

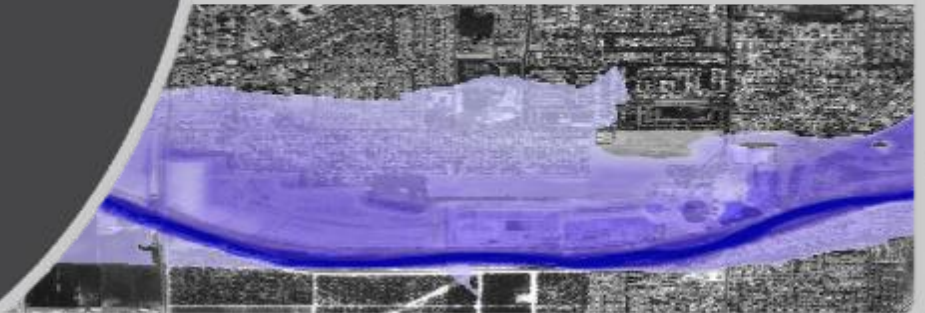
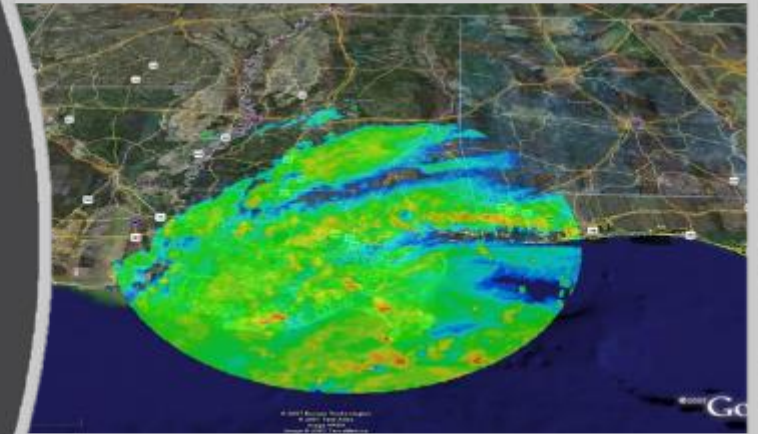


U.S. ARMY

# COMPOUND FLOODING

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US Army Corps  
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Overall Classification of Briefing is  
CUI



## What is Compound Flooding?

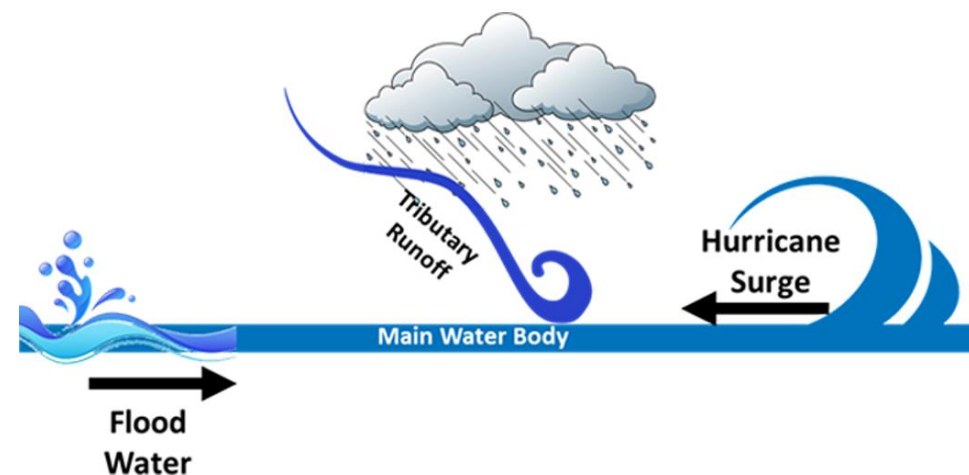
*Compound flooding refers to a phenomenon where two or more flooding sources occur simultaneously or subsequently within a short period of time.*



Compound flooding is flooding caused by two or mor sources

## Sources/Causes of Compound Flooding

- *In the inland setting*
  - *River overbank flooding*
  - *River backwater flooding*
  - *Flash flooding from intense local rainfall event*
  - *Overwhelmed drainage systems*
  - *Reservoir releases*
  - *Reservoir uncontrolled discharge*
  - *Structural failures*
- *In the coastal setting - Add*
  - *Storm surge*
  - *Wind/waves*
  - *Tides*



There are many possible sources/causes of compound flooding



## Other Considerations

### ➤ *Control features*

- *Levees/dikes*
- *Hydraulic structures*
- *Reservoirs/detention basins*
- *Pumps*
- *Surface drainage systems*
- *Subsurface drainage systems*
- *Structural failures*

### ➤ *Initial conditions*

- *Soil moistures*
- *Stream stages*
- *Reservoir levels*
- *Groundwater table*
- *Tidal stage*



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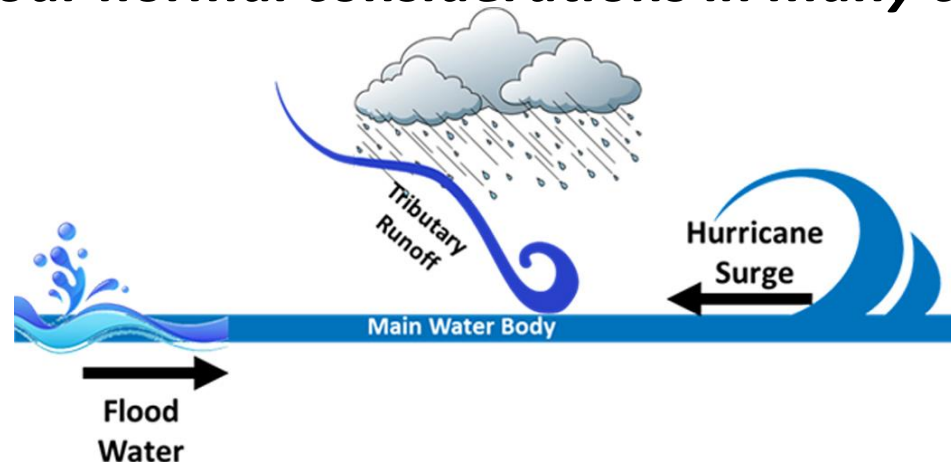
**Initial conditions and control structures are important to consider**

## Interactions are Key

*During a compound flooding event it's the interactions between different sources/causes of flooding that really cause the effects.*

- *High flows in a stream or river that might not normally be problematic could become so if high tides, reservoir levels, or storm surge prevent normal drainage.*
- *Runoff from an intense local storm could safely be transported by the system, unless the system is already at or near capacity from a larger scale event.*

*It's these kinds of issues that can be difficult to anticipate and plan for and have really been outside the realm of our normal considerations in many cases*

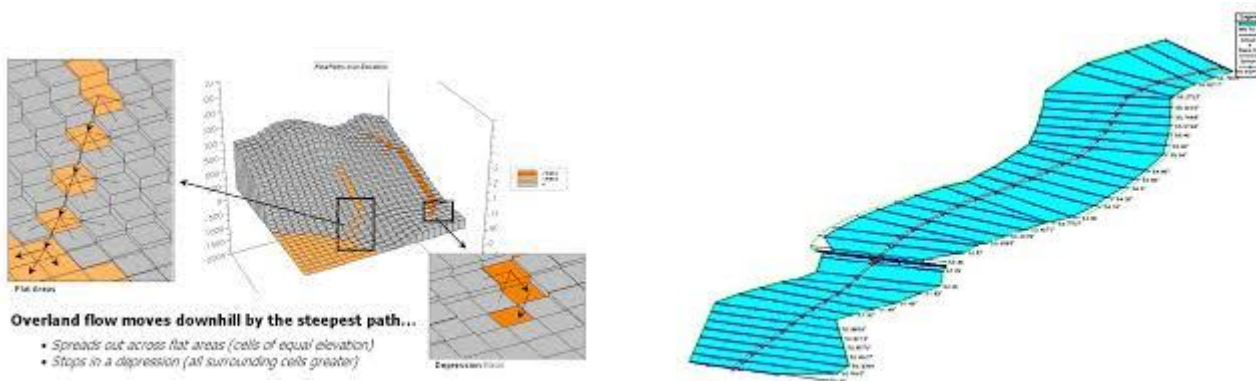


**In compound flooding, interactions are key**

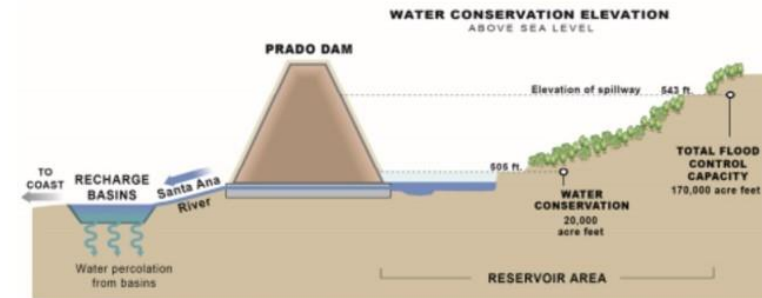
## Why is Compound Flooding Difficult to Simulate

*During a compound flooding event, the interactions among processes like tides, storm surge, sea-level rise, wind, and river discharge are very complex. Traditional models have been used to simulate one or more of the processes involved in compound flooding, but not all of them together.*

*In addition, you may not know apriori what conditions may occur. Making even conceptualizing a compound flood simulation difficult.*



USACE & OCWD cooperate to store and capture up to 20,000 acre-feet of storm water at a time

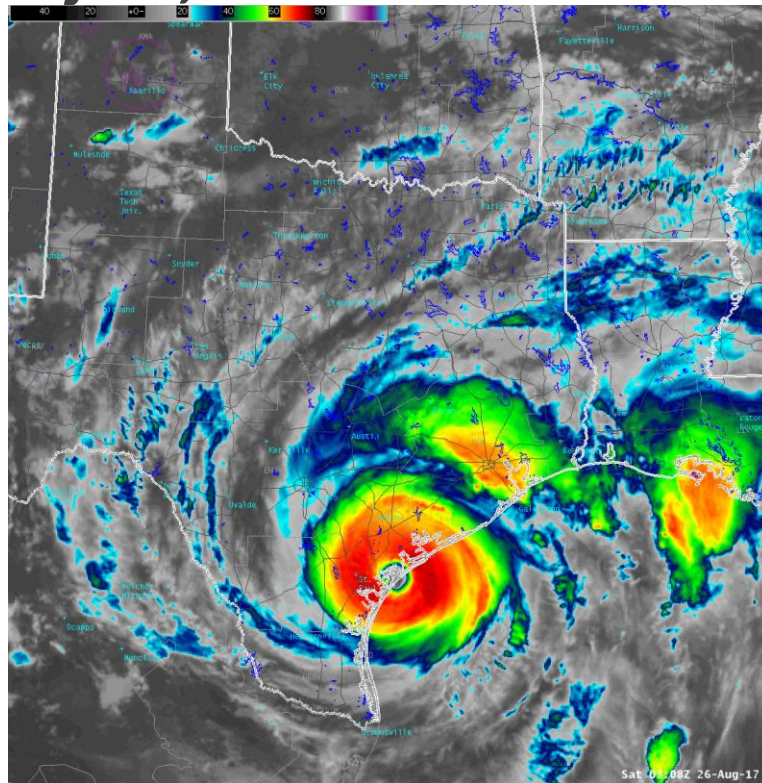


Compound flooding is difficult to simulate because many potential sources need to be considered



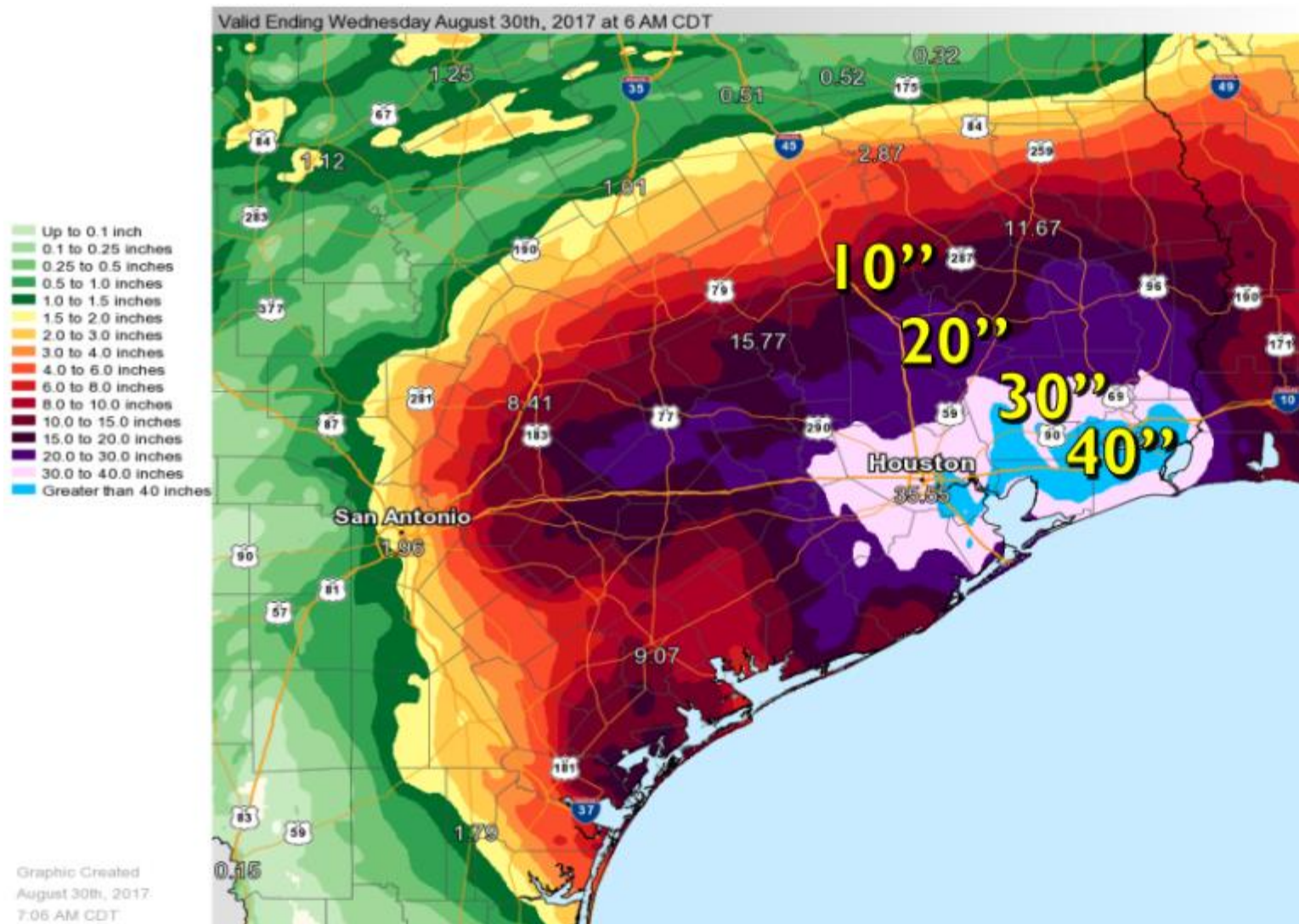
## Hurricane Harvey as an Illustrative Example of Compound Flooding

*Harvey came ashore near Port Aransas, Texas on August 25<sup>th</sup> 2017 as a Category 4 Hurricane with intense winds and storm surge. Harvey later stalled over southeast Texas for days causing flooding over a huge area, including the metropolitan Houston area. Storm surge, rainfall, streamflow, and reservoirs all contributed to historic flooding.*



Hurricane Harvey illustrates compound flooding concepts

# Rainfall



## 5 Day Point Rainfall Amounts in Inches

- Harvey continued to produce record breaking **rainfall totals** of **45 to over 50 inches**... with continued rainfall
- Cedar Bayou - 51.88**
- Berry Bayou - 44.88**
- League City - 49.84**
- Mary's Creek - 49.80**
- Goose Creek - 44.08**
- Greens Bayou - 41.36**
- Buffalo Bayou - 35.60**
- Addicks Dam - 33.44**

Agency View  
An interactive map of the Harris County Flood Control District

Point rainfall  
data courtesy

Compound flooding is difficult to simulate because many potential sources need to be considered



***Flash flooding occurs from intense rainfall overwhelming local drainage. During Harvey, much of southeast Texas experienced flash flooding, which caught drivers unaware.***



## Flash Flooding

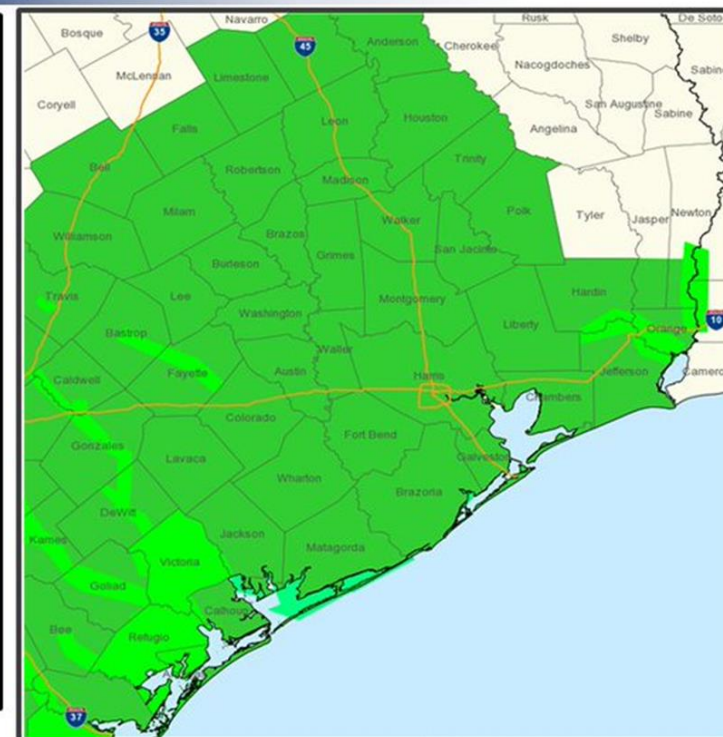


### Flash Flood Watch

National Weather Service Houston/Galveston

#### Flash Flood Watch in effect through Tuesday Evening

- There is the potential for catastrophic flooding over the next several days as Harvey continues to move inland and slowly over southeastern Texas.
- Rainfall totals of 15-30 are likely with maximum amounts of 40 inches through next Wednesday.
- Impacts: major flooding of rivers, bayous, low lying areas, and creeks. Streets will likely be impassible. Houses in low lying areas likely impacted by flood waters.



@NWSHouston

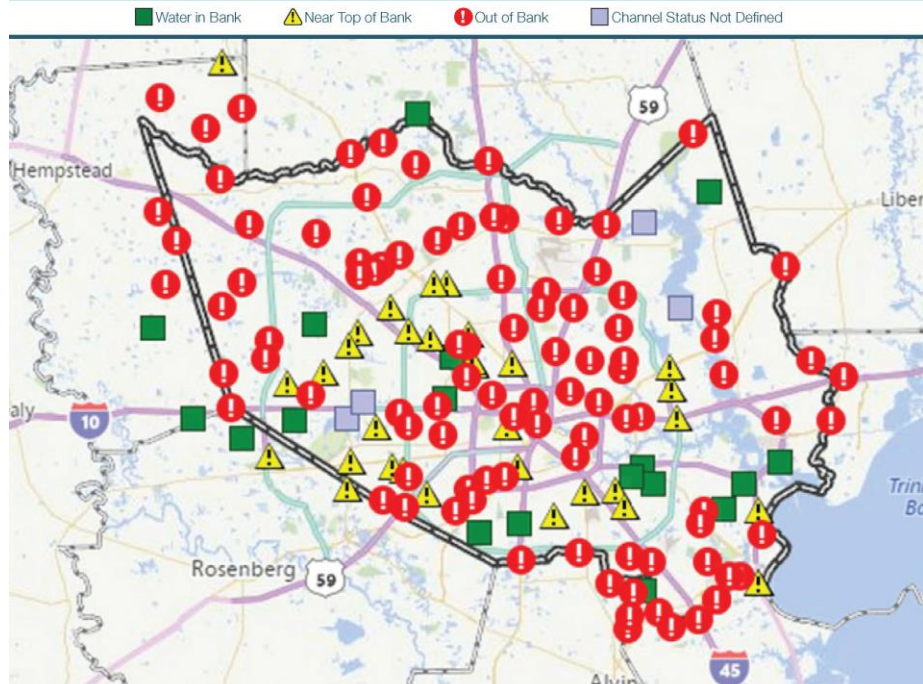
weather.gov/houston

Image 8/26/2017  
Created 4:31 AM

**Intense rainfall caused flash flooding before the effects of river flooding peaked**

## Streamflow

Screenshot of the Harris County Flood Warning System  
Sunday, August 27, 2017, at Approximately 11:00 A.M. CST

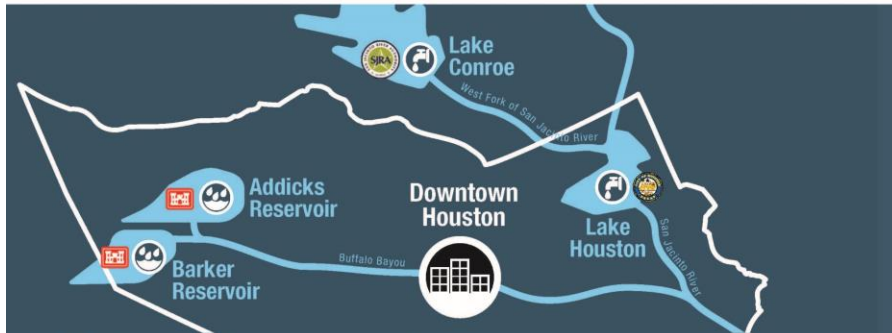


***Runoff from widespread heavy rainfall caused streams and rivers to swell with excessive runoff. 90% of stream gages in the area were at flood level and nearly 50% hit all time highs (62% in Harris county). Many streams experienced 500-yr flow/stages.***

**Compound flooding is difficult to simulate because many potential sources need to be considered**



# Reservoirs



## Water, water everywhere...

Many residents and businesses surrounding Addicks and Barker Reservoirs, as well as the Lake Houston and Lake Conroe Dams, flooded as a result of the massive amount of floodwater during Harvey.

### Lake Houston and Lake Conroe Dams

The San Jacinto River watershed is a very large watershed that originates well outside of Harris County, and two large water supply lakes are located along the river: Lake Conroe and Lake Houston. The channels within the watershed drain all or part of Harris, Montgomery, Walker, Walker, Grimes, Liberty and San Jacinto counties, for a total drainage area of approximately 4,500 square miles.

The lower San Jacinto River watershed occupies a rather narrow strip of land in eastern Harris County and joins with the Houston Ship Channel before flowing into Galveston Bay along the southeastern edge of the county. In Harris County alone, the San Jacinto River watershed covers about 487 square miles, and there are about 310 miles of open streams within the watershed, including the primary streams and tributary channels.

The West Fork of the San Jacinto River flows from its headwaters near Huntsville, through Lake Conroe and Lake Houston. Lake Houston, operated by the Coastal Water Authority, and Lake Conroe, operated by the San Jacinto

River Authority (SJRA), were both developed as water supply reservoirs and therefore do not provide significant storage during flood events.

In the instance of Lake Conroe, SJRA operators have limited discretion in how they operate the spillway gates and are not able to simply "let the lake rise" to further reduce downstream flows. There is only about 18 inches of "freeboard" between the top of the spillway gates and the water level at normal lake level. Freeboard is the distance between the water line and the point at which the water would overflow the gate. Operators cannot allow the water to overtop the gates because they are not designed to sustain that type of force. Therefore, the gates must be raised as the lake level rises to allow flood waters to be released through the flood spillway. The lake can rise a maximum of six feet within a flowage easement purchased for all property around the reservoir, thus reducing the dam flood releases to a flow level that is below the amount of inflow into the reservoir. Again, this lake is intended to be a water supply reservoir – not flood control infrastructure – and SJRA operators were charged with maintaining the integrity of the structures as Harvey caused rapidly increasing water levels on Lake Conroe.

***Reservoirs in the Houston area normally control floods while providing water and recreational opportunities. However, the high stream flows exceeded the capacity of the system and uncontrolled (spillway) flows were recorded at many of the lakes and reservoirs.***

Lake	Elevation (ft)	Discharge (cfs)
Houston	53.1	425,000
Conroe	206.2	79,140

**Compound flooding is difficult to simulate because many potential sources need to be considered**

# Coastal Flooding

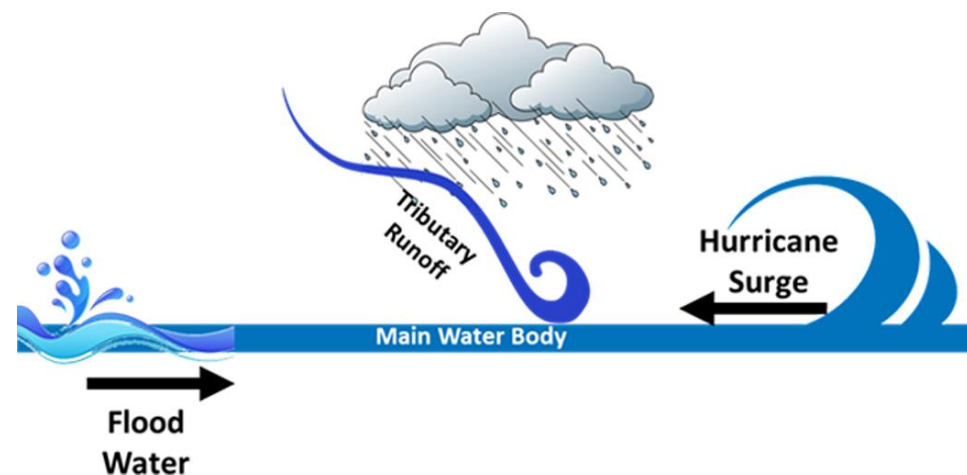


Compound flooding is difficult to simulate because many potential sources need to be considered



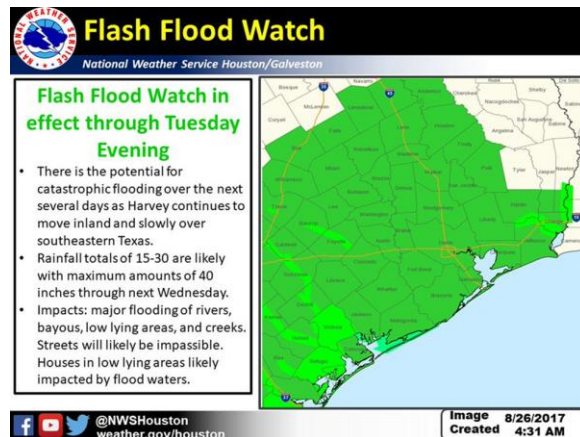
## Systems at Play

- *Flash flooding from intense local rainfall*
- *Overwhelmed local drainage system*
- *River overbank flooding*
- *River backwater flooding – reservoir and tide stages*
- *Reservoir releases*
- *Uncontrolled reservoir releases*
- *Storm surge*



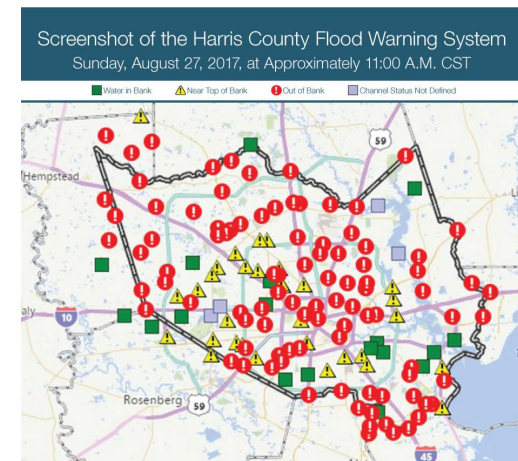
There are many possible sources/causes of compound flooding

# Synopsis

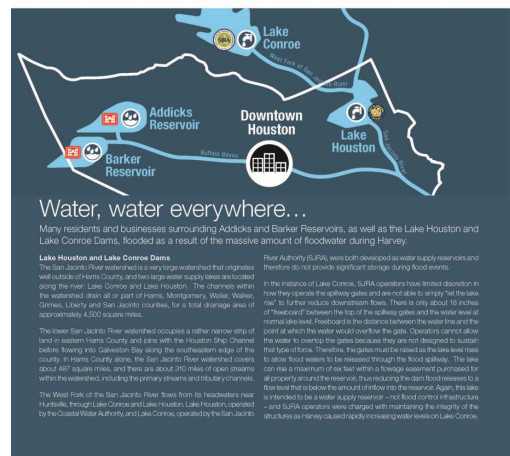


Local runoff adds to stream flooding

Overbank flow adds to local flooding



Stream flow adds to tidal flooding.

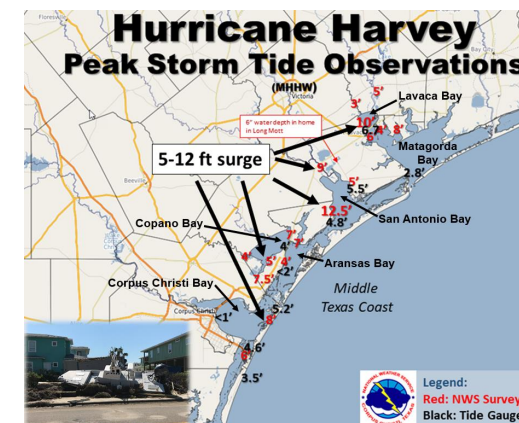


Lake discharges causes downstream flooding

Streamflow causes reservoir flooding

High lake levels cause backwater effect in streams

Lake discharge adds to tidal flooding



Tidal flooding causes backwater effect in streams.

**During Harvey many types of flooding and interactions occurred**



# Models?

## Needed Interactions

Hydrology  
Overland flow

Stream flow

Overbank and backwater effects

Stream inflows

Reservoir

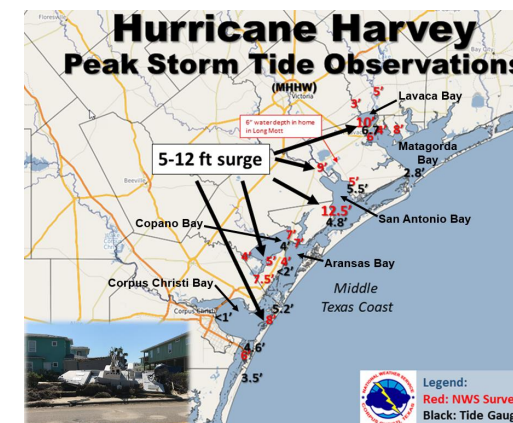
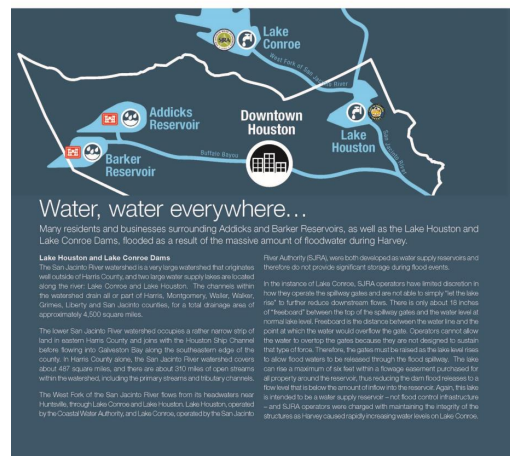
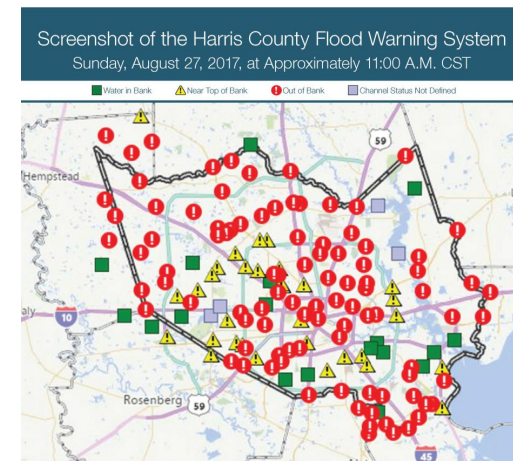
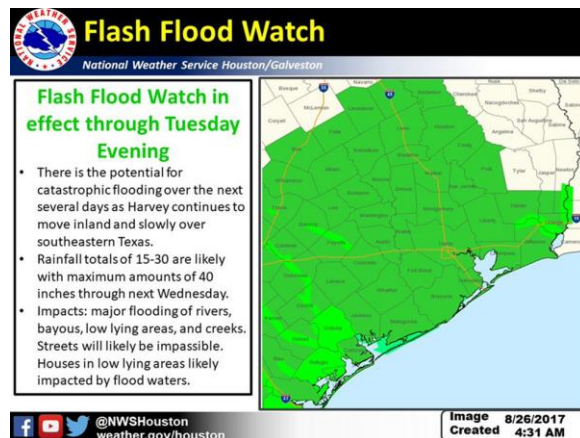
Backwater effects  
Discharge to stream

Discharge to tidal streams

Discharge to tidal streams

Backwater effect

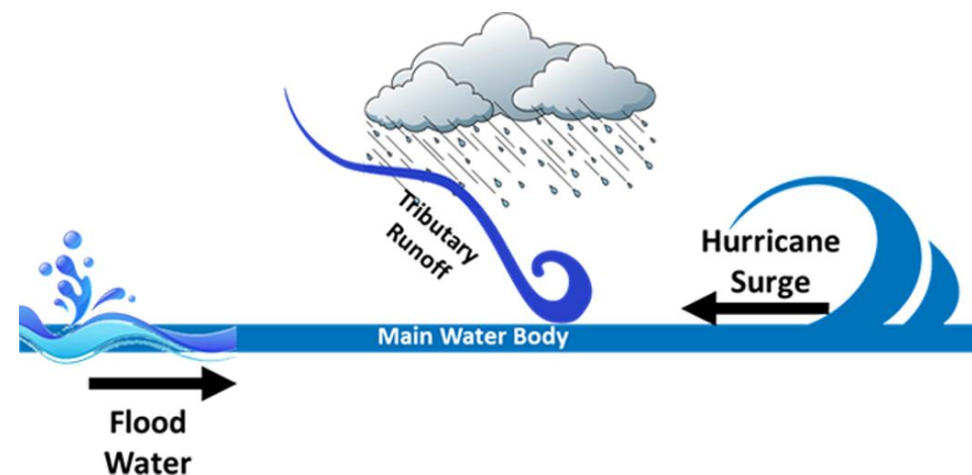
Coastal  
Open ocean



Compound flooding is difficult to simulate because many potential sources need to be considered

## Simulating Compound Flooding is a Work in Progress

- **Current USACE Systems**
  - *CEWMS – inland operational model*
  - *WAT – system to tie many tools together*
  - *CSTORMS – coastal storm modeling*
- **Current USACE Integrated Models**
  - *AdH*
  - *GSSHA*
- **Other Federal Systems**
  - *NWM (NWS)*
  - *GSFLOW/MODFLOW (USGS)*



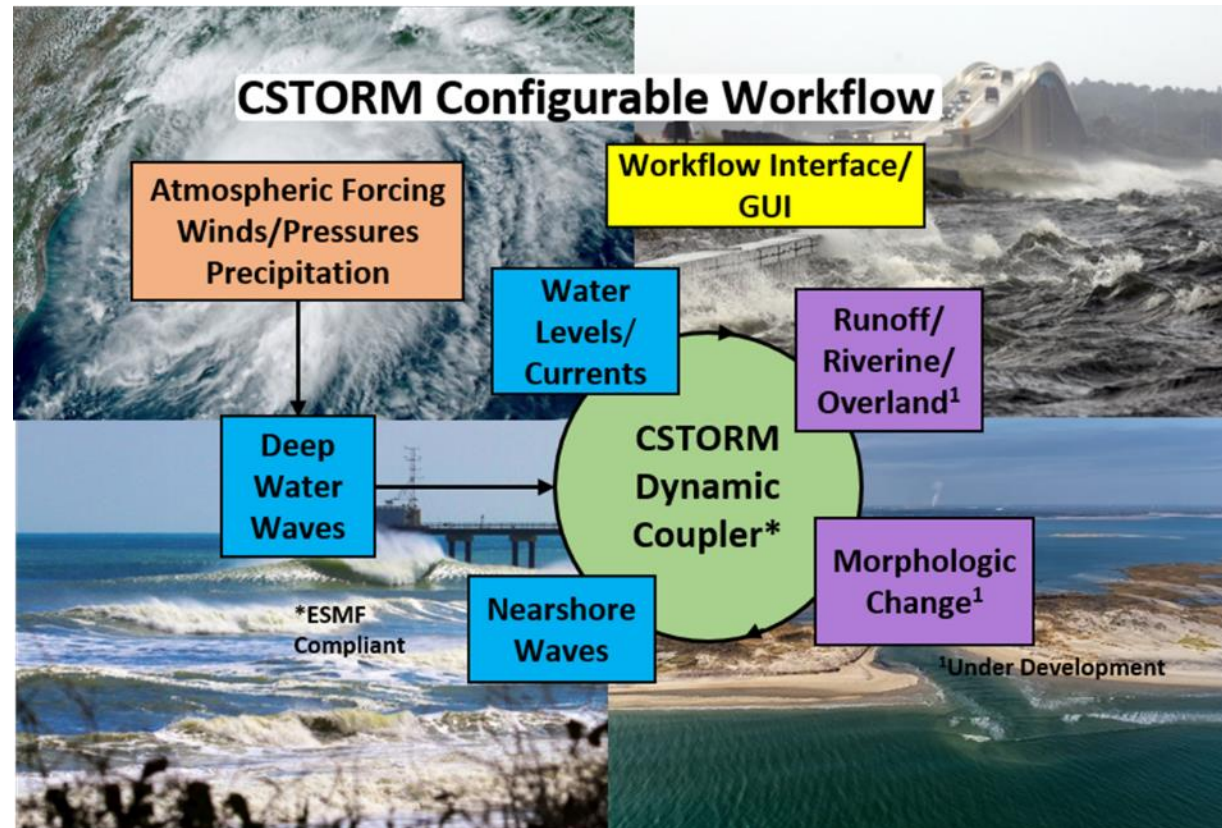
Simulating compound flooding is a work in progress in the Federal government





## CURRENT TECHNOLOGY – ERDC'S COASTAL STORM MODELING SYSTEM

- *CSTORM-MS is an efficient, highly skilled, extensible, integrated and robust modeling system for quantifying the risk of coastal communities to storm events including considerations for sea level rise.*



### Forcing

- Tropical cyclones
- Extratropical cyclones
- Precipitation (proposed)

### Response

- Water level (storm surge, astronomical tide, SLC)
- Currents
- Wave height, peak period, direction
- Wind speed, direction
- Overland runoff (proposed)
- Riverine (proposed)
- Sub-surface flows (proposed)

CSTORM is an Integrated Modeling Platform Currently for Coastal Analysis



# USACE Top 10 R&D Priorities

★  
**1**   
Mitigate and Adapt to  
**Climate Change**

**2**   
Win  
**Future Wars**

**3**   
Modernize  
our Nation's  
**Infrastructure**

★  
**4**   
Support  
Resilient  
**Communities**

**5**   
Enable Smart  
and Resilient  
**Installations**

★  
**6**   
Ensure  
**Environmental**  
Sustainability  
and Resilience

**7**   
Secure Reliable  
Installation  
**Energy**

★  
**8**   
Revolutionize  
and Accelerate  
**Decision Making**

**9**   
Improve Cyber  
and Physical  
**Security**

**10**   
Protect and  
Defend the  
**Arctic**

Priorities are  
not ranked;  
numbers  
are for  
identification  
purposes  
only



## USACE R&D STRATEGY

Scan the QR Code at right  
to download a copy of the  
**USACE R&D Strategy**  
and other USACE R&D  
communication products



★ SUPPORTING SCIENCE, RESEARCH, AND DEVELOPMENT TO DELIVER ENDURING WATER RESOURCE SOLUTIONS



# USACE CIVIL WORKS STRATEGIC FOCUS AREAS (SFAs)

## Sustainable Species Management



*Measuring, predicting, and managing harmful, nuisance, threatened and endangered species*

## NextGen Water Resources Infrastructure



*Building smarter, longer-lasting infrastructure*

## Innovations in Sediment Management

*Maximizing beneficial use of sediments*



## Comprehensive Water Risk Management



*Effectively and efficiently managing water before, during, and after it hits the ground*

## I-4A: Innovative Applications of Big Data Analytics, AI, & Autonomy



*Leveraging robotics, AI and data as a force multiplier*

## Crisis Mitigation, Response, & Recovery



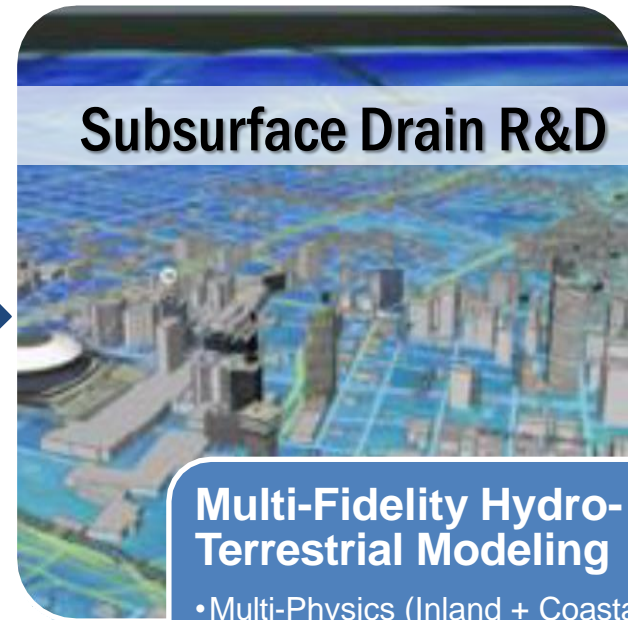
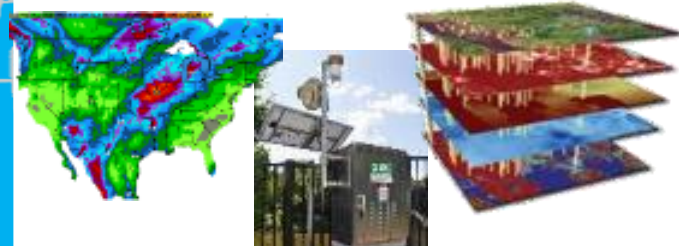
*Proactively saving lives and communities*

# Comprehensive Water Risk Management



## Integrated Earth Observations

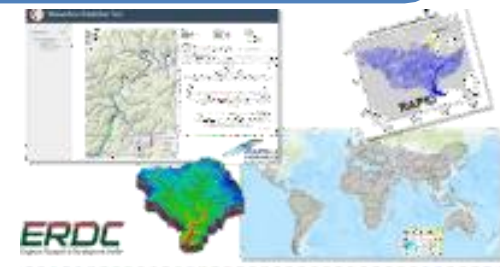
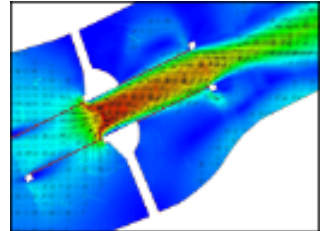
- Remote Sensing (Satellite +)
- In-Situ Sensing
- Atmospheric, Ocean & Land Surface
- Automated Updating
- Assimilation & Continuous Model Validation



## Subsurface Drain R&D

## Multi-Fidelity Hydro-Terrestrial Modeling

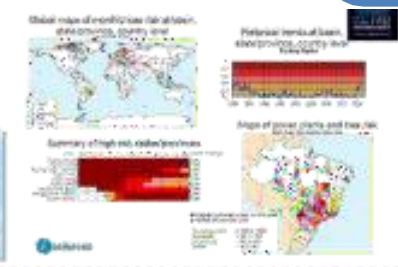
- Multi-Physics (Inland + Coastal)
- Ensemble Methods
- ML/AI Capabilities
- Modular, Modern, Efficient
- Open Science/Collaborative
- Driver for Environmental & Sediment Modeling



## Innovations in Sediment Management Support Crisis Response

## Decision Support

- National Storm Hazards Database/Tools for Efficient Lifecycle Planning & Design
- Robust Real-Time National Hydro-Terrestrial Simulation
- Tradespace Design Analysis
- Probabilistic Seasonal Projection Capability
- Updated Guidance



**Development of Comprehensive Water Risk Management – Key SFA Served by This Proposed Research**