AGU23

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COMPOUND FLOODING: A MANUAL OF PRACTICE

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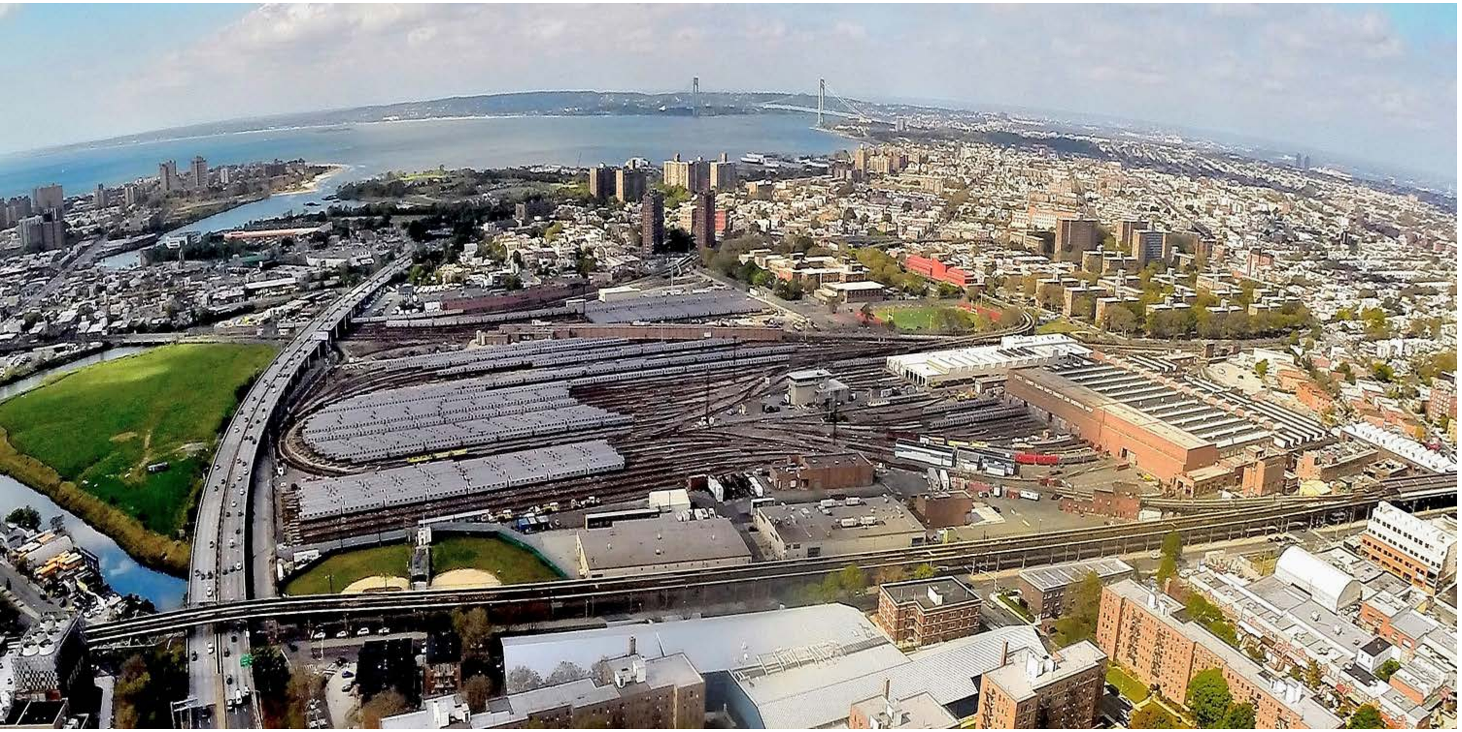
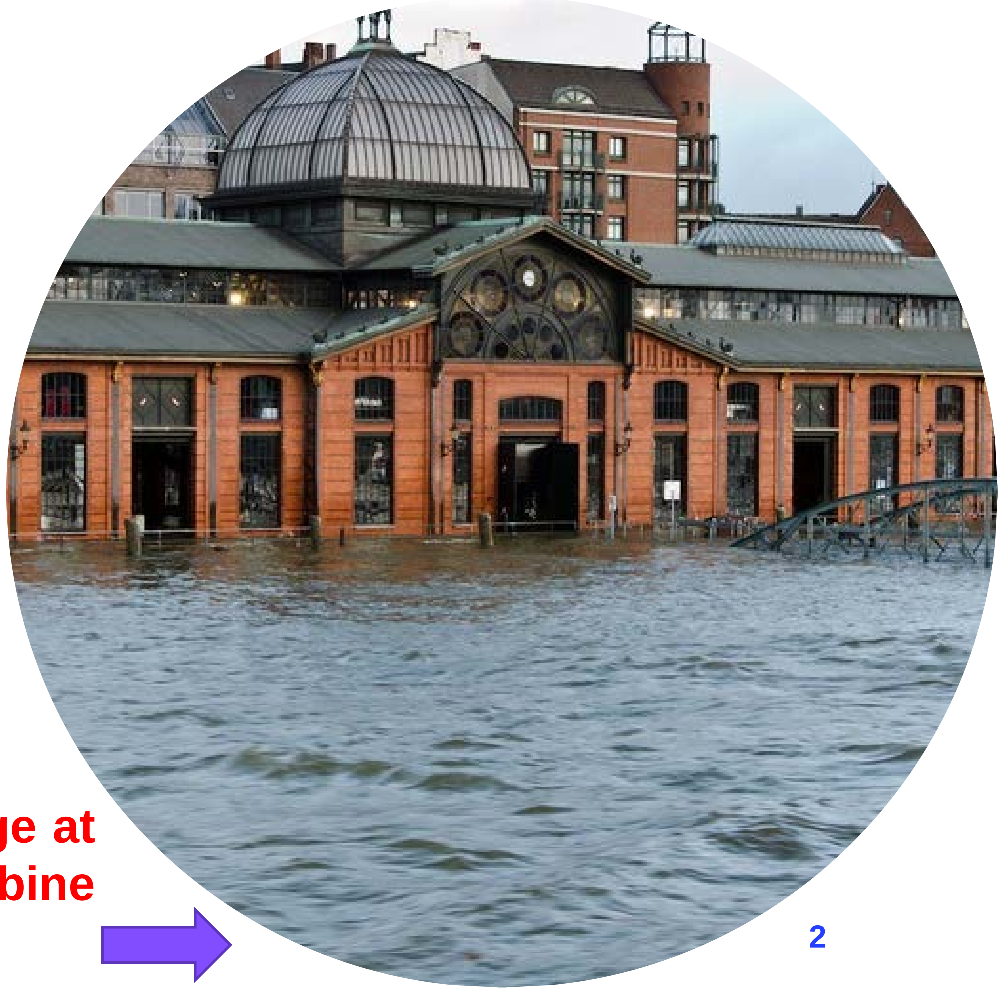
Introduction



German city, Hamburg, where **storm surge at coast & high discharge at Elbe combine** into *CCF* (Climatechange post, 2020)



Introduction

Top 10 Highest Historical Storm Surge Crests (NAVD 88 Feet)			24-Hour Rainfall During Storm Surge (Inches)
10/29/2012	14.1	Superstorm Sandy	0.5
09/12/1960	10.0	Hurricane Donna	3.8
12/11/1992	9.7	*Unnamed*	2.8
08/28/2011	9.5	Hurricane Irene	3.1

Source: ***NOAA****, at NY, JFK Int'l Airport*

Days	Country	Surge Height (feet)	Max. 24-hour Rainfall (inch)	*Source*
11/12/2019	Venice, Italy	6.1		HANZE v2.1
10/29/1999	Paradip, India	Up to 24	18.4	Kalsi, 2006; Sahoo & Bhaskaran (2018)
10/12/2013	Phailin, India	11.5	15	CEDIM (2013)

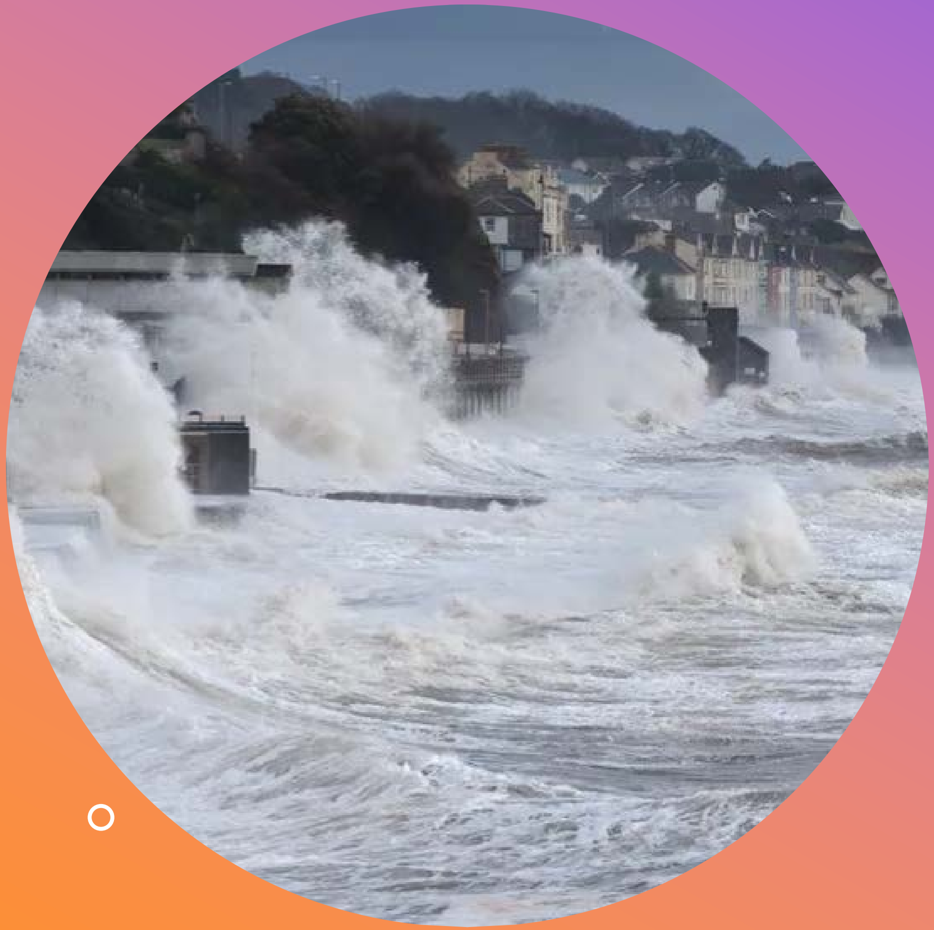
Manual of Practice

- Orderly **presentation of facts**, supplemented by **analyses of limitations and applications**
- Offers useful information & tools to the **practicing engineers** & **decision makers**
- MoP is in preparation under aegis of **ASCE**; will undergo **review and approval by a Blue Ribbon Panel** of experts & executive committee.

ORGANIZATION CHART

- **Committee on Technical Advancement**
  - **Committee on Adaptation to a Changing Climate** formed in 2011 to evaluate the technical requirements & engineering challenges to adapt changing climate
    - **Technical Committee on Hydroclimatology and Engineering Adaptation**
      - **Task Committee On Compound Flooding**

COMPOUND FLOODING: A MANUAL OF PRACTICE



AGENDA

Introduction

Overview of Chapters 3-8

Case Study

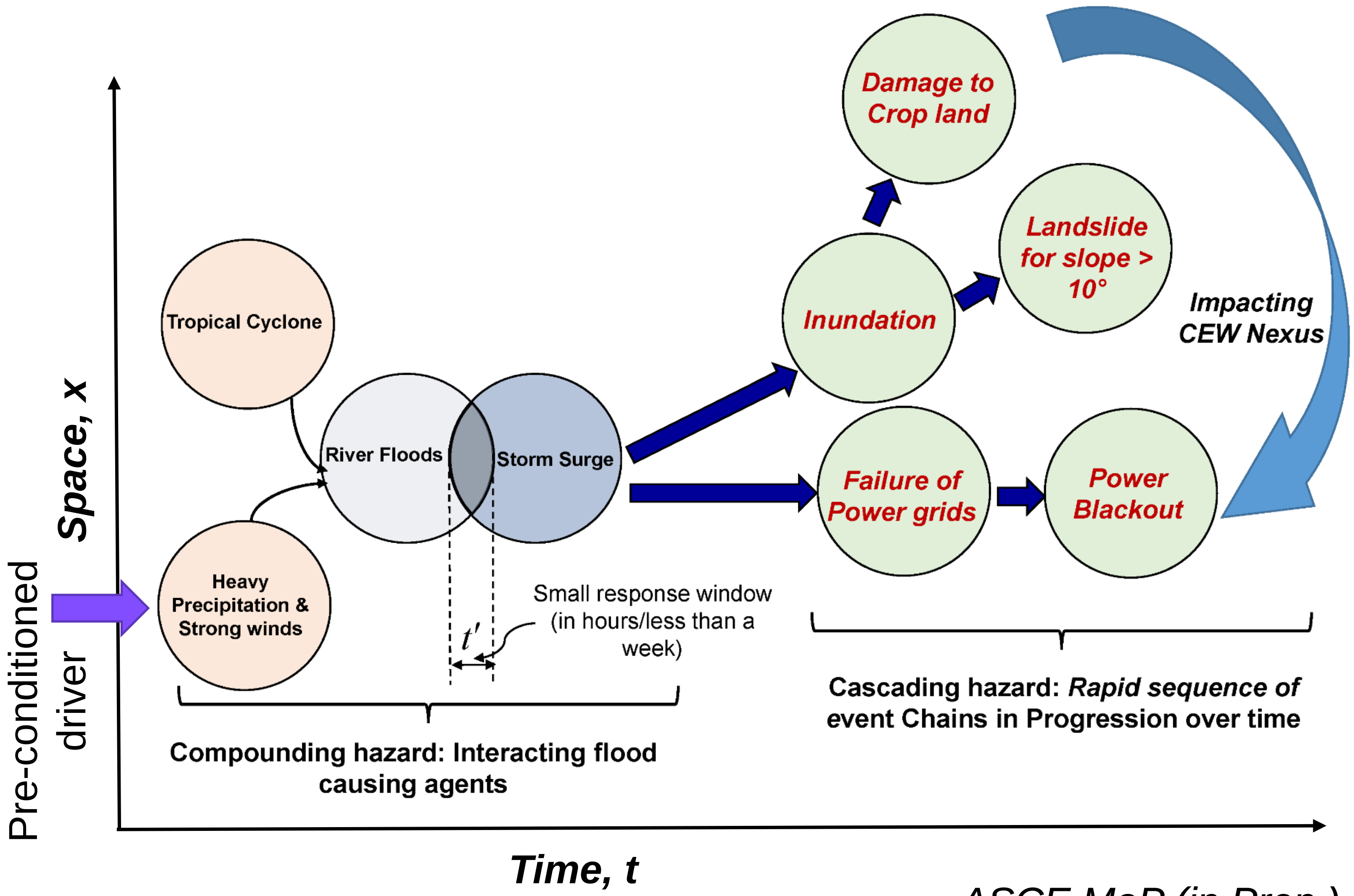
Q & A

Simultaneous *or* sequential floods due to meteorological, hydrologic & oceanographic drivers

Key Elements

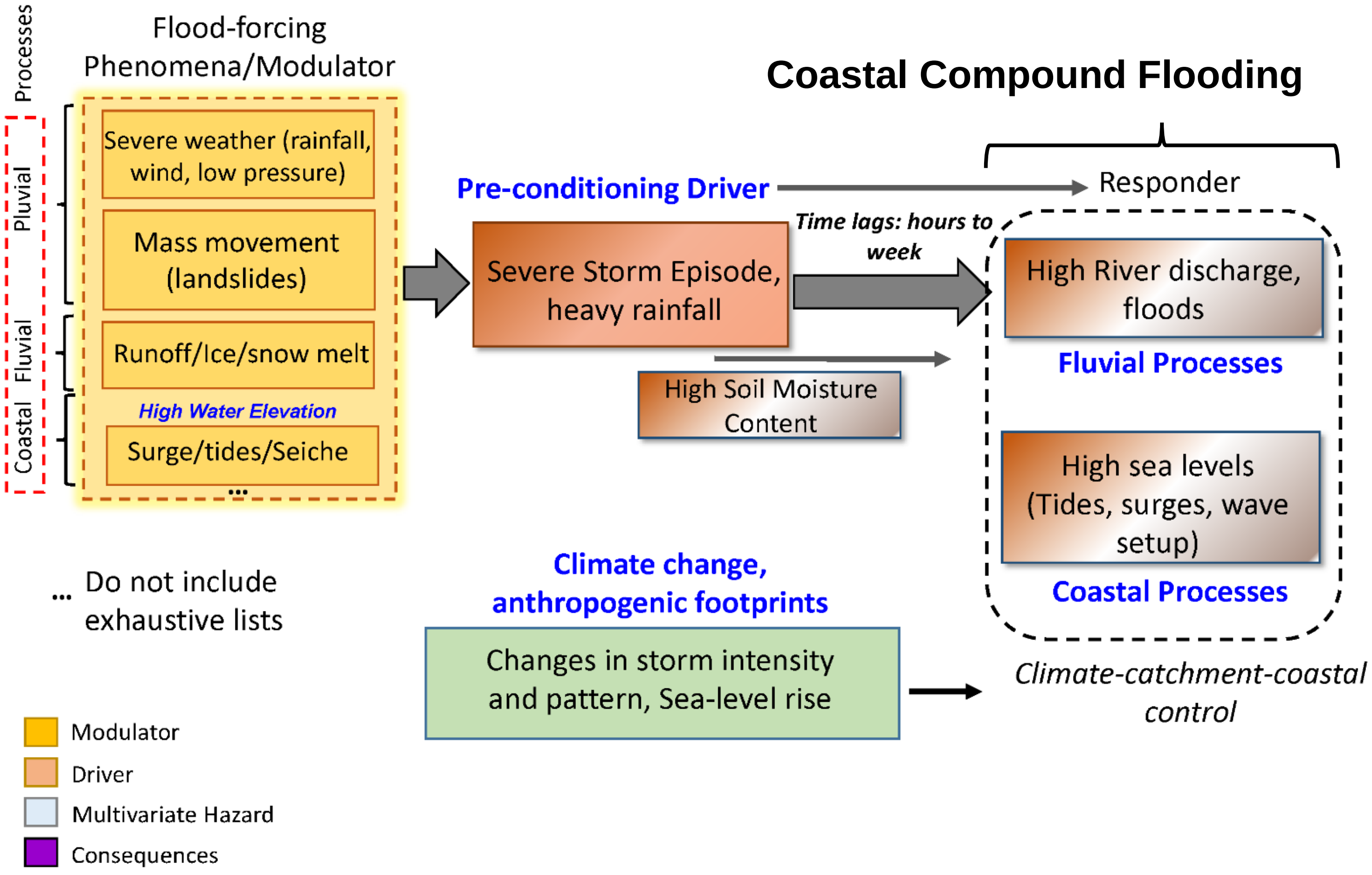
- Involvement of multiple drivers within concise time window
- Extremeness of impact
- Statistical interdependency

Neglecting interdependence b/n driver may lead to over/underestimation of hazard potential



ASCE MoP (in Prep.)

Physical Drivers Mediating Compound Flooding



Driving Mechanisms

- High **coastal water levels** impacting **river flow** due to backwater effect → prominent < 10 *m*
- High storm **surge height block/slow precipitation** drainage into the sea, triggering floods
- High coastal water levels and high river **discharge in deltas** → driven by a storm event

Geomorphological features, wind-facing direction, coastline shape

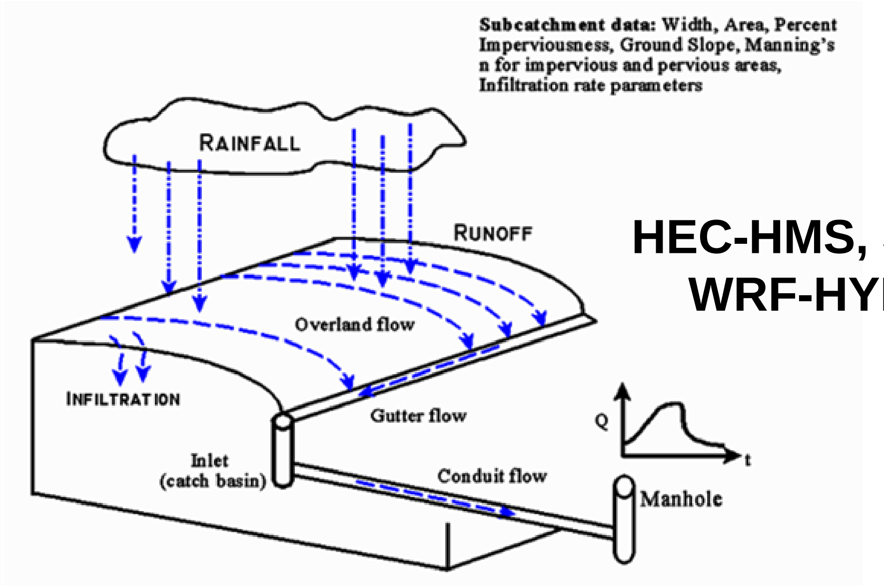
- Precipitation on **already saturated soil preceded** by river floods, **rain** on **snow** (ROS)

Hydrodynamic Process-Based Models of Compound Flooding

- Rainfall and Runoff
- Riverine Flows
- Coastal dynamics
- Coupling between these processes
- Important inputs for accurately capturing inundation

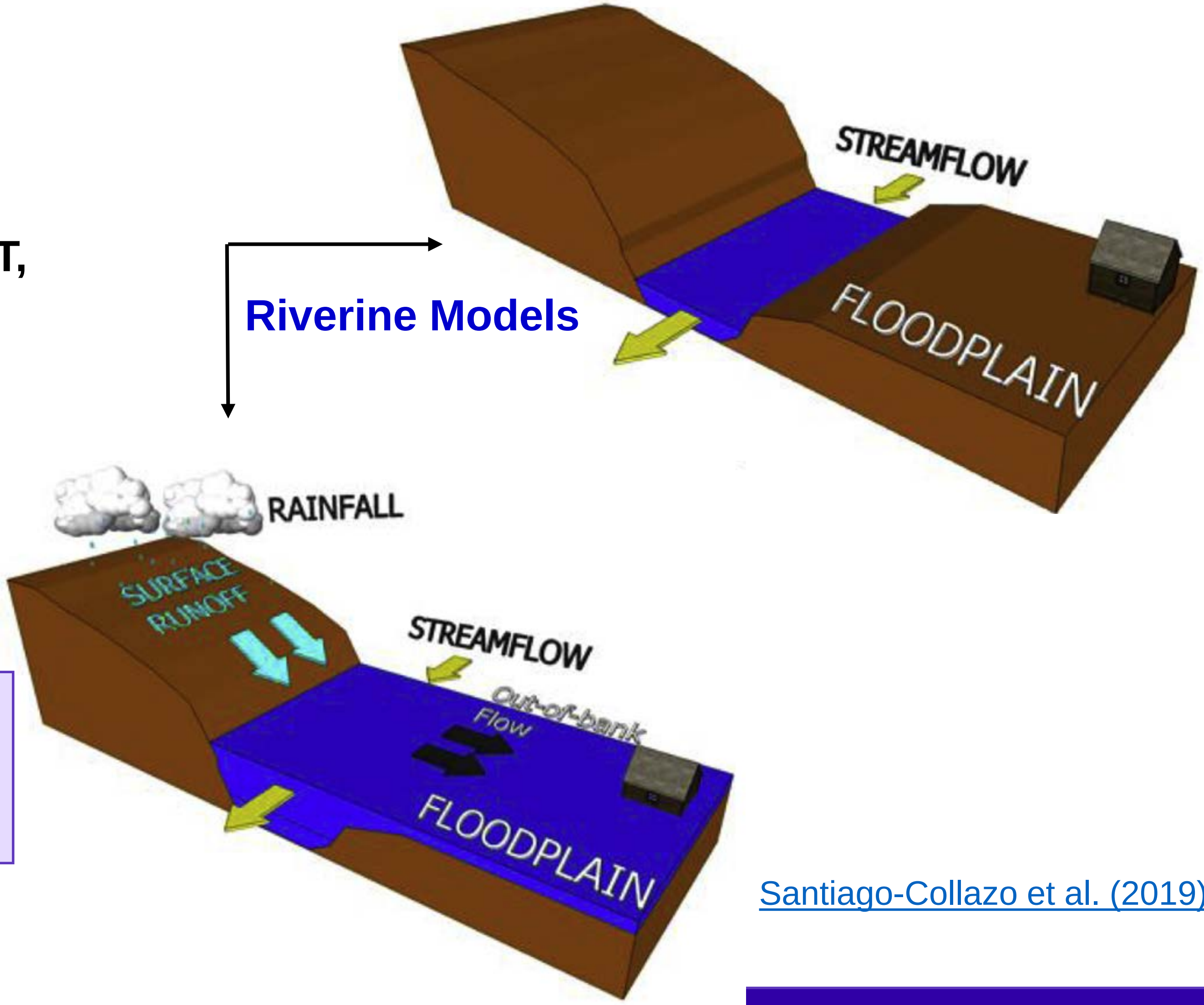
In Low-lying coastal areas storm surge and rainfall-runoff in coastal watersheds are not necessarily mutually exclusive hazards

Rainfall-Runoff Processes



HEC-HMS, SWMM, SWAT, WRF-HYDRO, PRMS

Riverine Models



1D/2D HD Models

HEC-RAS,

DFLOWFM 1D

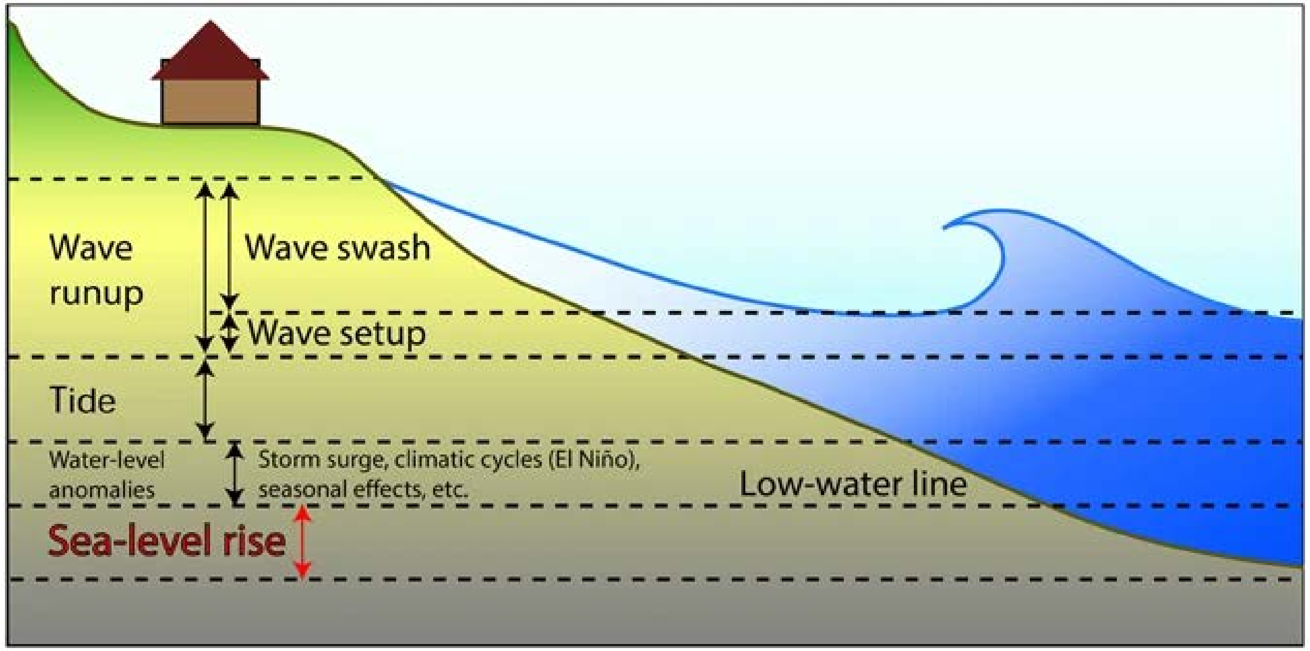
1D flow network in combination with 2/3D coastal simulation

Santiago-Collazo et al. (2019)

Coastal Processes

Wave Models

- Simulating Waves Nearshore (SWAN)
- Wave Watch III
- Xbeach



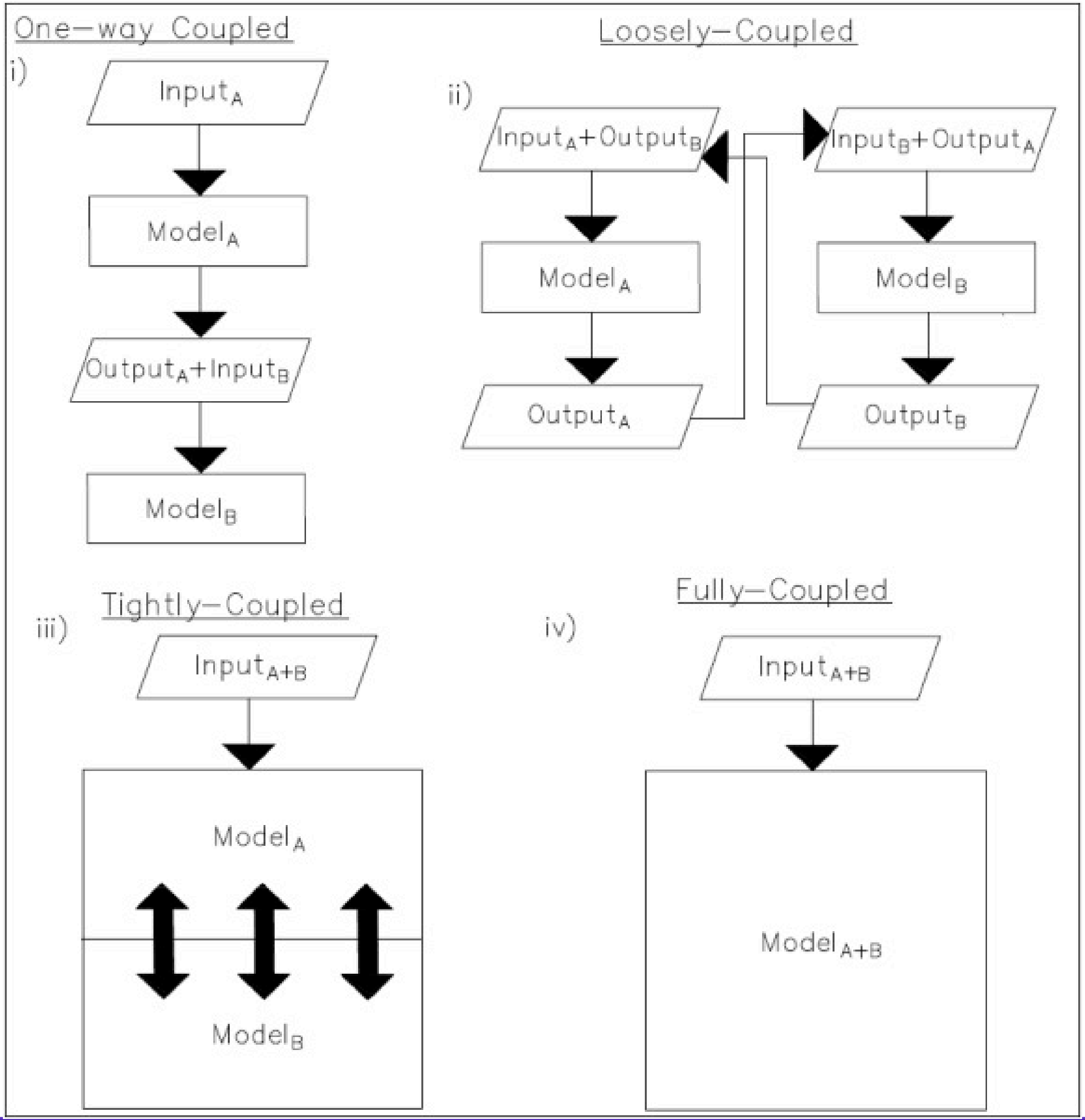
Coastal Circulation Models

- ADCIRC
- COAWST/ROMS
- Delft3d/Flexible Mesh
- Princeton Ocean Model
- MIT GCM
- Sea, Lake, and Overland Surges from Hurricanes (SLOSH)
- Stanford Unstructured Navier Stokes (SUNTANS)
- Finite Volume Coastal Ocean Model (FVCOM)

Modelling Compound Flood Requires Coupling Different Processes-based Models

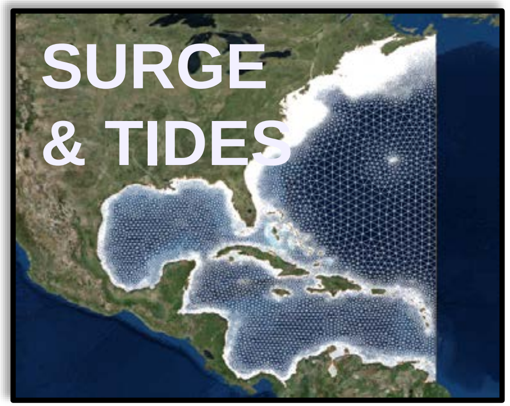
Coupling Technique	Methods
One-way	Computations that are transferred from one model and used as an input in another (i.e. linking technique)
Loosely	Separately-running models are coupled using information exchange in an iterative manner (i.e. two-way coupling)
Tightly	Independent models are integrated into a single modeling framework by combining their source code
Fully	Governing equations of all the physical processes considered are solved simultaneously within the same modeling framework

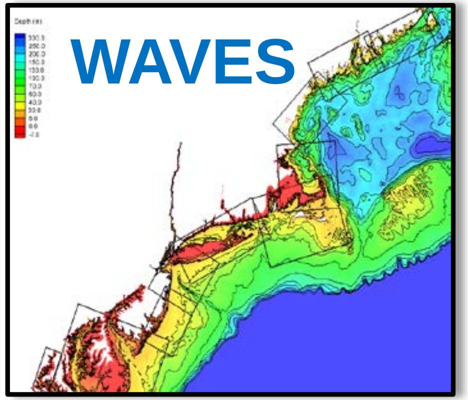
Source: Santiago-Collazo et al. (2019)

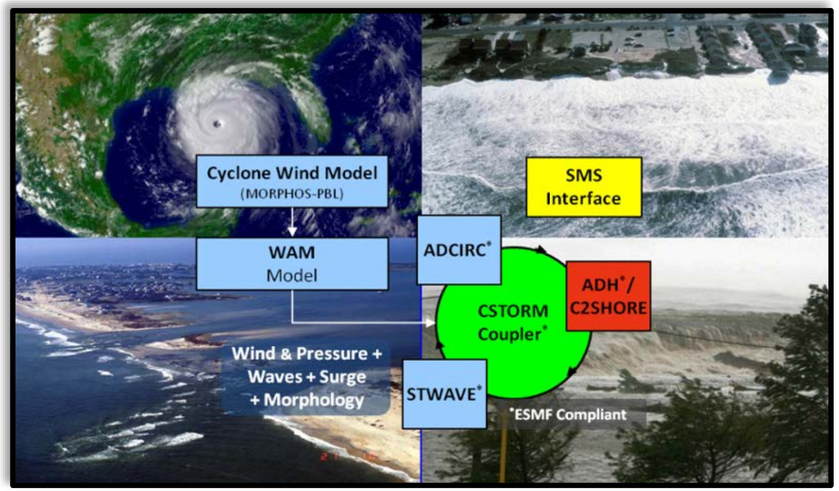


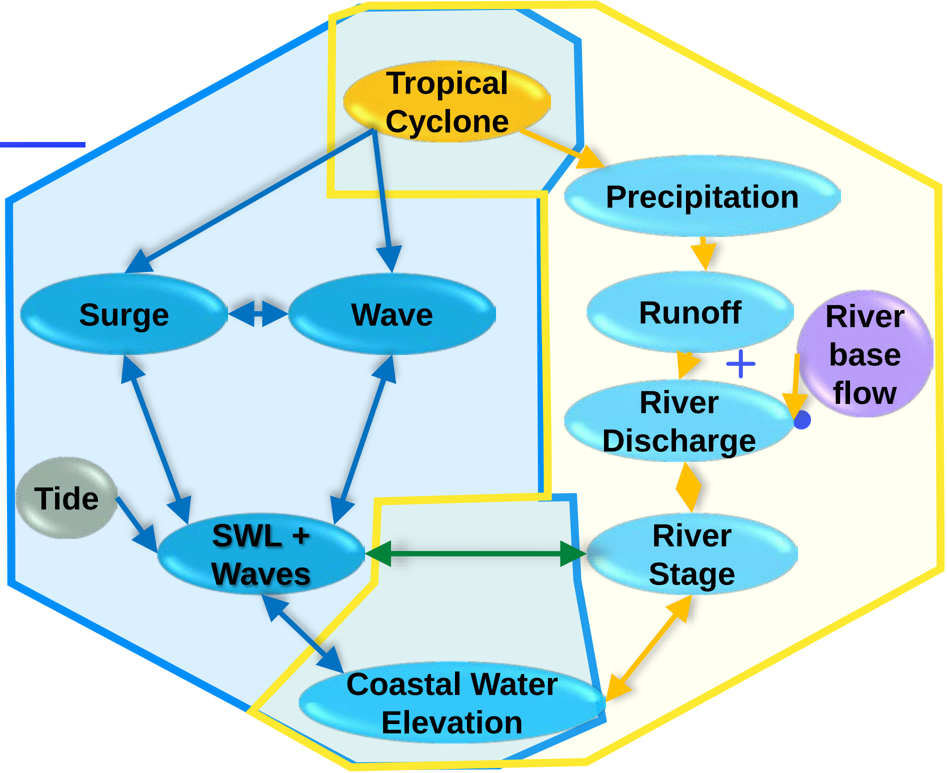
Joint Probability Method (JPM)

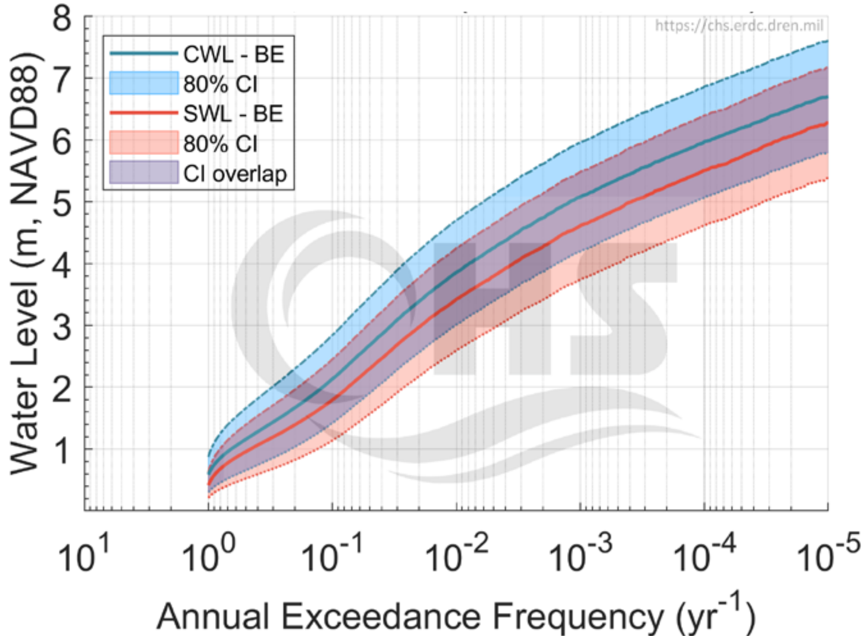
JPM is a probabilistic approach for hurricane/tropical cyclone (TC) storm surge and flood frequency analysis







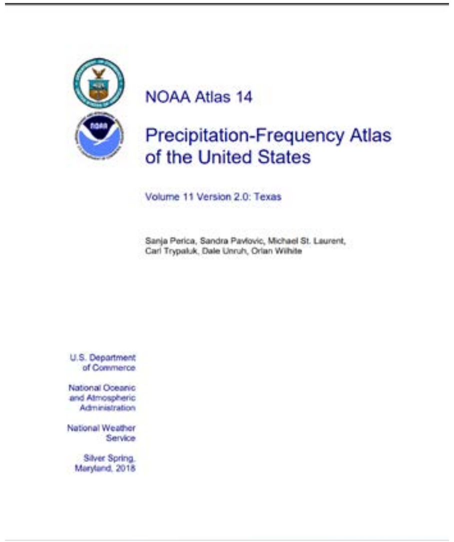




Enhanced JPM approaches are suitable for compound flooding applications.

Linking Statistical and Process Based Models

Common practice for flood hazard assessment is based on **univariate metrics**: analyzes flooding mechanism in isolation.


NOAA Atlas 14

Precipitation-Frequency Atlas of the United States

Volume 11 Version 2.0: Texas

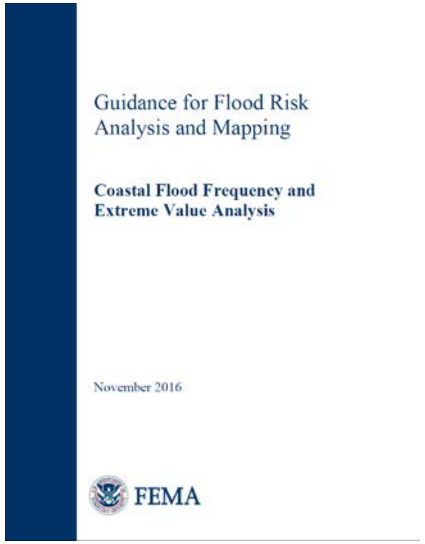
Sanja Perica, Sandra Pavlovic, Michael St. Laurent, Carl Trypaluk, Dale Unruh, Orlan Wilhite

U.S. Department of Commerce

National Oceanic and Atmospheric Administration

National Weather Service

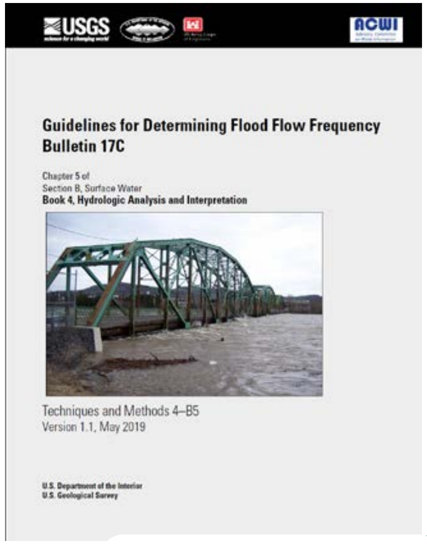
Silver Spring, Maryland, 2018


Guidance for Flood Risk Analysis and Mapping

Coastal Flood Frequency and Extreme Value Analysis

November 2016

FEMA


USGS

ACWI

Guidelines for Determining Flood Flow Frequency Bulletin 17C

Chapter 5 of Section B, Surface Water

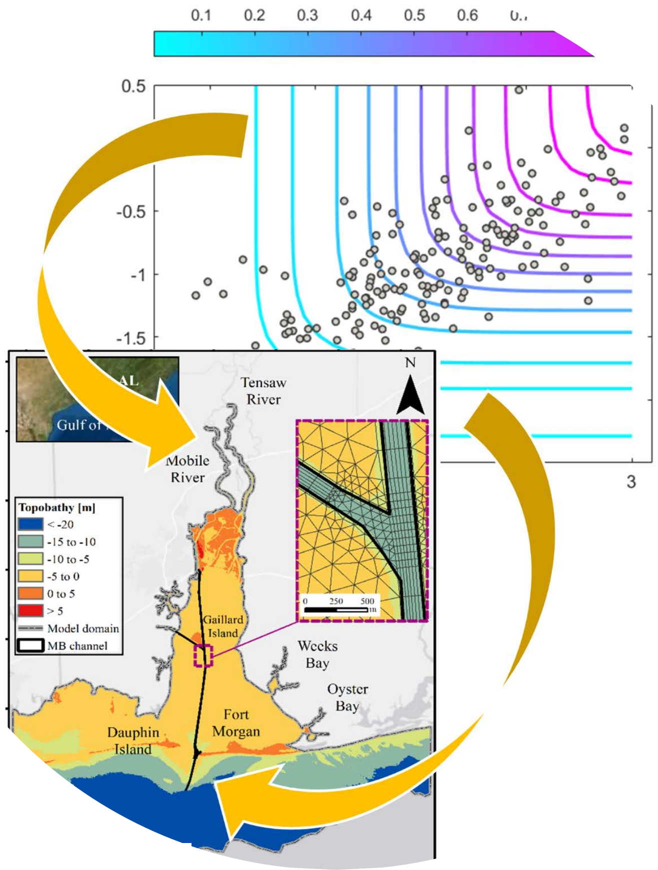
Book 4, Hydrologic Analysis and Interpretation

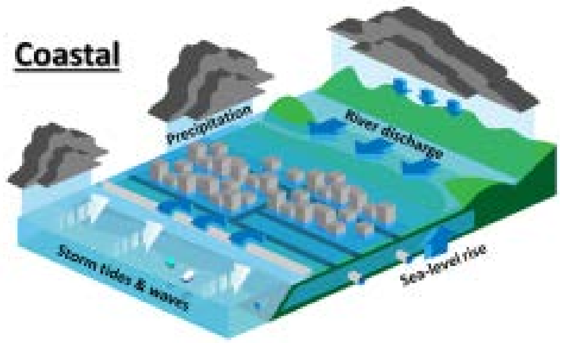
Techniques and Methods 4–B5

Version 1.1, May 2019

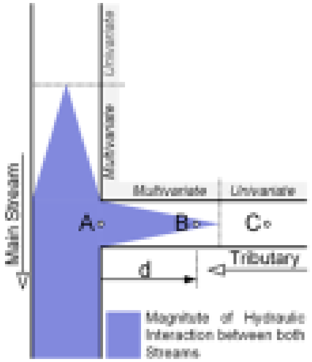
U.S. Department of the Interior

U.S. Geological Survey





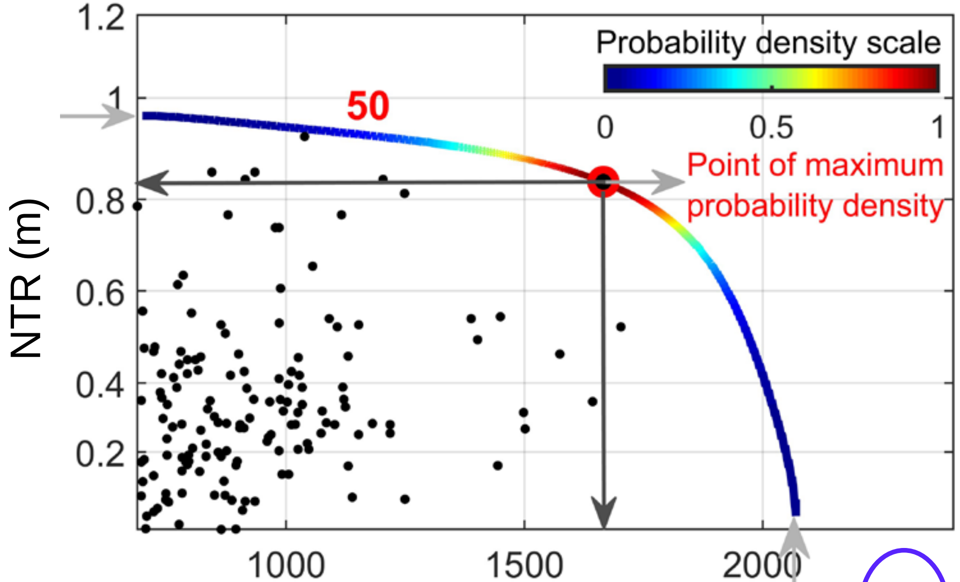
River confluences



Hybrid Approaches to Link Statistical and Processes-based Models

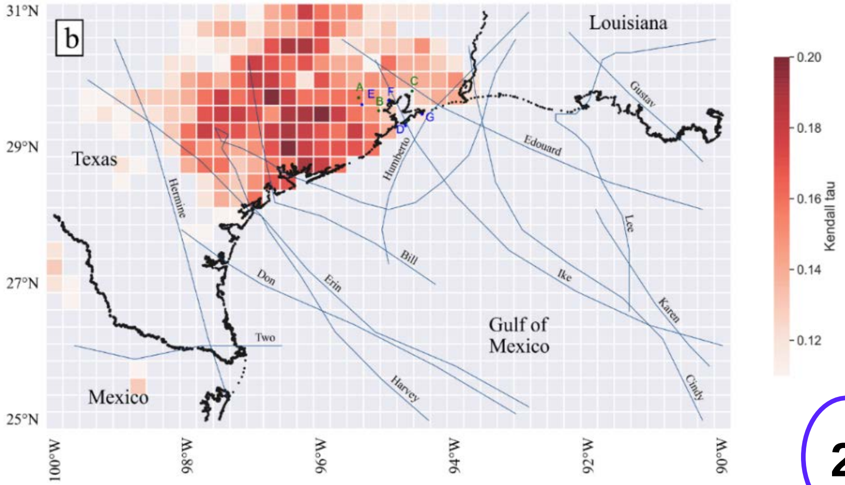
1) Dependence-informed sampling: A method to link bivariate statistical analysis and hydrodynamic modeling for flood hazard estimation in tidal channels and estuaries.

2) Cumulative Likelihood of Potential Impacts (CLPI): Probabilistic scheme that accumulates the potential hazardousness of TCs according to their intensity at a point.



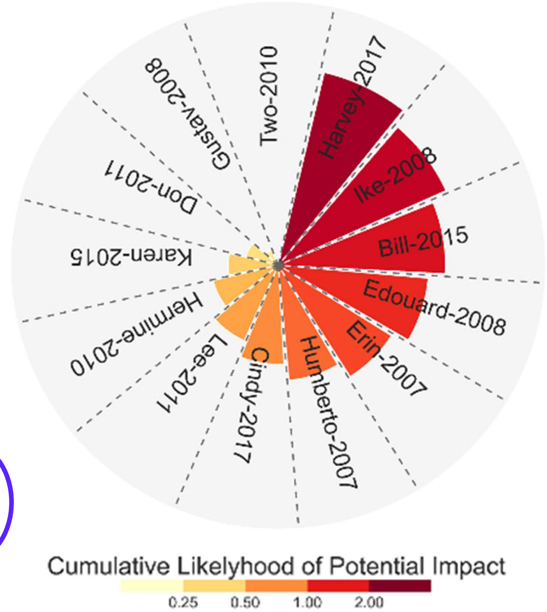
Moftakhari et al., 2019

1

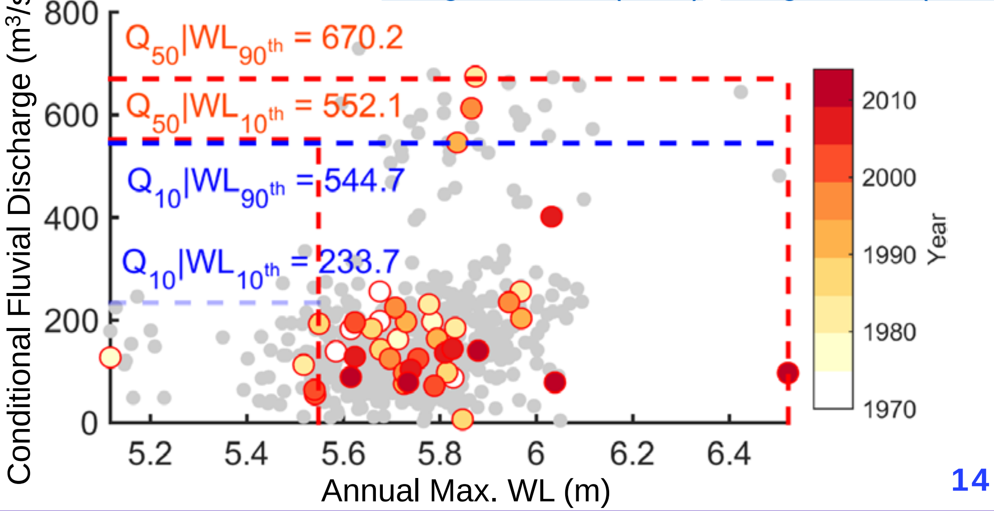


Sohrabi et al., 2023

2



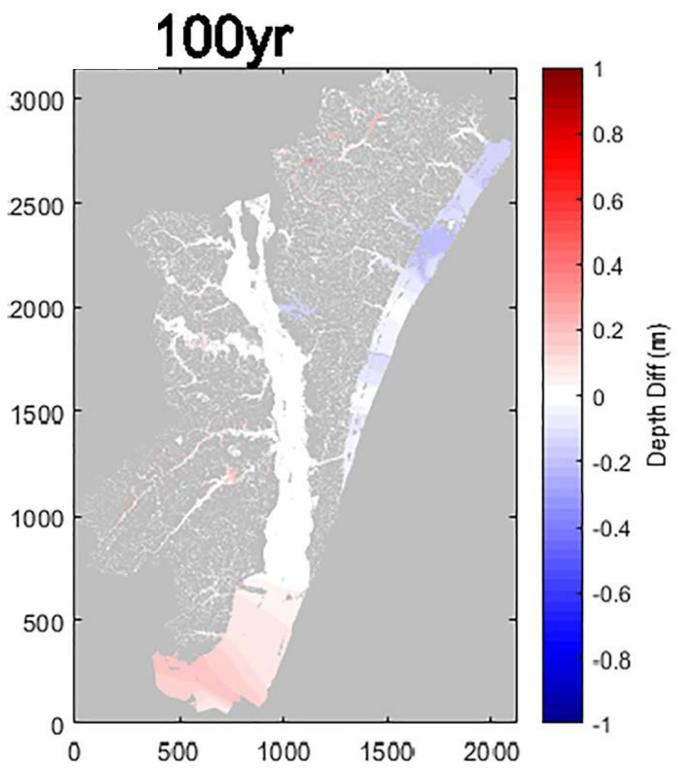
Ganguli & Merz (2019); Ganguli et al. (2020)



Hybrid Approaches to Link Statistical and Processes-based Models

3) Joint Probability Method with Optimal Sampling (JPM-OS): Determining storm surge probability distributions at given coastal location as a function of the TC storm parameters: intensity, size, forward speed, approach angle.

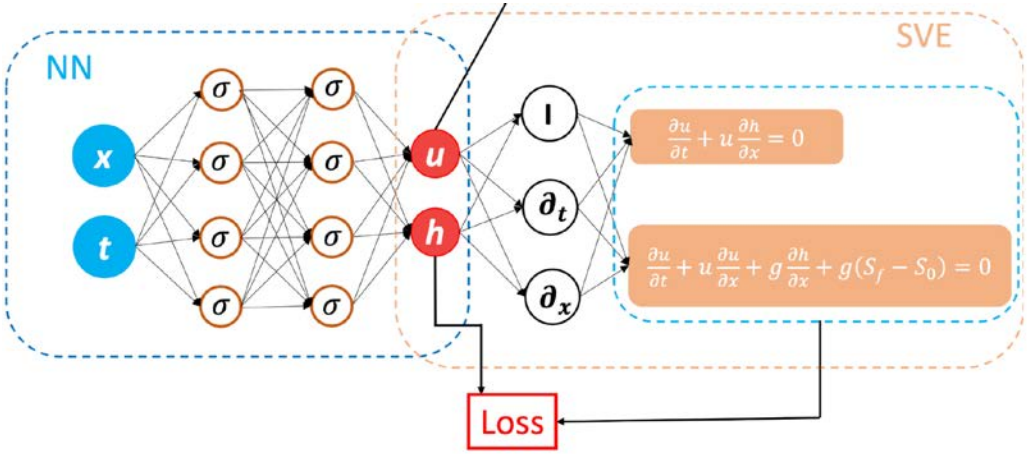
$$P(\eta_{max} > \eta) = \lambda \int \dots \int_{\boldsymbol{x}} f_X(\boldsymbol{x}) * I_{\{\eta_m(\boldsymbol{x})>\eta\}}(\boldsymbol{x}) d\boldsymbol{x}$$



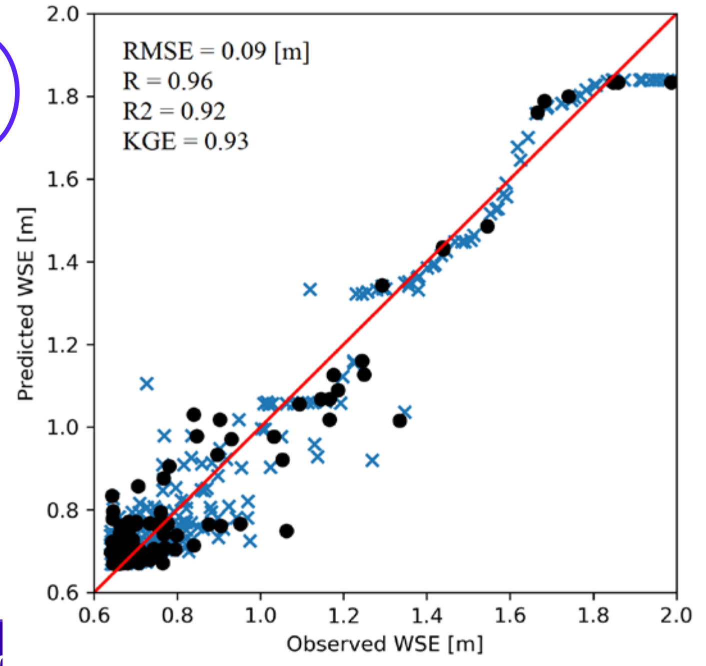
Gori and Lin., 2022

3

4) Physics-informed Machine Learning: ML-based algorithms that seamlessly integrate data and physical models (*e.g.,* 1D Saint-Venant Eqn.).



4



Feng et al., 2023

Nonstationarity in Climate Exacerbates Compound Hazard Potential

- Regional sea level rise and vertical land subsidence + coastal flood driver: storm surge & wave effects + pluvial and fluvial drivers, runoff river flows, rainfall

- Some processes such as Antarctic Ice Sheet melting are not well understood and may represent **deep uncertainty**.

Drivers Contributing Coastal Compound Floods

Source: NOAA, 2022

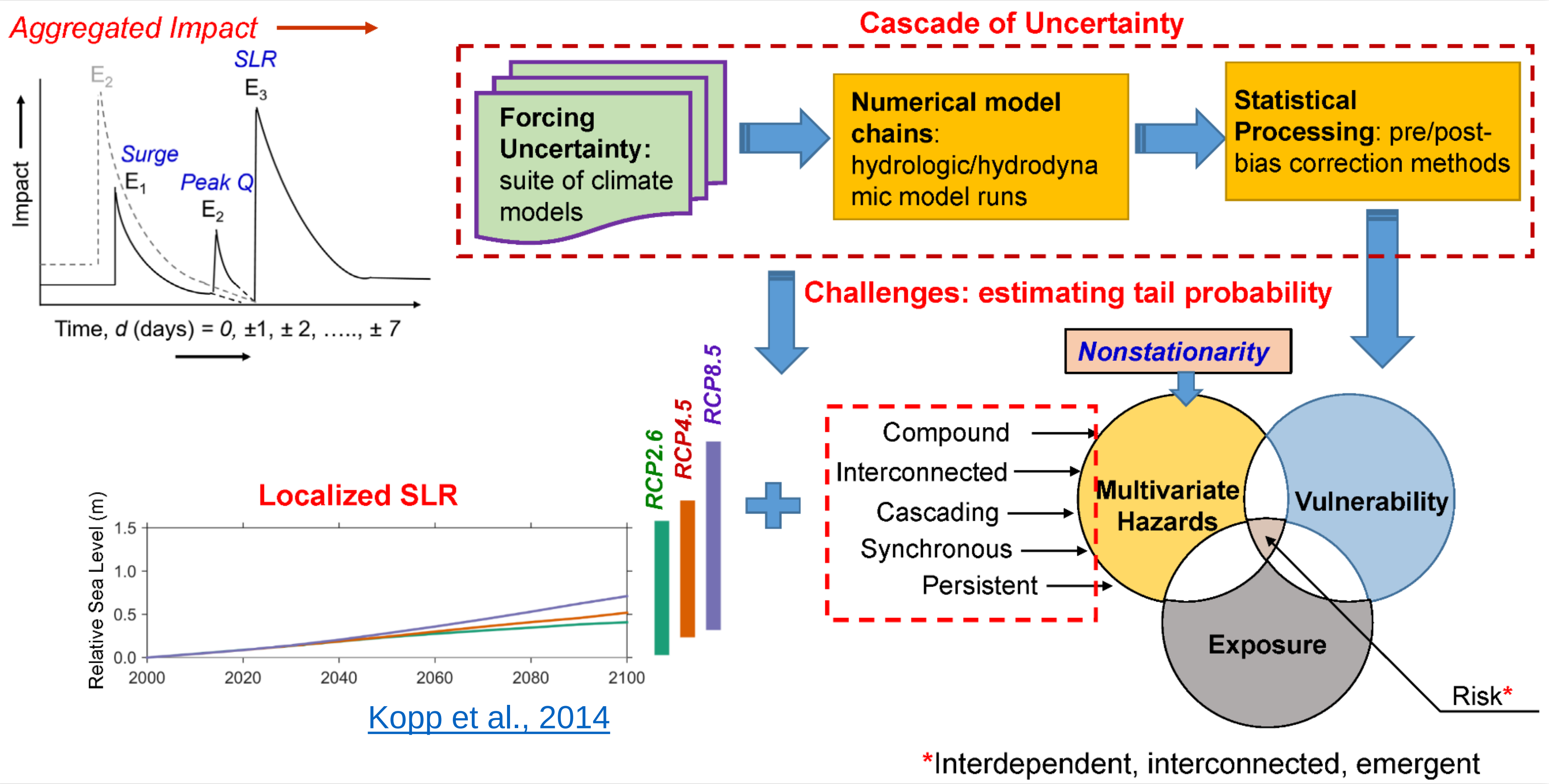
- Heavy precipitation events have the potential to be more intense
  - o Water holding capacity of the atmosphere increases about 7% for each 1º C of temperature rise
- Tropical cyclones may be more intense
  - o Proportion of tropical cyclones that are category 3 or higher has likely increased over the past forty years and will likely increase in the future

↑ Population and coastal development ↑ *impervious areas* and can **change runoff**

Sources of Uncertainty in Projected Trends in Compound Floods

Challenges for Analysis

- Correlation between drivers may be nonstationary
- Standard bias correction and downscaling approaches generally adjust individual variables independently

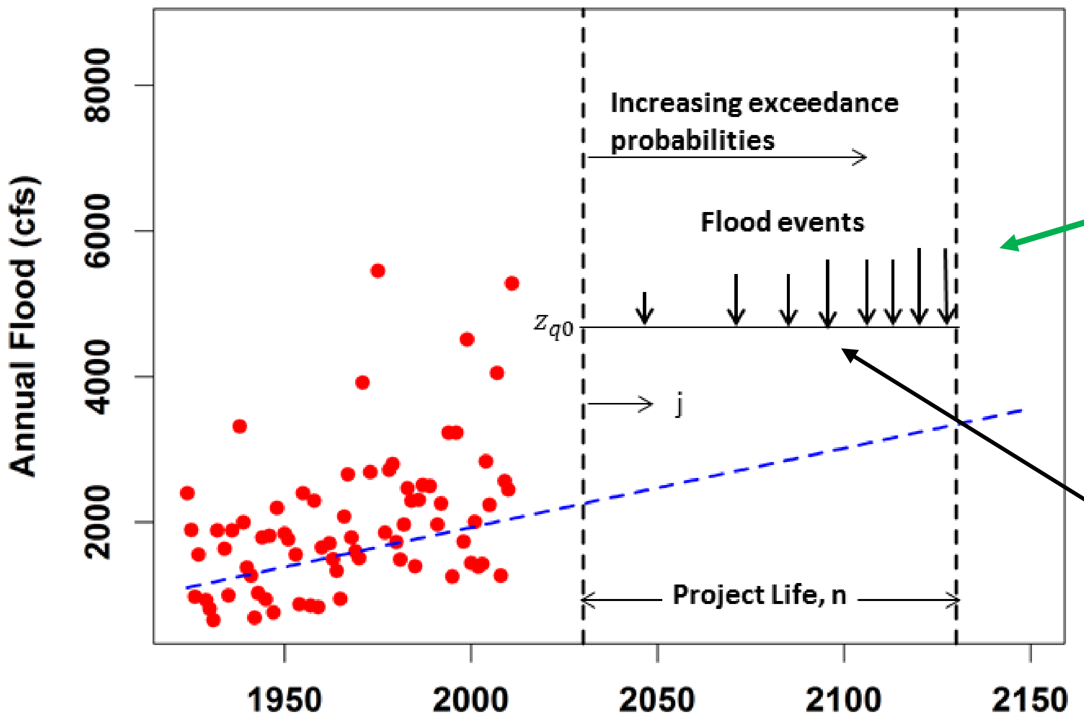


➢ Multivariate bias adjustment, corrects temporal persistence & inter-variable relationships ([Kim et al. 2023](#))

Hydrologic Design Considering Nonstationarity

Expected Waiting Time

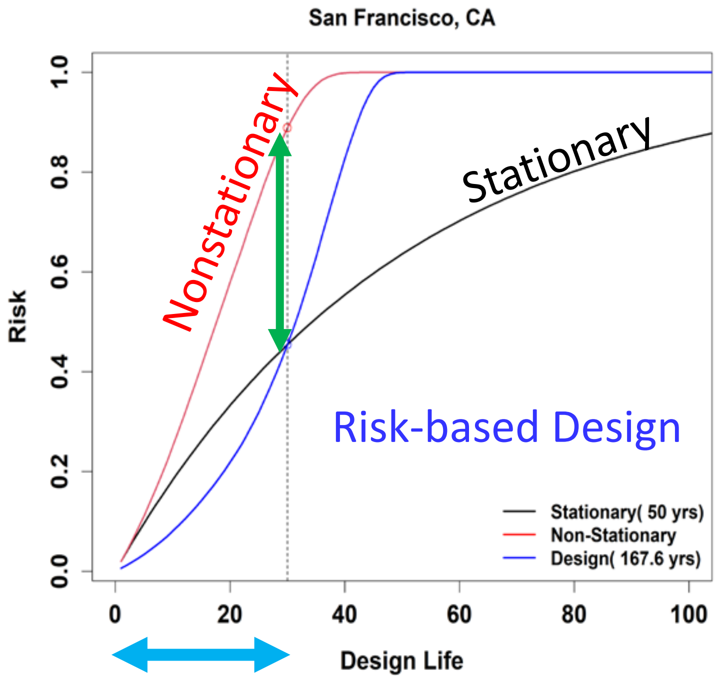
$$T = E[X] = 1 + \sum_{x=1}^{\infty} \prod_{t=1}^{x} (1 - p_t)$$



Risk-Based Design

$$R = 1 - \prod_{t=1}^{n} (1 - p_t)$$

Recurrent Flood Frequency



$$R = \int_{-\infty}^{\infty} V(z)\, C(z)\, f_Z(z)\, dz$$

Vulnerability Damage Probability


Hydrological Sciences Journal

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Techniques for assessing water infrastructure for nonstationary extreme events: a review

J. D. Salas, J. Obeysekera & R. M. Vogel

Revisiting the Concepts of Return Period and Risk for Nonstationary Hydrologic Extreme Events

Jose D. Salas, M.ASCE[1]; and Jayantha Obeysekera, M.ASCE[2]

Gateway of India during cyclone Tauktae in Mumbai, May, 2021 (HT Times, 2021).

Thank You!

Any questions?

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