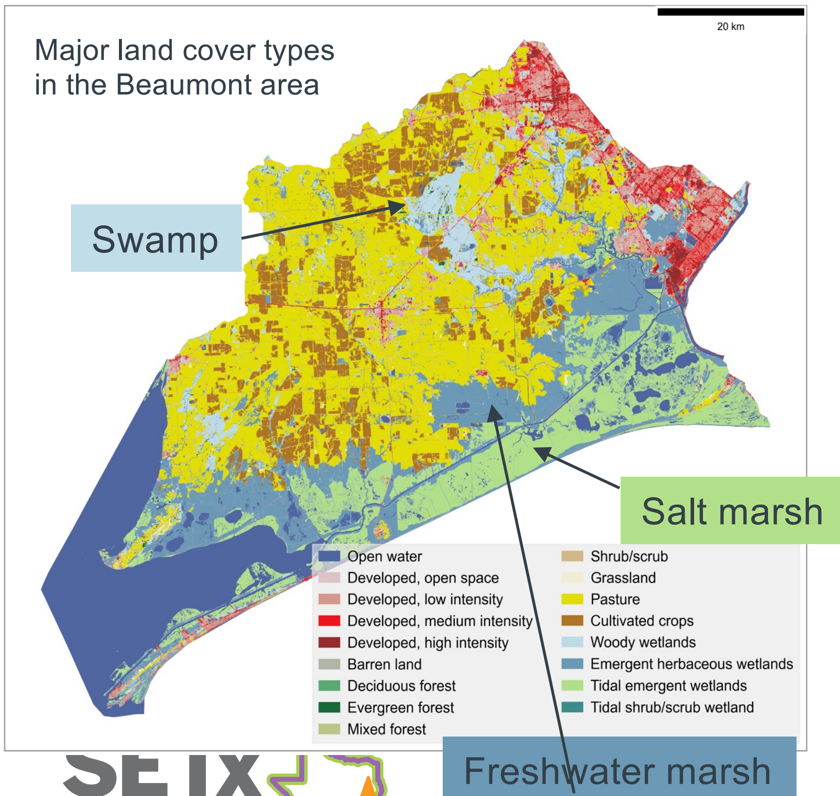
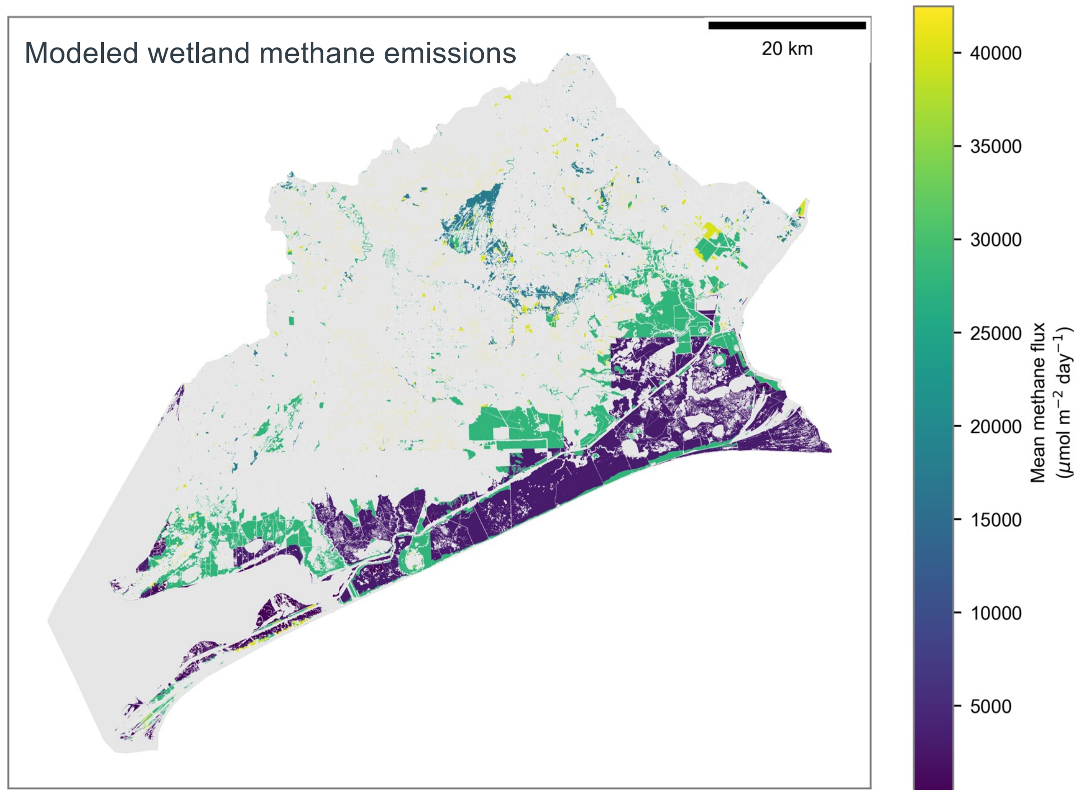
Nick Brake

Wetland modeling and scaling

We are using the E3SM Land Model simulations of wetland types across the Beaumont area to scale observations to regional patterns of wetland health, carbon storage, and methane production





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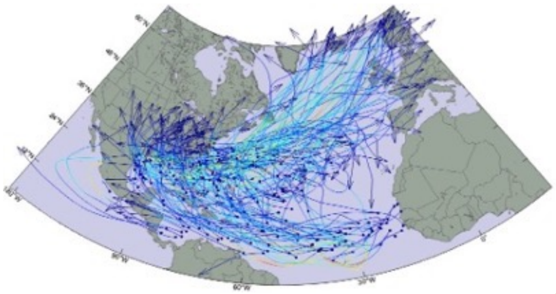
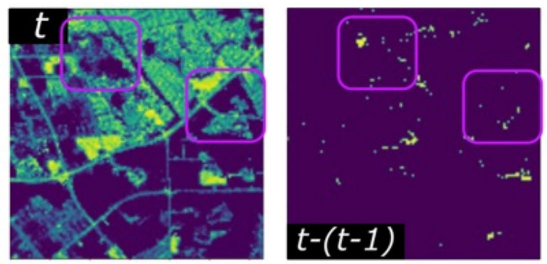
Ben Sulman

Informing decisions on water

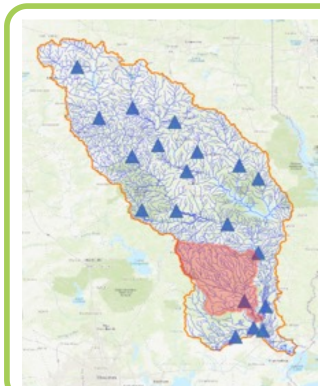
Downscaled, bias-corrected storm events from climate model trends in hurricane statistics



Artificial Intelligence models for Land Cover/Imperviousness projections



Flooding management representations, including green and gray infrastructure, wetlands



Hi-res, uncalibrated hydrologic modeling, informed by a network of flood sensors

Flood Inundation Mapping at the neighborhood-scale

Co-design of solutions