Return Period Economics:

The Impact of Sea Level Rise

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Disclaimer

- This presentation is my personal research
- Information presented here is not an official position of the U.S. Navy

The Road Ahead

- What is return period and how is it used?
- How is it calculated?
- Does sea level rise affect return period?
- How does this change the probability of flooding?
- What is the economic impact?

Source: UK DailyMail.com

What is return period?

- What is return period? How is it used?
- How is return period calculated?
- Does sea level rise affect return period?
- How does this change the probability of flooding?
- What is the economic impact?

"I knew you wouldn't miss the 50-Year Storm, Bodhi."

Source: Point Break (1991)

- What is return period? How is it used?
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What is return period?

- Return Period, T_r , is "the average time interval between successive events of the design wave being equaled or exceeded." (from USACE Coastal Engineering Manual)

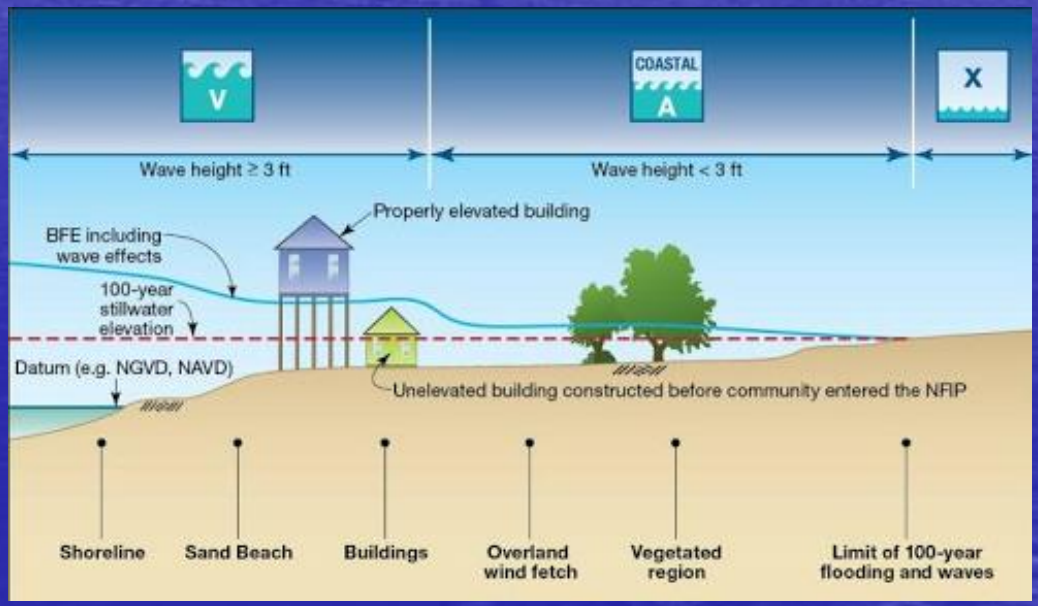
- E.g. For T_r = 100 yr → 100 year wave height, S_{100}, is equaled or exceeded, on average, once every 100 years

- In any given year, $P_{occurrence} = 1 / T_r$
  - T_r = 500 yr → P = 1/500 = 0.002 each year
  - T_r = 100 yr → P = 1/100 = 0.01 each year
  - T_r = 50 yr → P = 1/50 = 0.02 each year
  - T_r = 20 yr → P = 1/20 = 0.05 each year

How is return period used?

- What is return period? How is it used?
- How is return period calculated?
- Does sea level rise affect return period?
- How does this change the probability of flooding?
- What is the economic impact?

- T_r is often used to set the Base Flood Elevation (BFE)
  - Coastal Construction Control Line (CCCL)
  - Construction
  - Insurance
  - Land use policy
  - Other industries.



Source: FEMA (2015)

How is return period calculated?

- What is return period? How is it used?
- How is return period calculated?
- Does sea level rise affect return period?
- How does this change the probability of flooding?
- What is the economic impact?

- Historical water level data
- Annual maximums or events above threshold
- Rank order events
- Period of each event is

  T_r = Rank Order / # Years of Data
- Fit data set (period vs. height) to a best fit curve
  - Semi-Log relationship
    - Height = Normal; Period = Log
  - Weibull 2 Parameter
  - Weibull 3 Parameter
- Best fit curve used to predict return period heights

Annapolis, MD
82 Years of Data

Detrended Ranked Storm Tide (ft from MSL)	Rank Order	Tr (years)
6.31	1	82
6.12	2	41
4.67	3	27
4.48	4	20
4.07	5	16
3.98	6	14
3.96	7	12
3.91	8	10
3.89	9	9
3.77	10	8
3.72	11	7
3.31	12	7
3.20	13	6
3.18	14	6
3.12	15	5
3.08	16	5
2.91	17	5

How is return period calculated? – Best Fit Curve

- What is return period? How is it used?
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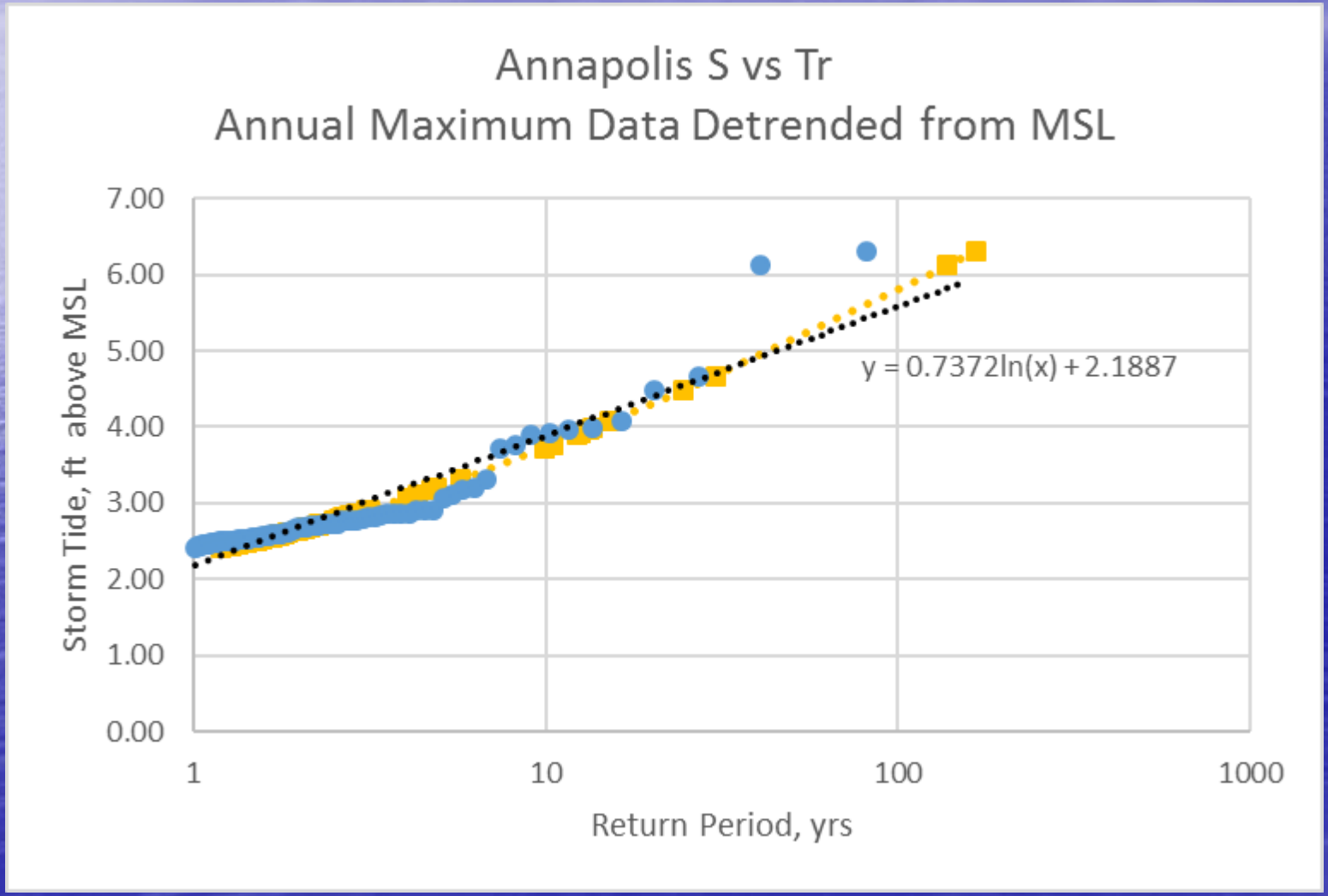

How is return period calculated? – Encounter Probability

- What is return period? How is it used?
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- Does sea level rise affect return period?
- How does this change the probability of flooding?
- What is the economic impact?

- Encounter Probability, P_E – the probability of experiencing a given extreme event within a given time period, L

- Traditional Calculation of P_E assumes that the annual probability of exceeding a flood height, $P = 1/T_r$, stays the same from year to year

$$P_E = 1 - (1 - P)^L$$

- E.g. for T_r = 100 yr and L = 50 yr

$P_{Tr=100yr,\ L=50yr} = 1 - (1 - 0.01)^{50} = 0.395$

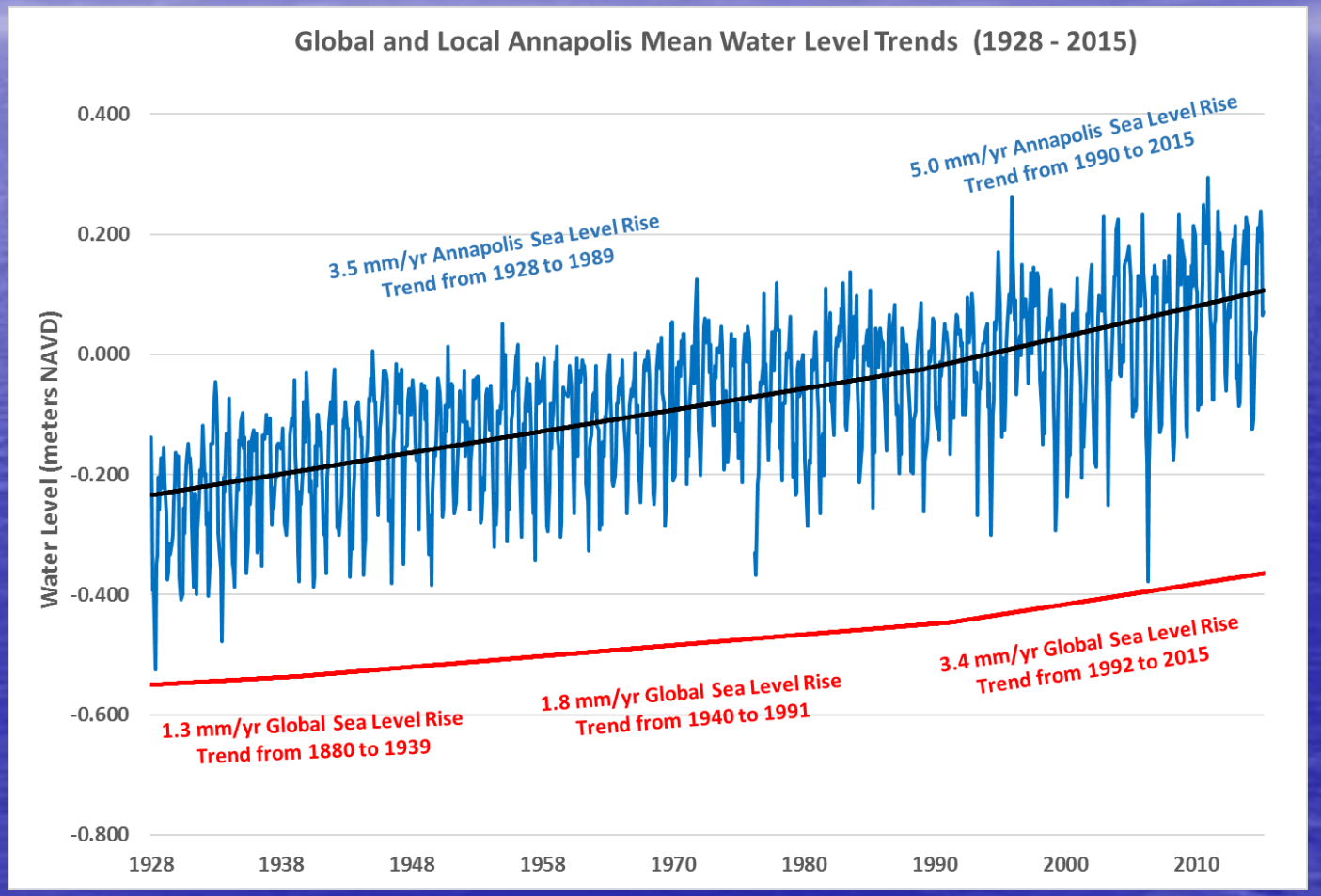
Tr = Return Period = 100 years

Year	P	(1 - P)	Encounter Probability
1	0.01	0.99	0.0100
2	0.01	0.99	0.0199
3	0.01	0.99	0.0297
4	0.01	0.99	0.0394
5	0.01	0.99	0.0490
6	0.01	0.99	0.0585
7	0.01	0.99	0.0679
8	0.01	0.99	0.0773
9	0.01	0.99	0.0865
10	0.01	0.99	0.0956
11	0.01	0.99	0.1047
12	0.01	0.99	0.1136
13	0.01	0.99	0.1225
14	0.01	0.99	0.1313
15	0.01	0.99	0.1399
16	0.01	0.99	0.1485
17	0.01	0.99	0.1571
18	0.01	0.99	0.1655
19	0.01	0.99	0.1738
20	0.01	0.99	0.1821

Does sea level rise affect return period?

- What is return period? How is it used?
- How is return period calculated?
- Does sea level rise affect return period?
- How does this change the probability of flooding?
- What is the economic impact?

- Global Sea Level Rise
  - 1.7 mm/yr since 1900
  - 3.4 mm/yr since 1992
- Local Sea Level Rise in Annapolis
  - 3.6 mm/yr since 1928
  - 5.0 mm/yr since 1990



Sources: Adapted from National Climate Assessment (2014), Church & White (2011), NOAA tidesandcurrents.noaa.gov

Does sea level rise affect return period? – Max Water Level

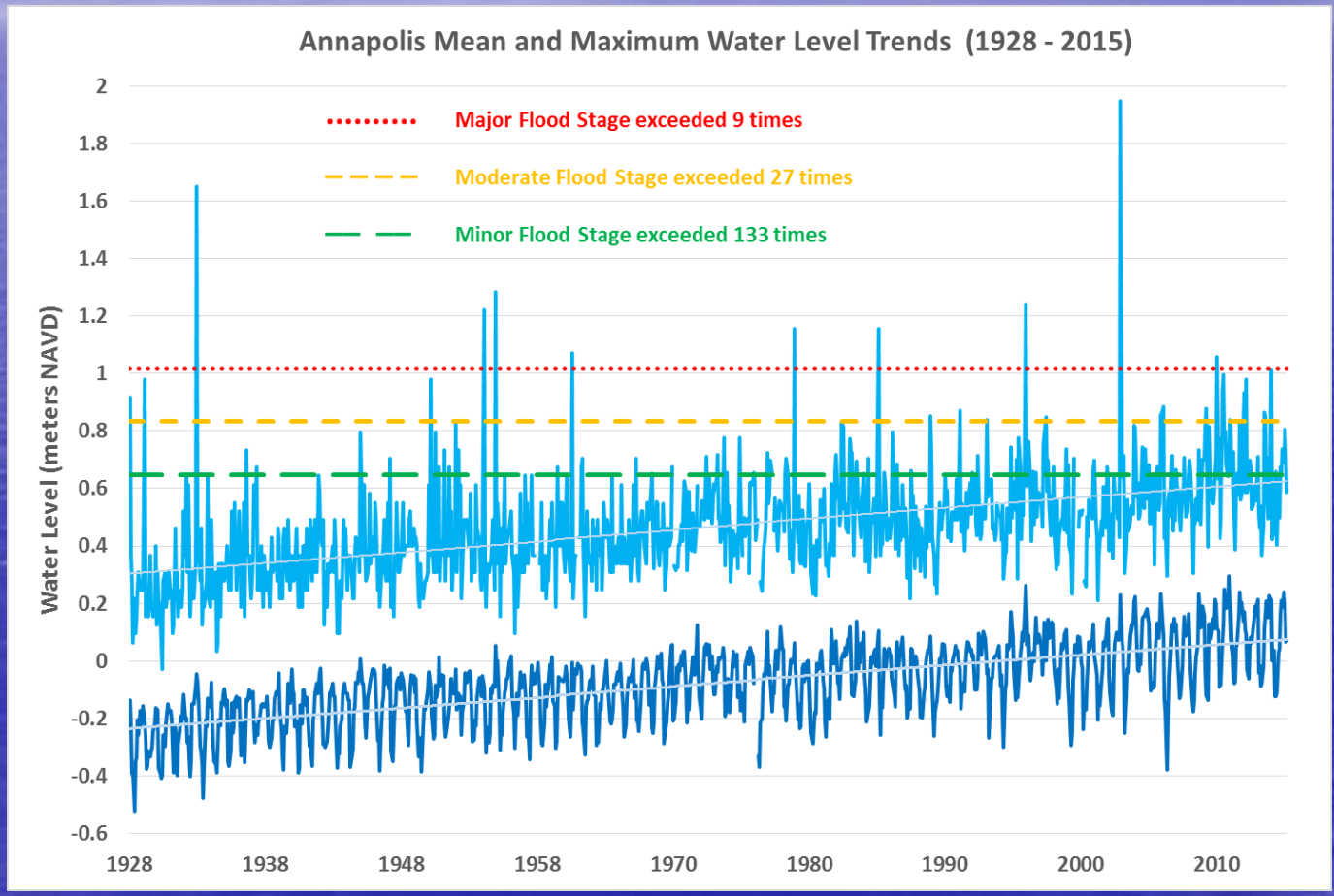
- What is return period? How is it used?
- How is return period calculated?
- Does sea level rise affect return period?
- How does this change the probability of flooding?
- What is the economic impact?

- Maximum flood heights have same trend as mean sea level
- 240 mm of Global Sea Level Rise Since 1880

≈1/3 in First 6 Decades

≈1/3 in Next 5 Decades

≈1/3 in Last 2.5 Decades

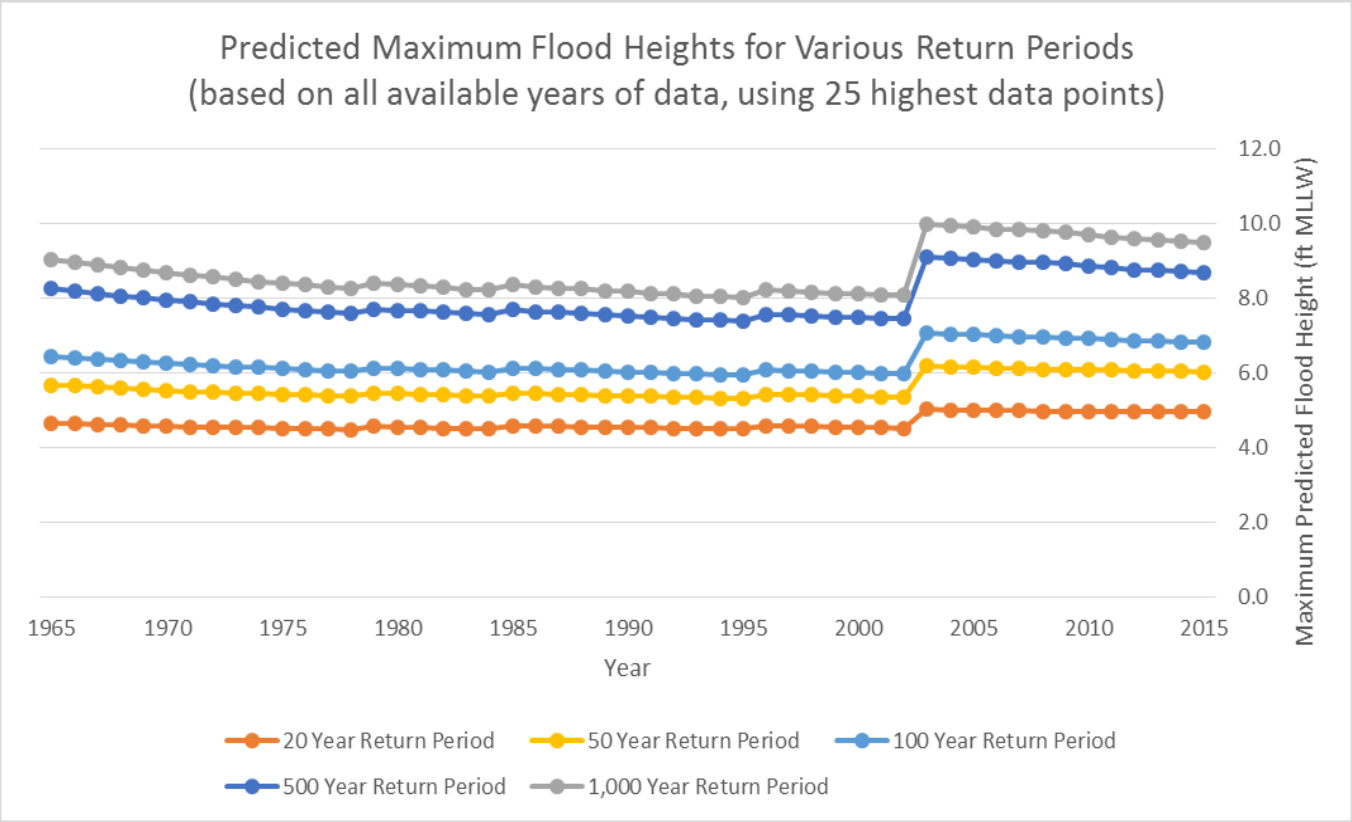


Sources: Adapted from NOAA tidesandcurrents.noaa.gov, National Weather Service, water.weather.gov

Does sea level rise affect return period? – T_r over time

- What is return period? How is it used?
- How is return period calculated?
- Does sea level rise affect return period?
- How does this change the probability of flooding?
- What is the economic impact?

- T_r calculated for each year based on all available data up to that date (conservative with SLR)
- In years without major events, T_r decreases slightly
- In years with major events, T_r spikes upward



Does sea level rise affect return period? – T_r over time

- What is return period? How is it used?
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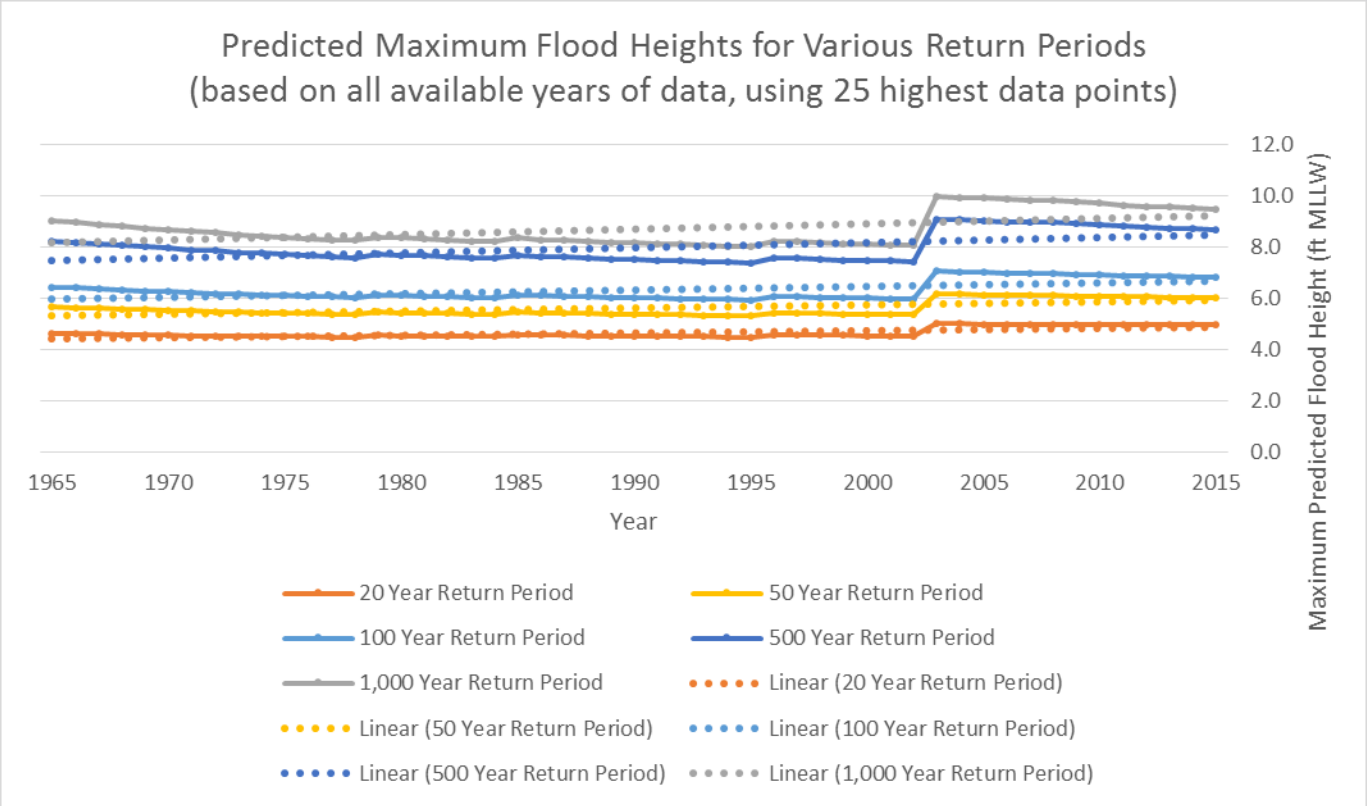
- T_r has an overall upward trend
- T_r trend similar to local sea level rise trend



Does SLR affect return period?
– An unconventional calculation of T_r

- What is return period? How is it used?
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- Does sea level rise affect return period?
- How does this change the probability of flooding?
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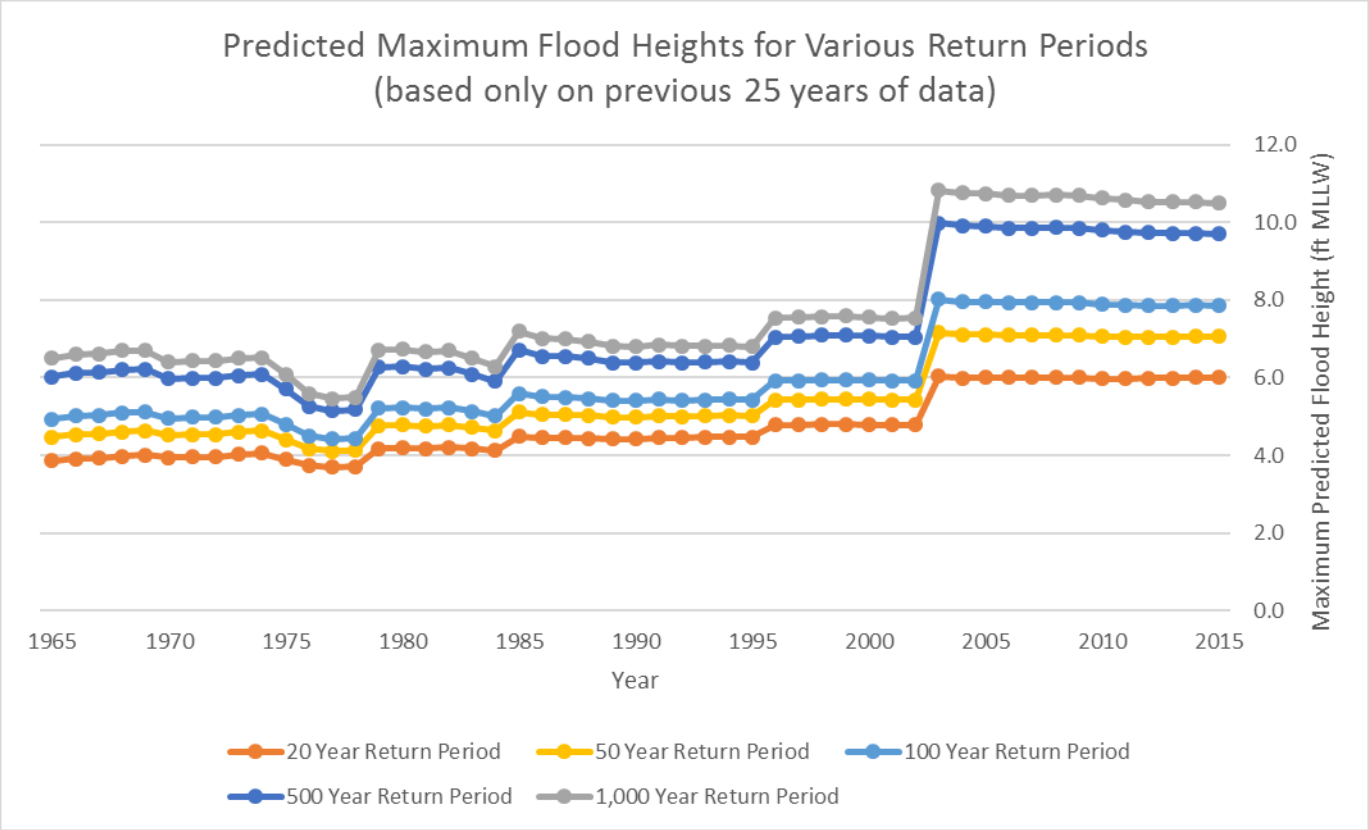
- Calculate T_r based only on most recent 25 years of data
- Less influence of "old" data points but higher uncertainty (due to fewer data points)
- Upward trend mirrors SLR



How does SLR change the probability of flooding?

- What is return period? How is it used?
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- How does this change the probability of flooding?
- What is the economic impact?

- Traditional Calculation of Encounter Probability, P_E , for constant $P=1/T_r$

$$P_E = 1 - (1 - P)^L \quad \text{(for constant P)}$$

$$P_E = 1 - \prod_{i=1}^{L} (1 - P_i)$$

- For T_r = 100 years
  - For L = 5 years → P_E = 4.9%

$$P_E = 1 - (0.99)(0.99)(0.99)(0.99)(0.99)$$

  - For L = 50 years → P_E = 40%
  - For L = 83 years → P_E = 57%

Traditional Calculation of Encounter Probability

T_r = Return Period = 100 years

Annapolis S_{100} = 6.83 ft MLLW in 2017

Year	L	P	(1 - P)	Encounter Probability
2017	1	0.01	0.99	0.0100
2018	2	0.01	0.99	0.0199
2019	3	0.01	0.99	0.0297
2020	4	0.01	0.99	0.0394
2021	5	0.01	0.99	0.0490
2022	6	0.01	0.99	0.0585
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2028	12	0.01	0.99	0.1136
2029	13	0.01	0.99	0.1225
2030	14	0.01	0.99	0.1313

How does SLR change the probability of flooding?

- What is return period? How is it used?
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- How does this change the probability of flooding?
- What is the economic impact?

- SLR Adjusted Encounter Probability, P_E , for non-constant $P=1/T_r$

$$P_E = 1 - \prod_{i=1}^{L} (1 - P_i)$$

- Starting with T_r = 100 yr height and assuming 3 ft SLR by 2100
  - For L = 5 years → P_E = 5.0%

$P_E = 1 - (0.9900)(0.9899)(0.9897)(0.9896)(0.9895)$

  - For L = 50 years → P_E = 66%
  - For L = 83 years → P_E > 99%

SLR Adjusted Calculation of Encounter Probability

Annapolis S_{100} = 6.88 ft MLLW in 2017

Based on SLR Projection of 3 ft by 2100

Year	L	P	(1 - P)	Encounter Probability
2017	1	0.0100	0.9900	0.0100
2018	2	0.0101	0.9899	0.0200
2019	3	0.0103	0.9897	0.0301
2020	4	0.0104	0.9896	0.0401
2021	5	0.0105	0.9895	0.0503
2022	6	0.0107	0.9893	0.0604
2023	7	0.0109	0.9891	0.0706
2024	8	0.0111	0.9889	0.0809
2025	9	0.0112	0.9888	0.0913
2026	10	0.0114	0.9886	0.1017
2027	11	0.0117	0.9883	0.1121
2028	12	0.0119	0.9881	0.1227
2029	13	0.0121	0.9879	0.1334
2030	14	0.0124	0.9876	0.1441

How does SLR change the probability of flooding?

- What is return period? How is it used?
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- How does this change the probability of flooding?
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- Different sea level rise projections lead to different encounter probabilities for flooding

Summary of SLR Adjusted Calculations of Encounter Probability

Annapolis S_{100} = 6.88 ft MLLW in 2017

Encounter Probabilities for Flooding Based on SLR Projections

	Amount of Sea Level Rise by the Year 2100						
L	**0 ft**	**1 ft**	**2 ft**	**3 ft**	**4 ft**	**5 ft**	**6 ft**
20 yr	18%	20%	21%	21%	21%	22%	22%
50 yr	40%	52%	58%	66%	72%	80%	90%
83 yr	57%	84%	97%	>99%	>99%	>99%	>99%

How does SLR change the probability of flooding?

- What is return period? How is it used?
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- With sea level rise, to achieve an acceptable level of risk over a building's lifespan, it must be at a higher elevation (greater T_r) than if SLR were not a factor.

- For an 83 year building lifespan built to today's T_r = 100 yr height ($S_{100,(2017)}$ = 6.88 ft) in Annapolis, the risk of flooding is 57% if there is no SLR.

- With 3 ft of sea level rise by 2100, the building must be built to today's T_r = 650 yr height ($S_{650,(2017)}$ = 8.71 ft) in order to achieve a 57% risk of flooding

How does SLR change the probability of flooding?

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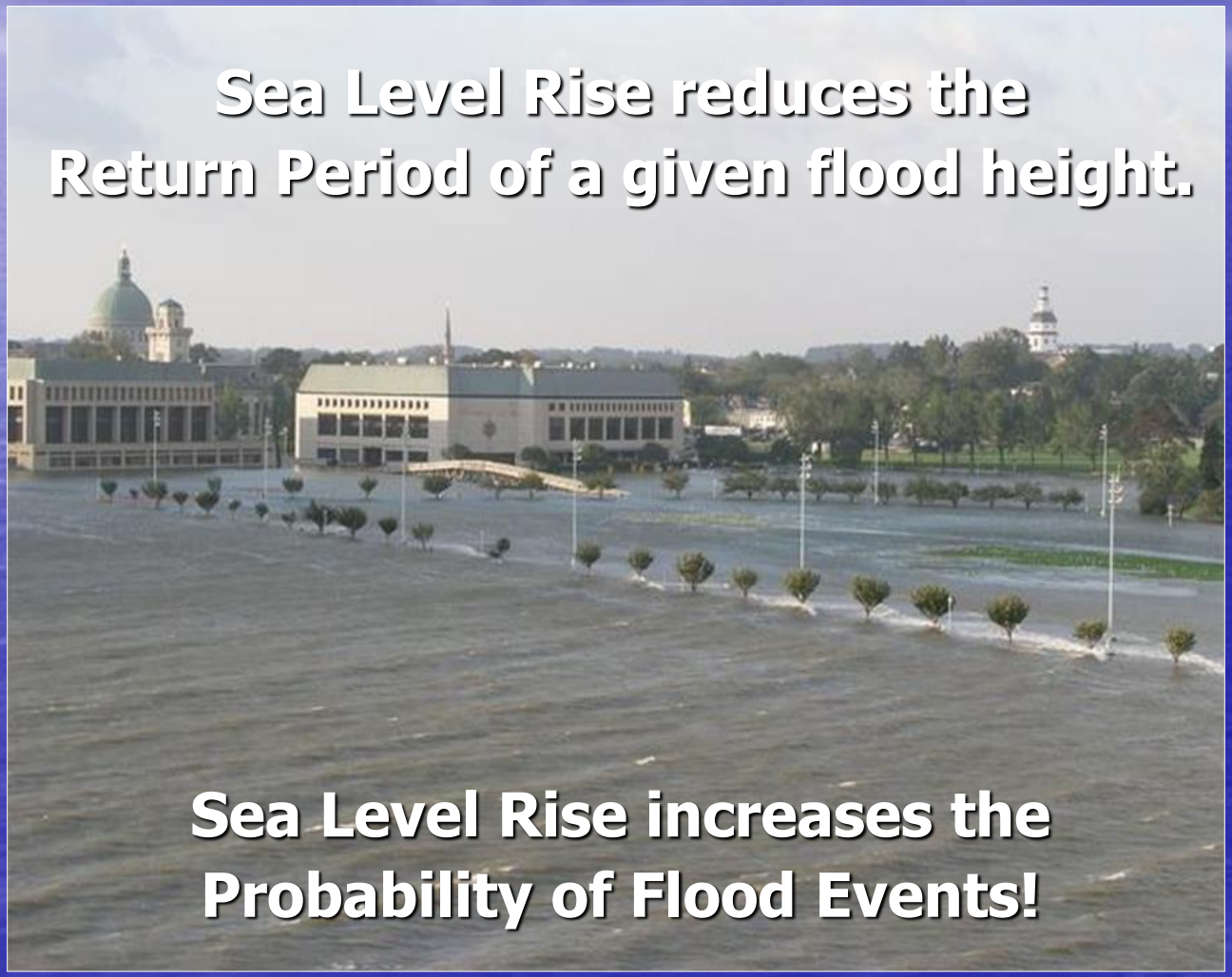

Source: wunderground.com

What is the economic impact?
– Future SLR Projections

- What is return period? How is it used?
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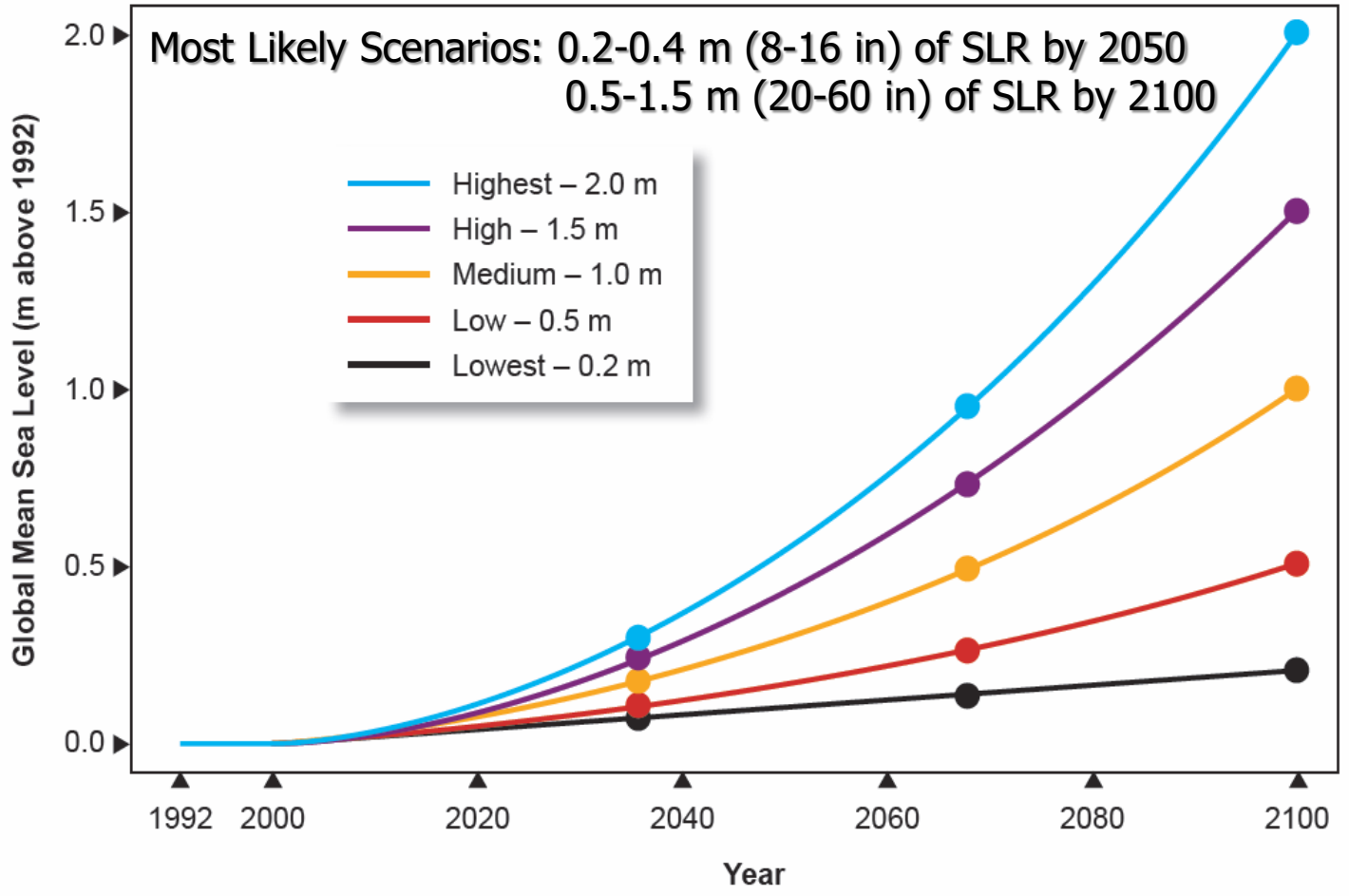

Maximum physically plausible land ice loss by 2100, with warming from unchecked carbon emissions

Upper limit mandated by USACE (2013)

Upper limit in IPCC 2013 report (small contribution from land ice)

Moderate - major carbon cuts (Paris Accord goal)

Linear extrapolation of tidal gauge trend

Source: Adapted from Hall et al (2016)

What is the economic impact?
– Probability of future floods

- What is return period? How is it used?
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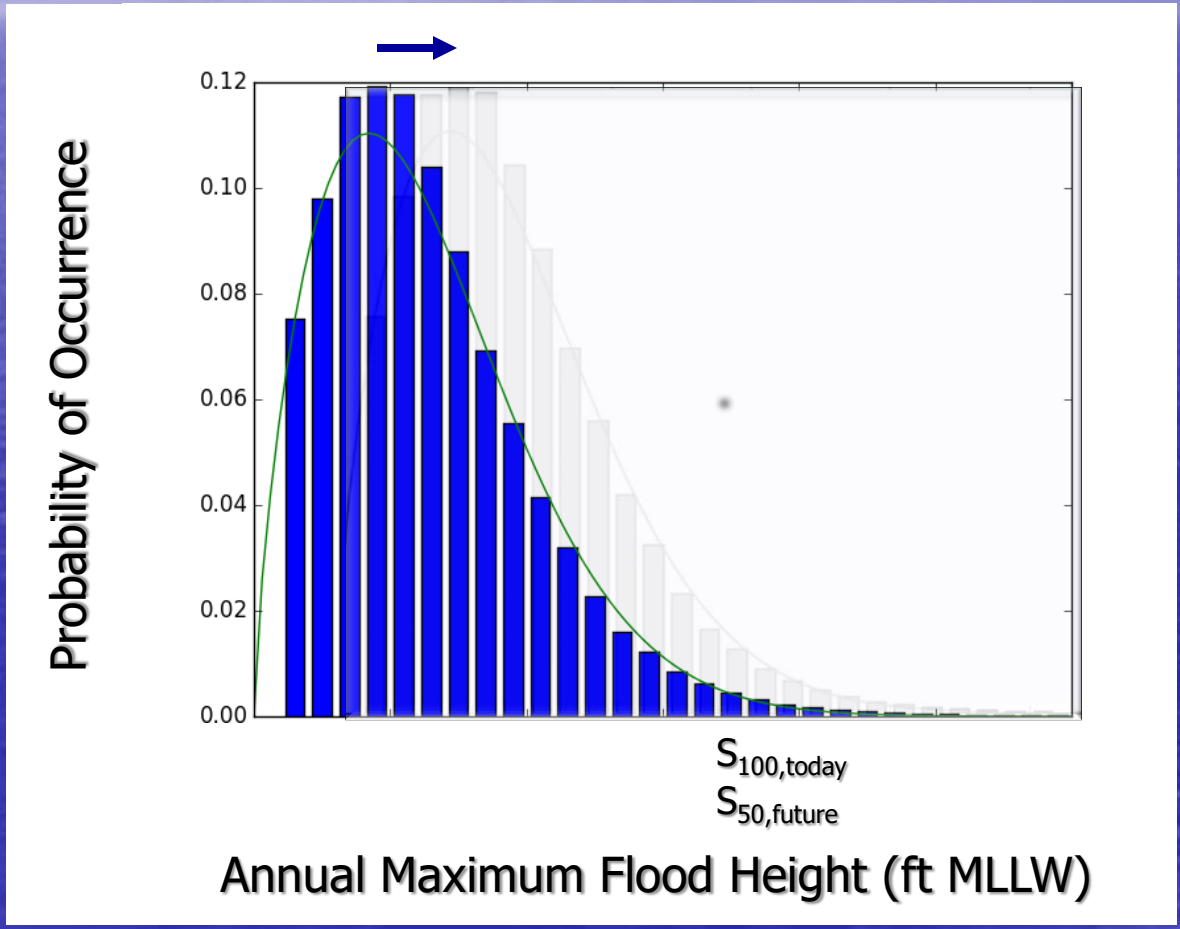
– Probability of future flood events

(Probability curve shifts right as sea level rises)



What is the economic impact?

– Flood damage costs

- What is return period? How is it used?
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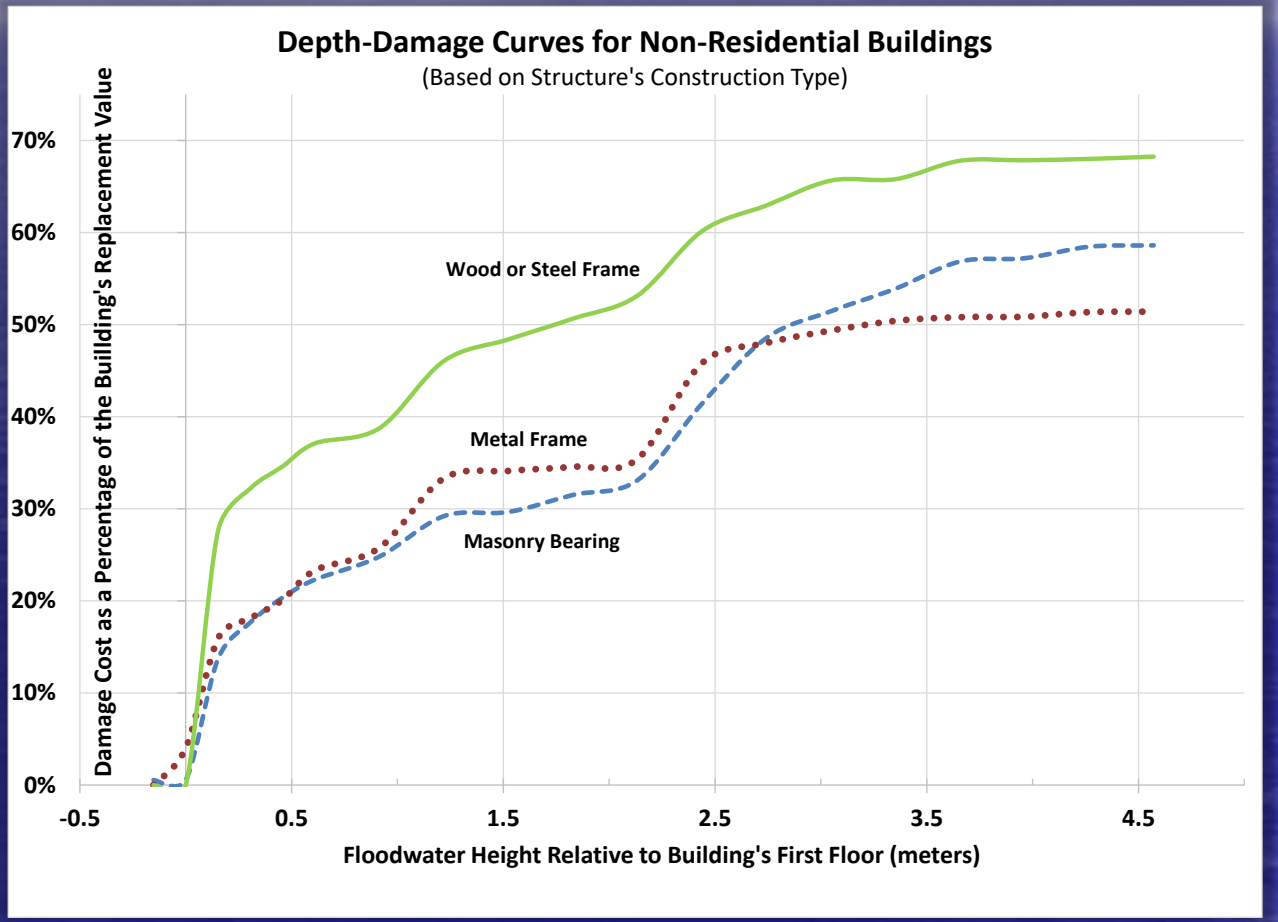
– Probability of future flood events

– Multiplied by flood damage costs

("Bins" of damage costs associated with different flood levels)



Source: Adapted from U.S. Army Corps of Engineers (2006)

What is the economic impact?
– Expected Monetary Value (EMV)

- What is return period? How is it used?
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- Does sea level rise affect return period?
- How does this change the probability of flooding?
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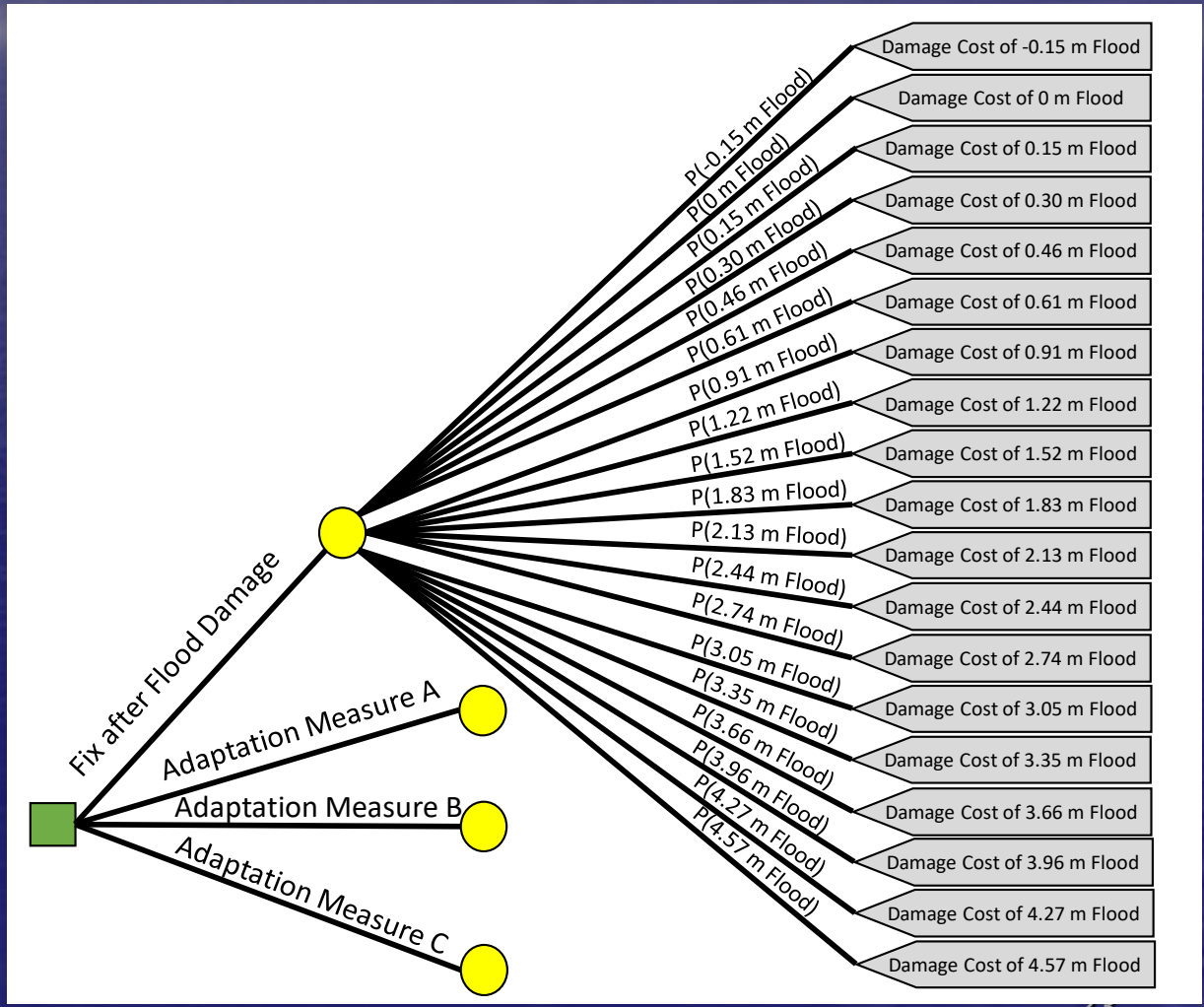
– Probability of future flood events

– Multiplied by flood damage costs

– Find Expected Monetary Value
$EMV = \Sigma P_i C_i$

(Probability times cost for each "bin." All values summed up.)



What is the economic impact?

– EMV over time

- What is return period? How is it used?
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- How does this change the probability of flooding?
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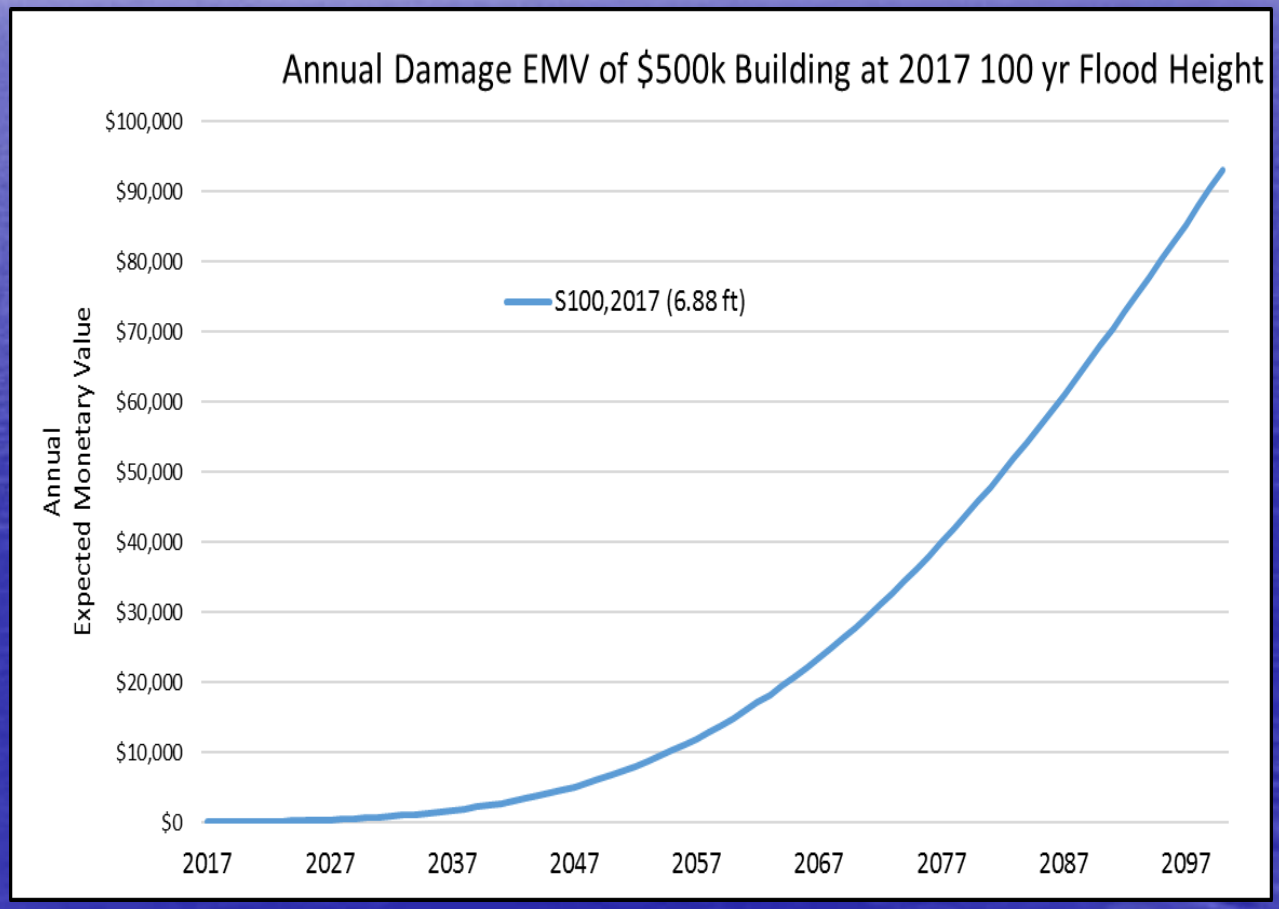
– Probability of future flood events

– Multiplied by flood damage costs

– Find Expected Monetary Value

– Calculate EMV for each year. Increases as sea level rises.



What is the economic impact?

– Increasing Base Flood Elevation (BFE)

- What is return period? How is it used?
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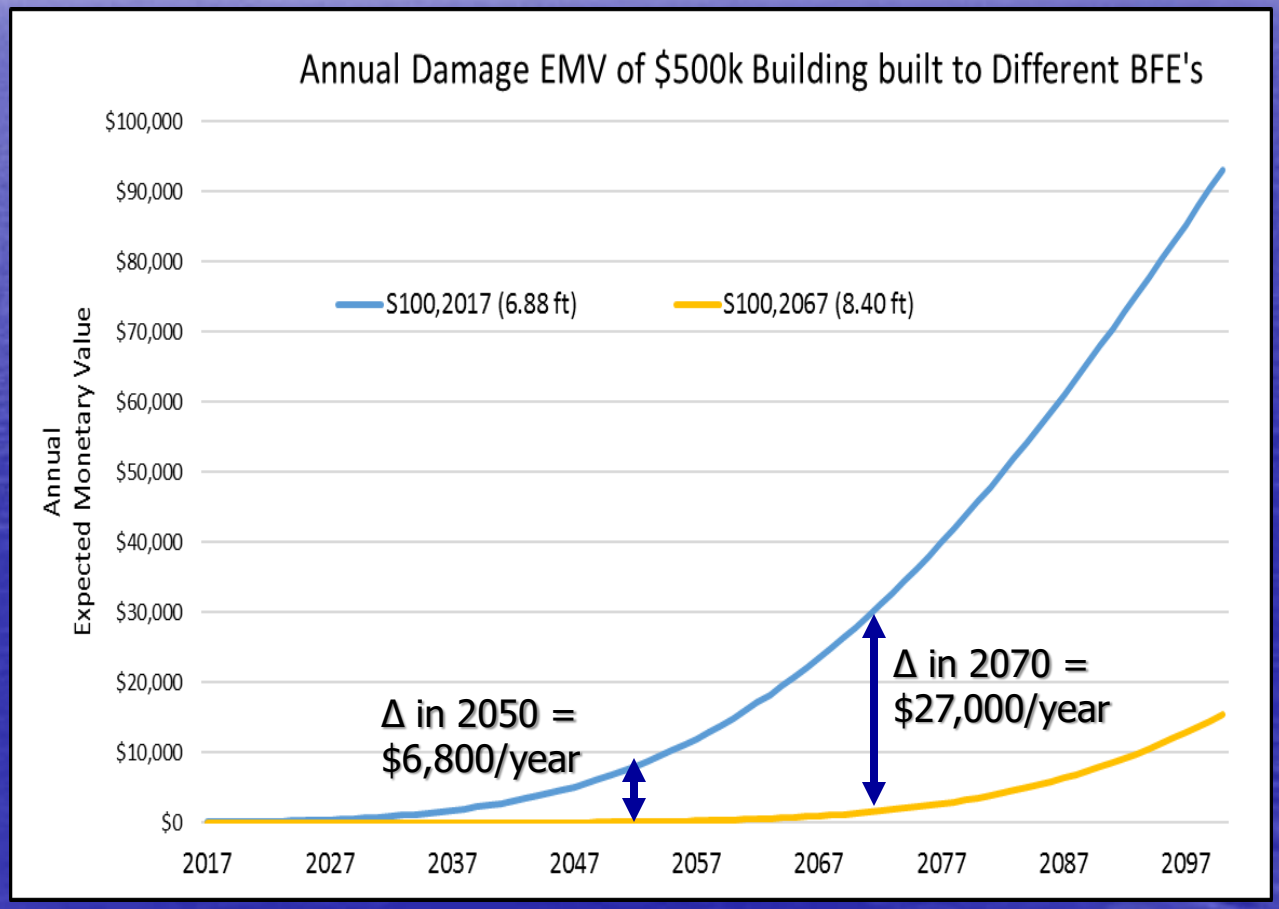
– Increasing Base Flood Elevation reduces EMV over time

– Difference between annual EMV curves is annual "savings"

– Compare lifespan savings vs. initial cost of elevating (compliance cost)



What is the economic impact?
– Choosing between BFE options

- What is return period? How is it used?
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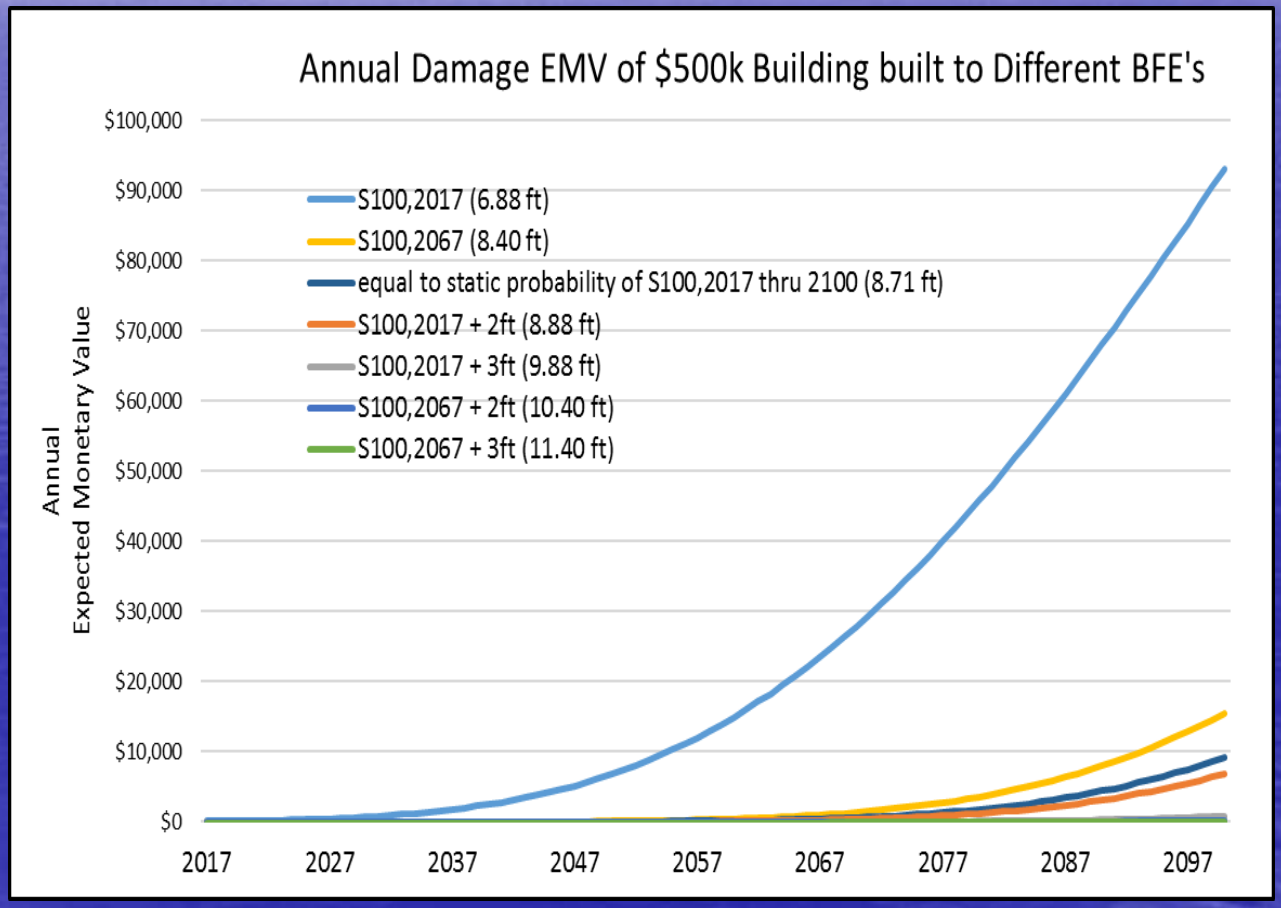
- Example:
  3 ft SLR by 2100
  Annapolis, MD;
  $500k initial cost;
  wood framing;
  50-year lifespan

– Various options for Base Flood Elevation

– Total EMV of flood damage over 50 year lifespan:
  – $S_{100\ (2017)}$ --- $312k
  – $S_{100\ (2067)}$ --- $1,800
  – $S_{100\ (2017)}$+3 ft --- $50
  – $S_{100\ (2067)}$+3 ft --- $0



Key Take-Aways

- Return Period is not fixed. It changes due to sea level rise.
- Consider Return Period for the entire lifespan of a facility, not just at the time of construction.
- Evaluate the economic impact of elevating a structure over its entire lifespan.

Sources: Annapolis Capital (2003); Palm Beach Post (2012)

Questions?

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