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A non-stationary, risk-based approach for determining design flood elevations under sea-level rise

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Facility elevation choice is a critical flood-relevant decision

Bolivar Peninsula, Texas (FEMA/Greg Henshall)

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Conventional approaches for selecting the design flood elevation

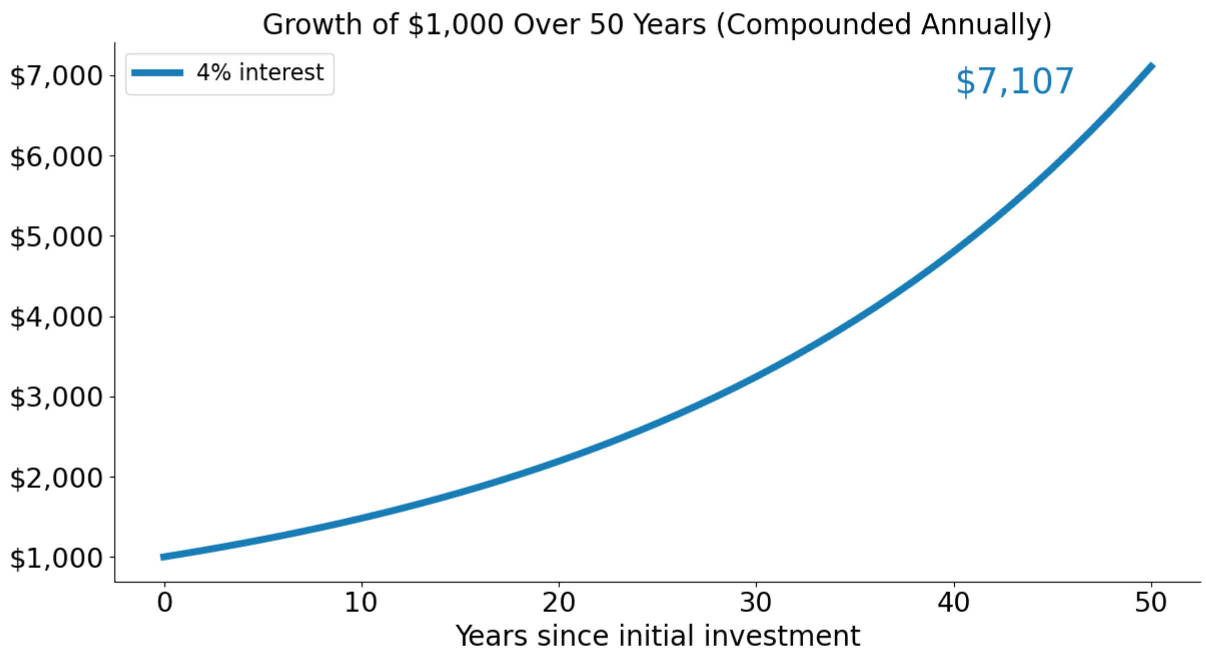
- Using the locally defined Base Flood Elevation (BFE) in Special Flood Hazard Areas (SFHA)
  - e.g., flood elevation with 1% annual exceedance probability (AEP)
  - Usually with an additional safety buffer ("freeboard")
- Prescribed by the local authority having jurisdiction
- Federal Flood Risk Management Standard (FFRMS)
- ASCE/SEI 7-22 Flood Supplement (released May 2023)

Areas for improvement in selecting design flood elevation

1. Stakeholders may a desire a higher level of protection
   - Canonical design standards (e.g., the "100-yr event") may not be desirable in the context of a long-lived facility
     - e.g., for facilities supplying essential services, such as hospitals

2. Account for changing hazard frequency (hazard "non-stationarity")
   - Facilities can have very long lifetimes (half century or more)
   - No longer a 1:1 relationship between return level and return period. For example, 6 ft of coastal flooding in 2000 may have a 1% AEP, but in 2050 will have a different AEP

Consider the growth of $1000 at 4% interest…



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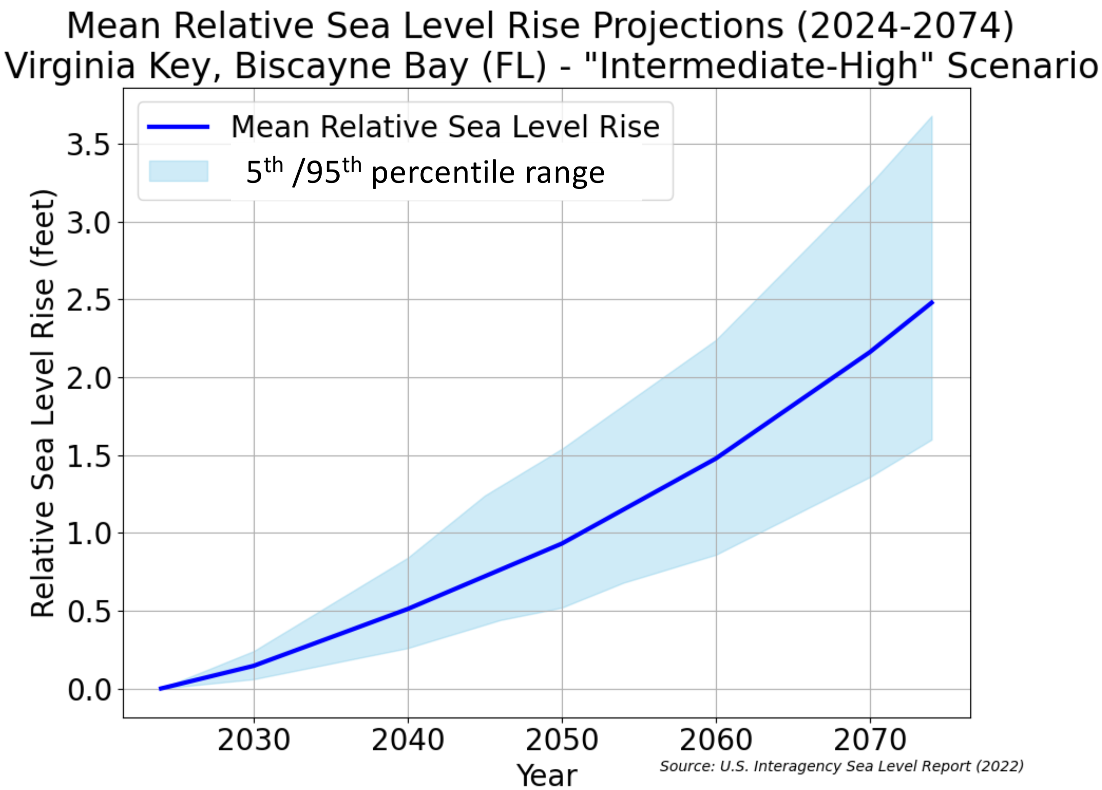
Over a long time horizon, “rare events” are likely to occur…

- Assume independent, potential events each having an AEP (*p*). Over *N* years, what is the probability of at least one of them occurring and leading to failure (*R*)?
- $R = 1 - (1-p)^N$ "Risk of failure" equation (common engineering practice; USGS “Bulletin 17B”; ect.)
- Consider an AEP of 1% per year; $1 - (1 - \frac{1}{100}))^{50} = 0.395$
- So, “100-yr event” has a about a 2-in-5 chance of being exceeded over a period of 50 years!

Increasing probabilities of hazards can significantly impact the likelihood of at least one exceedance over the design life (e.g., coastal flood)



- Rising mean sea levels raise the baseline from which historical floods have occurred
- For example, 1.6 ft to 3.6 ft of local sea-level rise in South Florida occurring over 50 years

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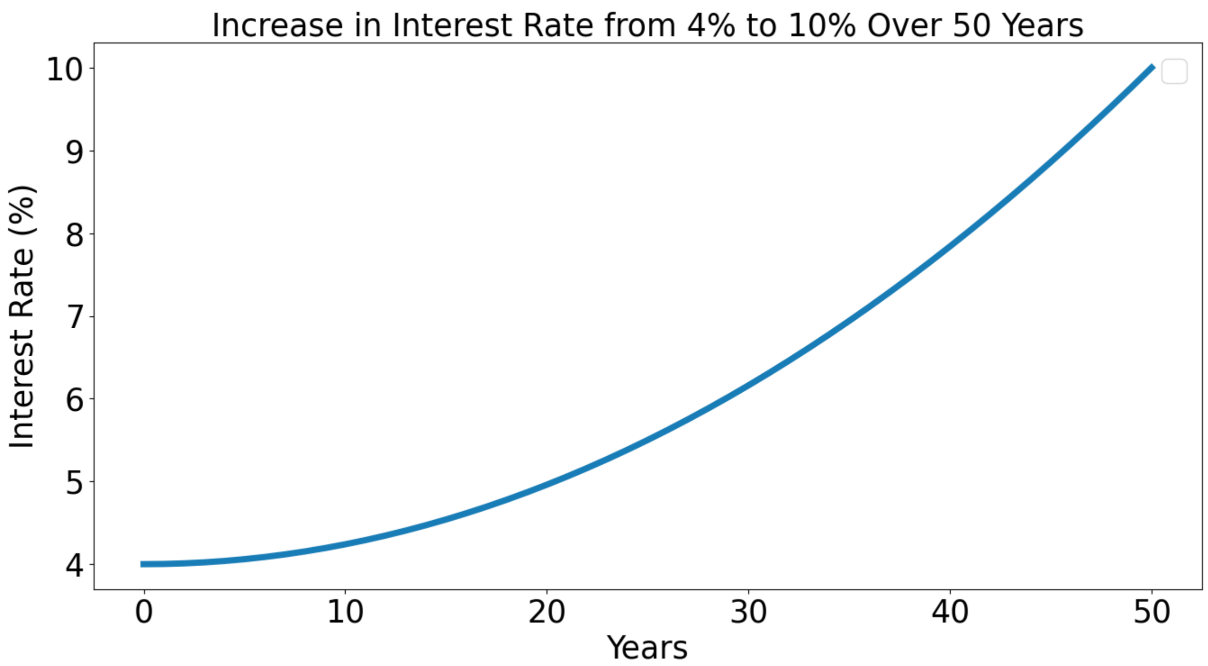
What if the interest rate grows from 4% to 10% over the 50-year time period?



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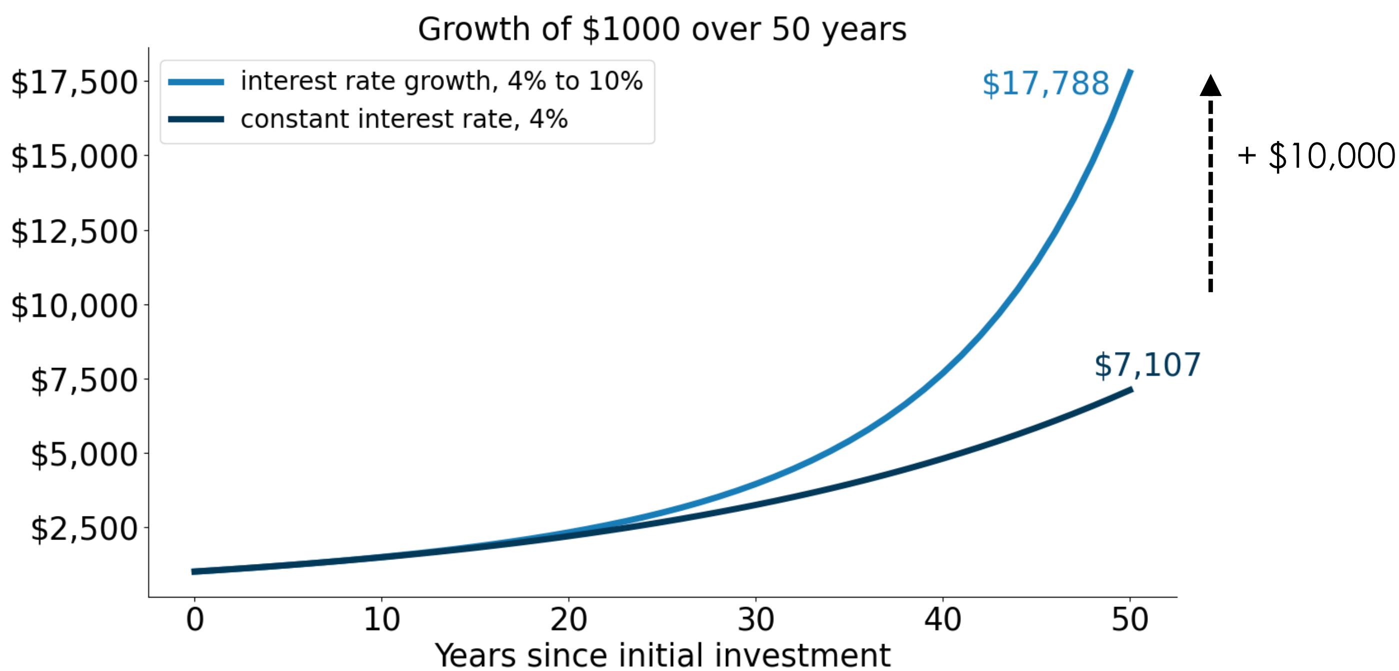
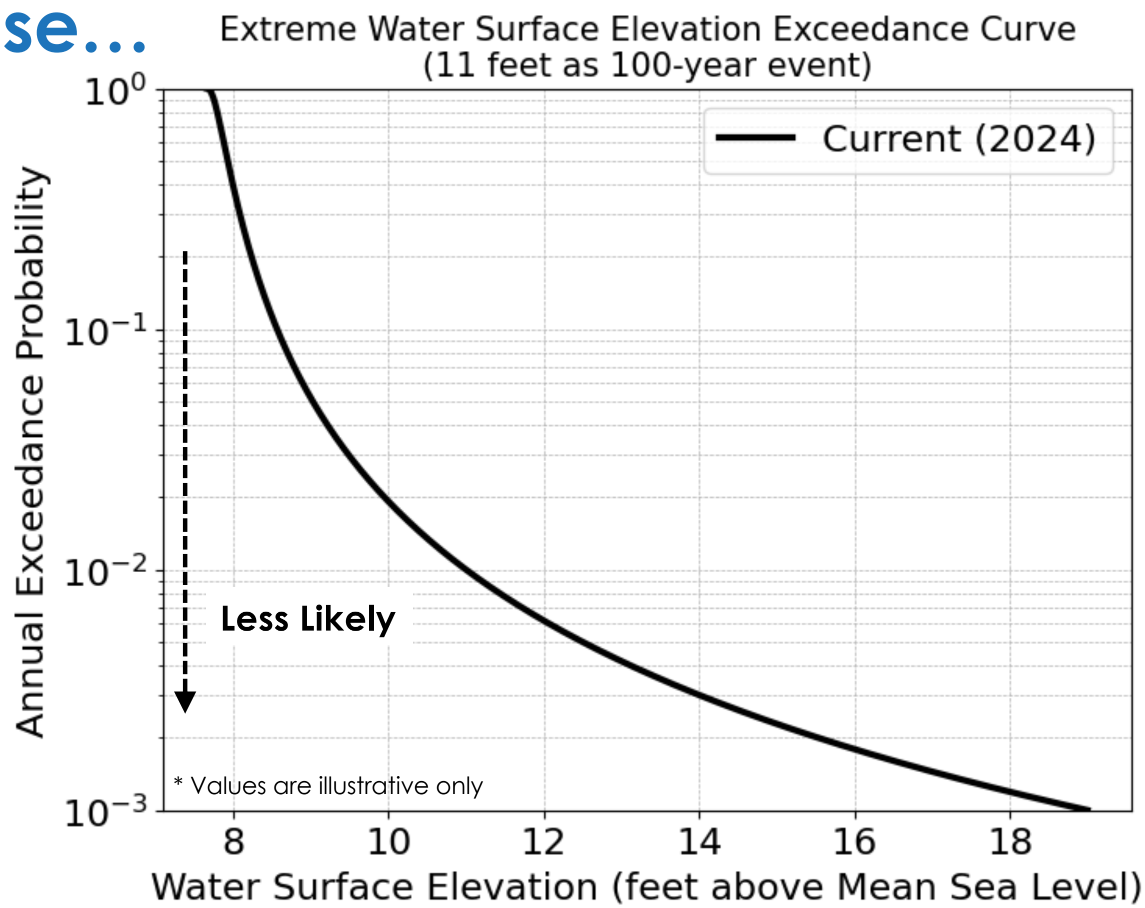
The initial investment of $1,000 grows to nearly $18,000!



As sea-levels rise, annual exceedance probabilities increase…

Notes:

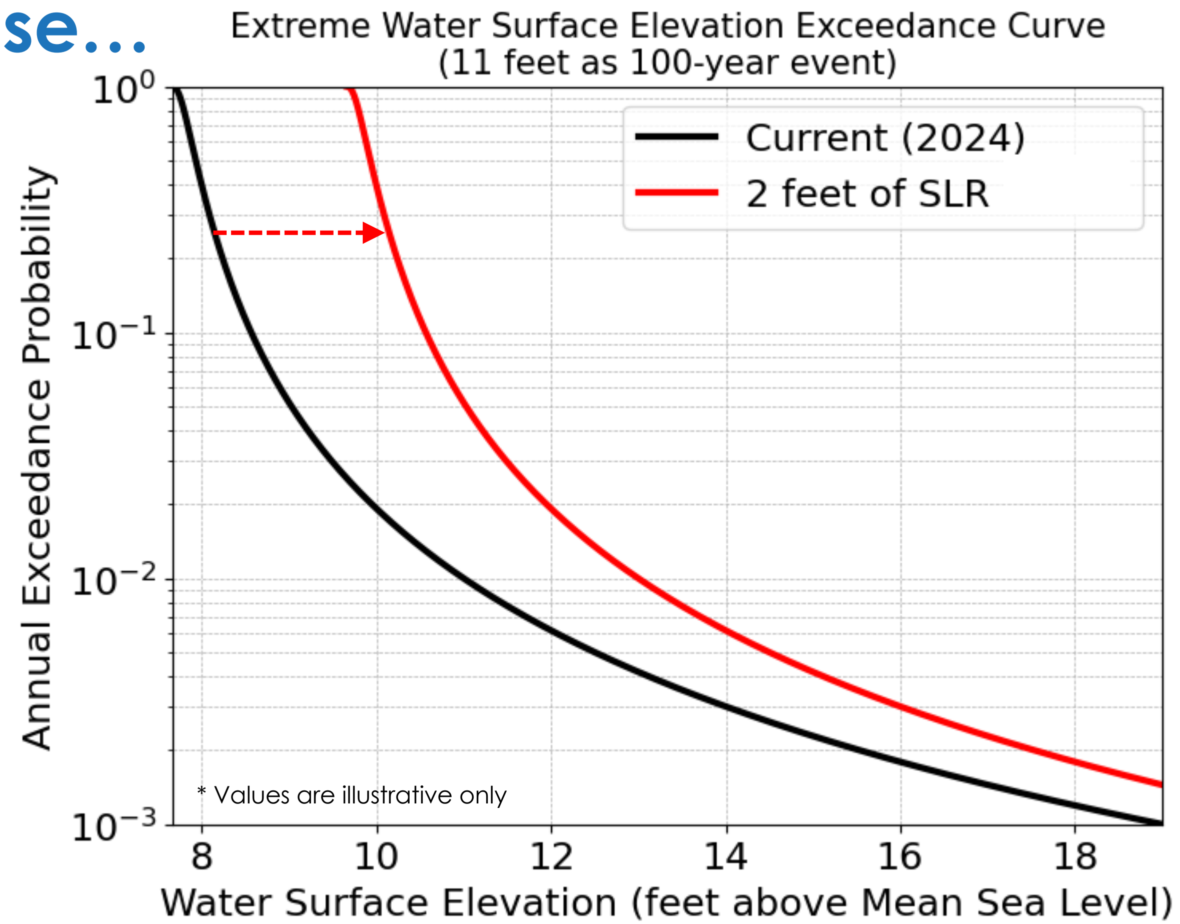
- 1/AEP is the return period, or average waiting time between events



As sea-levels rise, annual exceedance probabilities increase…

Notes:

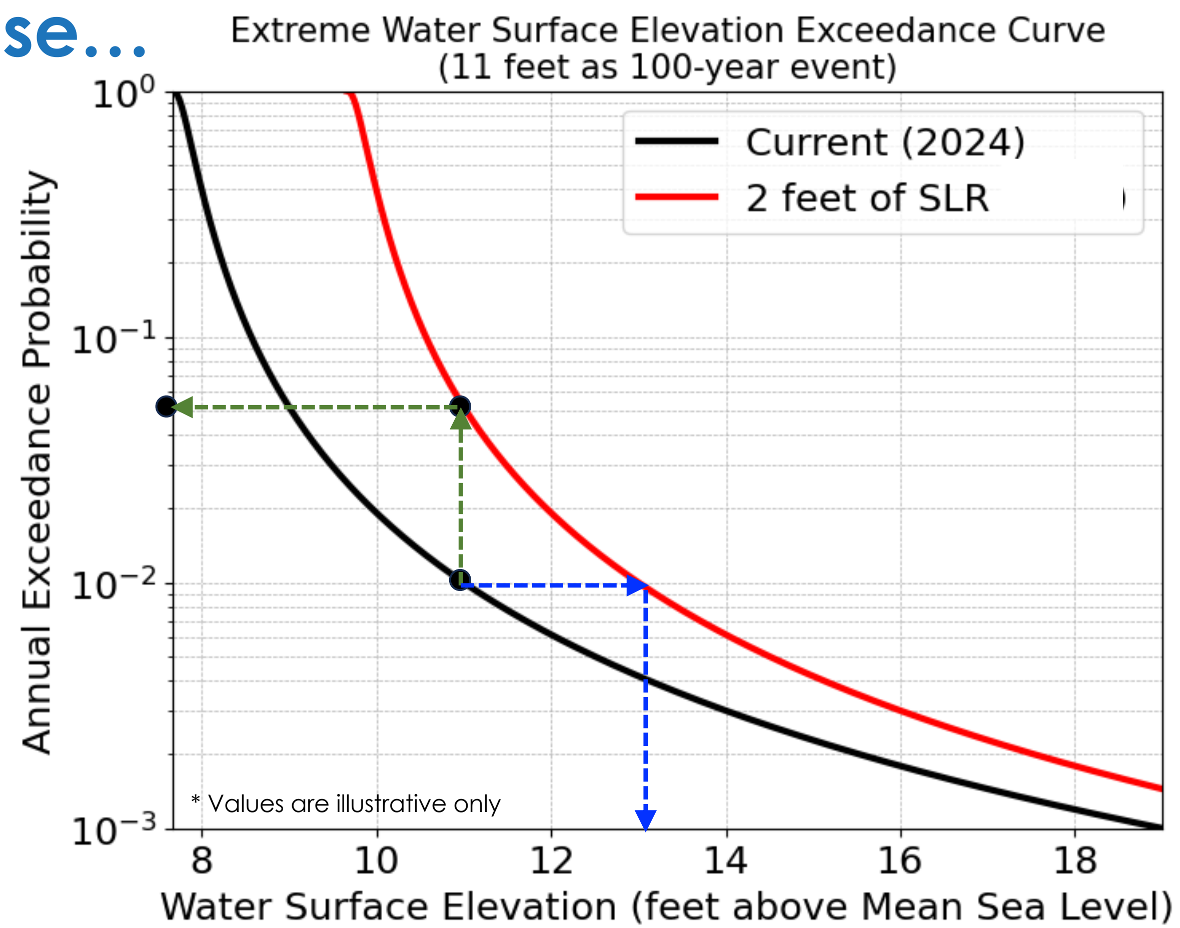
- Sea-level rise increases the frequency of all water surface elevations…



As sea-levels rise, annual exceedance probabilities increase…

Notes:

- The current 1% AEP event increase from 11 ft to 13 ft
- The current 1% AEP water surface elevation become the 6% AEP event (6x more frequent)



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Facilities may underperform if stakeholder risk tolerance and changing hazard conditions are not incorporated

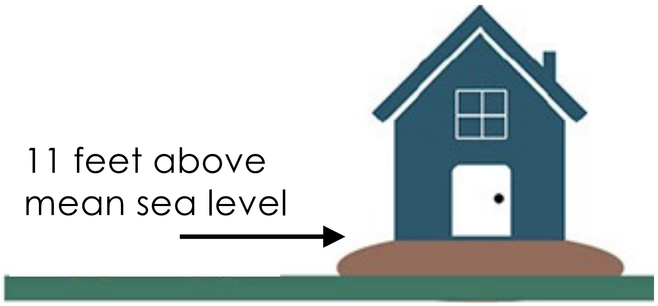
"Risk of failure" equation under non-stationarity (Salas and Obeysekera, 2014; Cooley, 2013; Wigley, 2009)…

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

Where, R is the "risk of failure", N = facility design life in years, p_t is the AEP of the water surface elevation in year t that increases over time

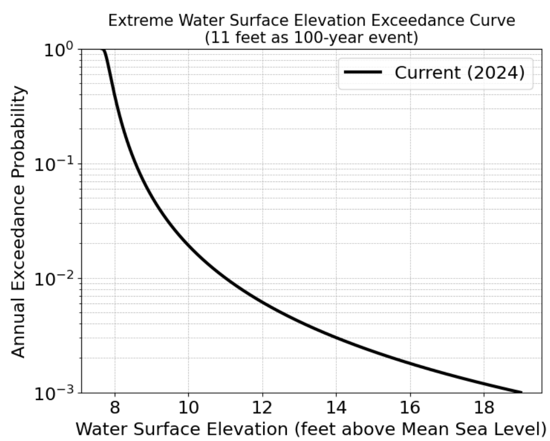
Let’s illustrate the equation with a hypothetical example…

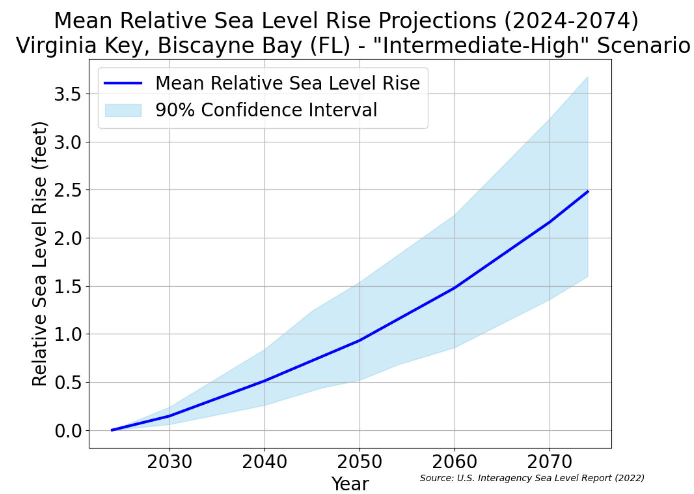
- Consider a water surface elevation of **11 feet** above mean sea-level (the chosen facility elevation) that *currently* has a **1% AEP**
  - Facility has a 50-year design life
  - Assume sea-level rise of 2 feet over 50 years



What is the probability of at least one exceedance of 11 feet over this facility lifetime?

1. Historical water surface elevation return curve





2. Sea-level rise over time

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

3. "Risk of failure" equation

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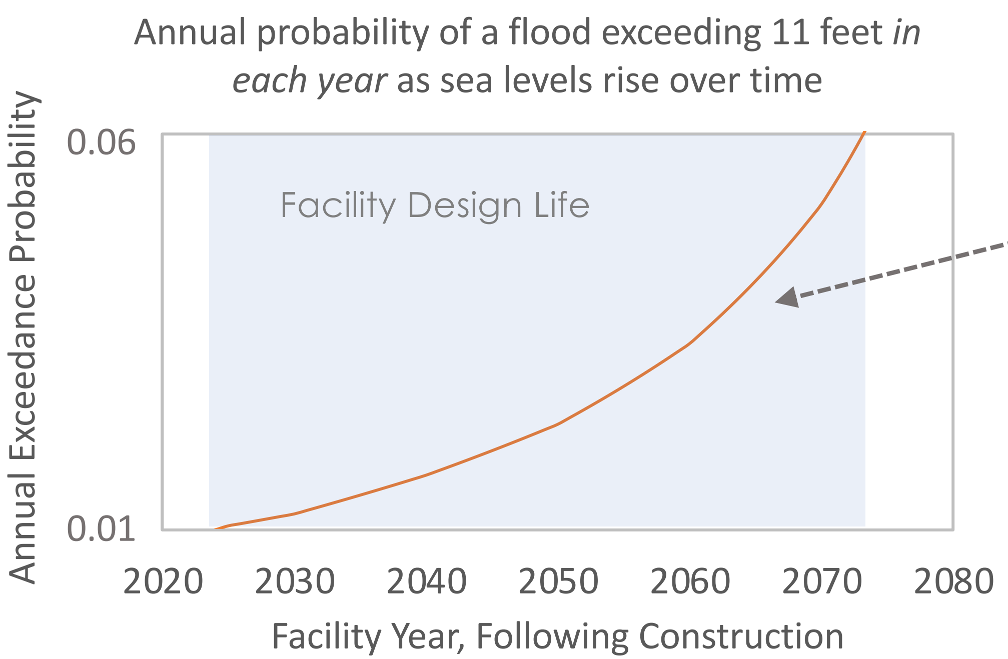
Using the "risk of failure" equation, there is roughly a 7-in-10 chance that a flood will exceed the 11 ft facility elevation over the 50-year design life!



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

values of p_t

- Multiple alternative facility elevations could be assessed to understand the "risk of failure"

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Example Application: Transit Operations and Bus Maintenance Facility in South Florida

- New construction, 50-year life (ending in 2070s)
- Plan to store 100 electric busses during a hurricane
- Developed a menu of “risk of failure” probabilities for the facility over its intended useful life
  - Client selected a design elevation that met their desired risk tolerance

Approach

- For multiple plausible facility design elevations, estimate the probability of at least one exceedance over the facility design life

Multiple plausible design elevations

Facility Design Elevation (feet above MSL)	**Annual Exceedence Probability (AEP) of Design Elevation**		**Probability of at least one flood over 50 years**
	2024	**2074**	
11 ft	1%		
13 ft	0.4%		
14 ft	0.3%		
15 ft	0.2%		

Determine this information…

* To ensure client confidentiality, values are illustrative only

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Approach

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Determine this information…

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- For each facility design elevation, determine the AEP of over time under a single sea-level rise curve
- Use non-stationary "risk of failure" equation to get probability of flooding at least once over 50-yr facility lifespan

Data sources

- Storm surge modeling from USACE South Atlantic Coastal Study (SACS)
  - Still water surface elevations (several return periods)
    - Neglected wave action and erosion (facility was inland)
  - One sea-level rise scenario
    - 2.7 ft of local sea-level rise (incl. non-linear interactions)
- Local sea-level rise projections (U.S. Government Interagency Report, 2022)
  - Projections from nearest tide gauge (Virginia Key/Biscayne Bay, Florida)
  - "Intermediate-High" scenario (4.9 ft of global mean sea-level rise by 2100)

Results

Facility Design Elevation (feet above MSL)	Annual Exceedence Probability (AEP) of Design Elevation		Probability of at least one flood over 50 years
	2024	2074 (2.7 ft of SLR)	
11 ft	1%	11.0%	77%
13 ft	0.4%	1.3%	29%
14 ft	0.3%	0.8%	20%
15 ft	0.2%	0.5%	15%

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- Client subsequently selected a facility floor elevation from the table, weight risk tolerance with additional costs

Results

Facility Design Elevation (feet above MSL)	Annual Exceedence Probability (AEP) of Design Elevation		Probability of at least one flood over 50 years
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Chosen design elevation

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- Client subsequently selected a facility floor elevation from the table, weight risk tolerance with additional costs

Summary

- Canonical flood return periods used for design can have a noteworthy likelihood of exceedance over a long lifetime (e.g., designing to the current 1% AEP)
  - Stakeholders may desire a higher level of protection
- Existing non-stationary engineering tools facilitate estimates of "risk of failure" over the facility design life
- Tabulating alternative risk levels facilitates more informed design flood elevation selection for stakeholders

Other opportunities

- Consideration of uncertainty in flood frequency and sea-level rise
  - Only consider 2.7 ft of sea-level rise, but other amounts possible
  - Sea-level rise allowances frameworks set design flood elevation and incorporate uncertainty in the timing of sea-level rise and in the frequency of water surface elevations (e.g., Hunter, 2012; Buchanan et al., 2016)

Other opportunities

- Account for the impact of a flood events (what gets wet and what are the associated consequences?)
  - E.g., employing flood vulnerability/fragility functions to link flood depth to damage

- Other flood sources
  - e.g., consideration of local stormwater flooding

Summary

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