Assessing Current And Future Nuisance Flood Frequency Throughout The U.S. Atlantic Coast

David Kriebel, PhD, PE and Gina Henderson, PhD
United States Naval Academy
kriebel@usna.edu
ghenders@usna.edu

Outline

- What is nuisance flooding?
- How often are we flooding now?
- What will happen with future sea level rise?
  - Probabilities of historical high tides
  - Projection of future high tides with SLR
- How can we evaluate actions to limit future flooding?

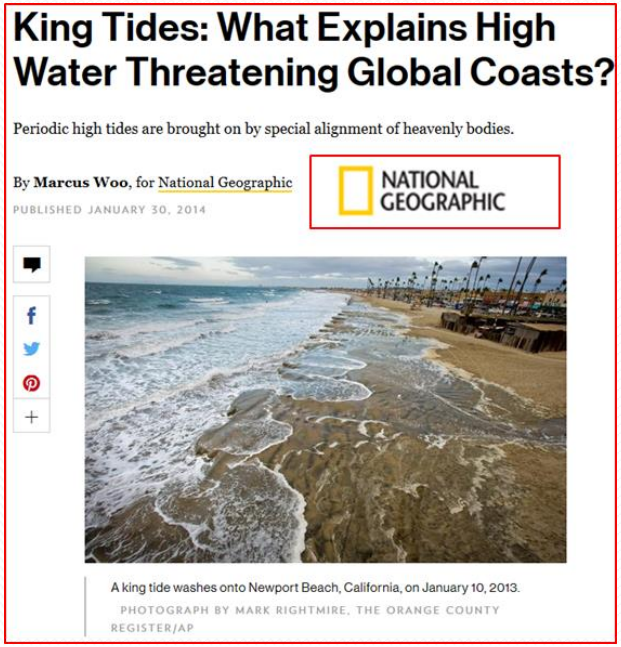
Terminology

Nuisance Flooding - flooding that causes public inconveniences such as frequent road closures, overwhelmed storm drains and compromised infrastructure (NOAA)

Recurrent Flooding - flooding that happens repeatedly in the same areas, typically leading to economic losses (VIMS)

Chronic Flooding - flooding that occurs more than 24 times per year or every two weeks on average (Union of Concerned Scientists)

King tide - a colloquial term for an especially high tide, such as a perigean spring tide. "King tide" is not a scientific term, nor is it used in a scientific context. (Wikipedia)



South Florida

Flooded streets of Miami Beach, Collins Ave and 30th Street, during a King Tide on Sept. 28, 2015. (Miami Herald)

Las Olas Isles, Fort Lauderdale, Oct. 17, 2016. (Joe Cavaretta/Orlando Sentinel via AP)

A flooded street in Miami Beach during the high tide on Sept. 29, 2015. (NOAA)

Other Areas of US East Coast

Flooding at Long Wharf in Boston. (Robin Lubbock/WBUR)

Flooding and Resilience in Charleston,

Image Credit: Chuck Burton/Associated Press

Savannah flooding

December 28, 2015 by WBBJ 7 Eyewitness News

Tom Gitto, 55, shares his memories of countless times when Arizona Avenue has flooded including at it's worst during Hurricane Sandy when his family had to stay at Fema, where their baby was born. Tuesday, December 29. (The Press of Atlantic City/ Viviana Pernot)

Buy Now

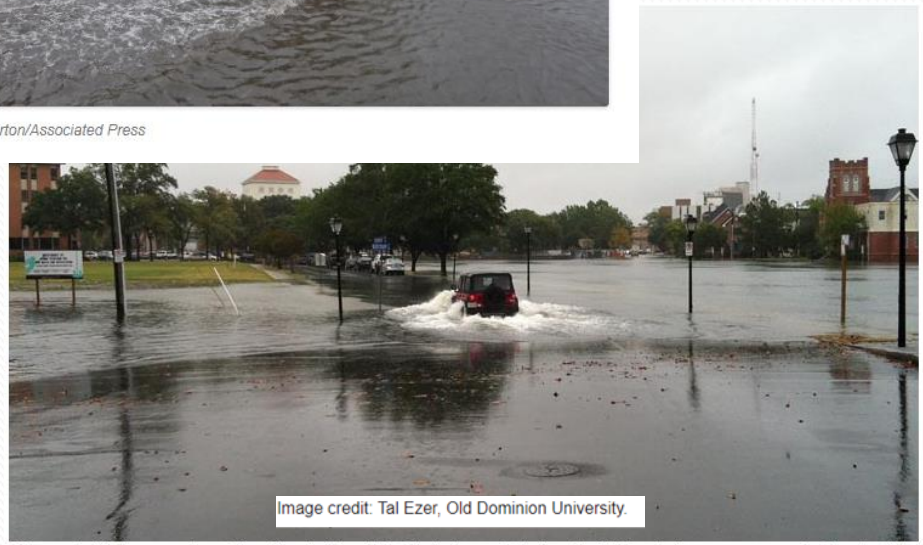
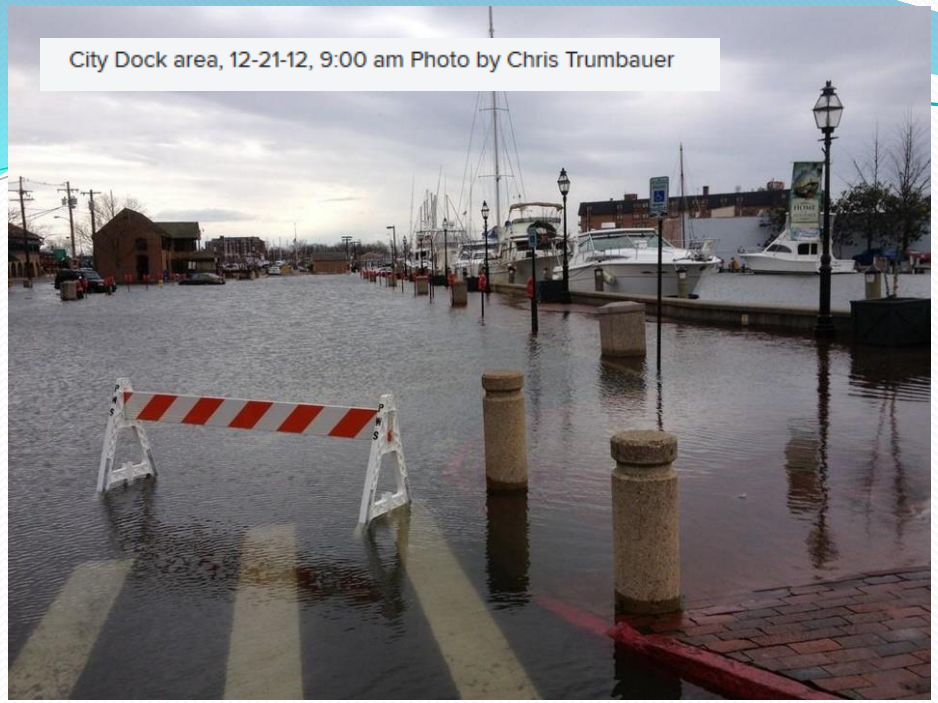


Image credit: Tal Ezer, Old Dominion University.

Figure 1. Nuisance street flooding in Norfolk, Virginia on October 9, 2013, during passage of a front at high tide.

Annapolis City Dock

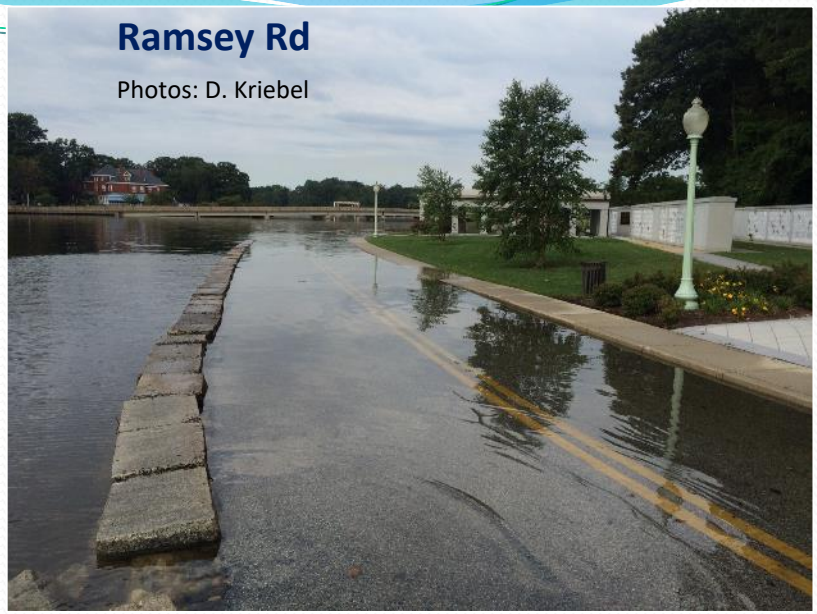


Sept 30, 2016
Photo: Alderman Joe Budge

Donna L. Cole on Twitter

"The Starbucks manager going above and beyond to serve customers in Annapolis this morning. #flooding #nuisanceflooding #wx #mdwx

U.S. Naval Academy



What happened in 2017?

26 high tides exceeded road elevations

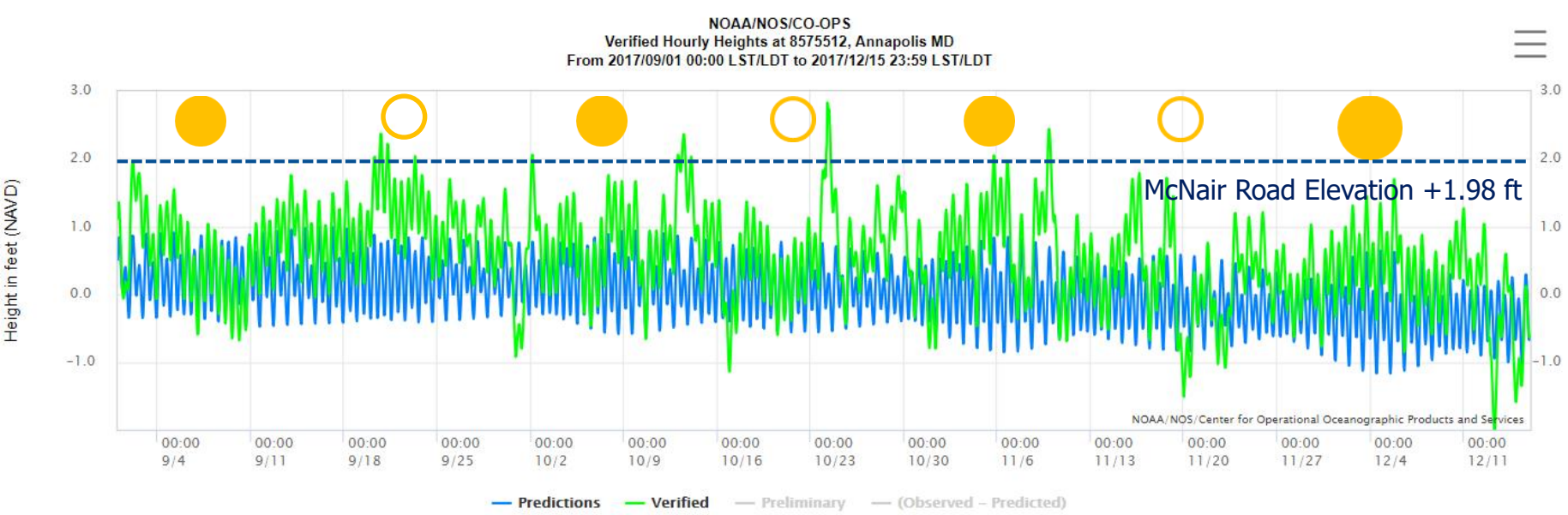
What is Coming in Future?

~100 high tides within 6 inches (15 cm) below road elevation

~300 high tides within 12 inches (30 cm) below road elevation

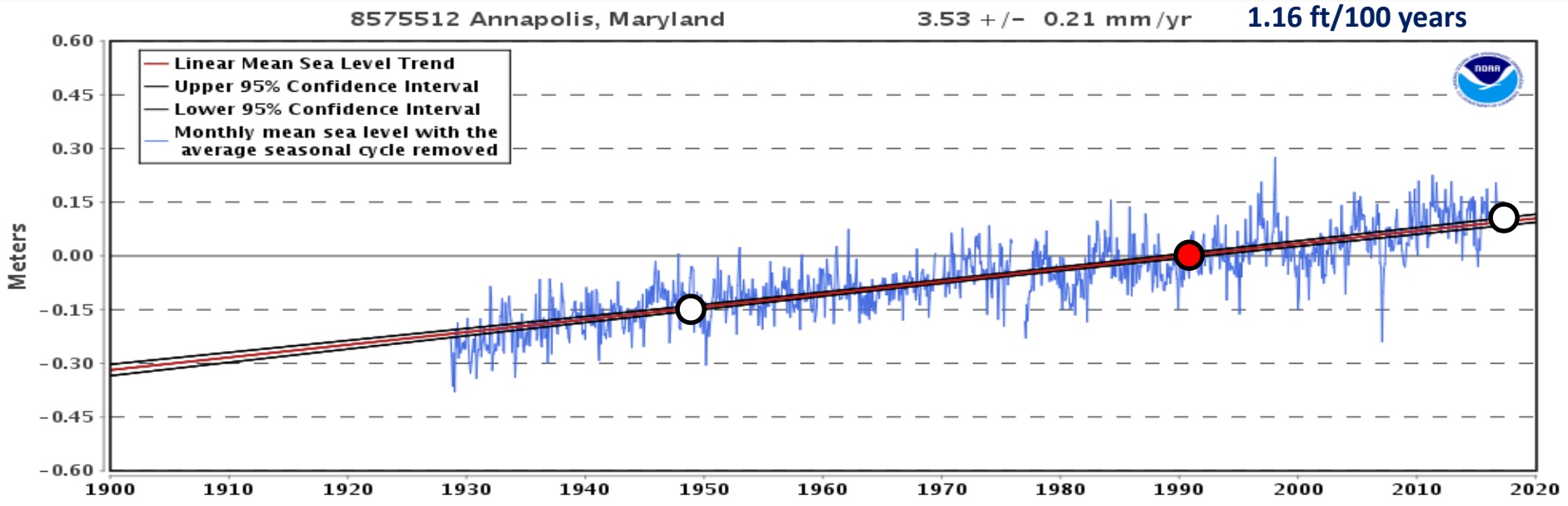
USNA Flooding on McNair Road

Example of 12 Flood Events in September-December 2017

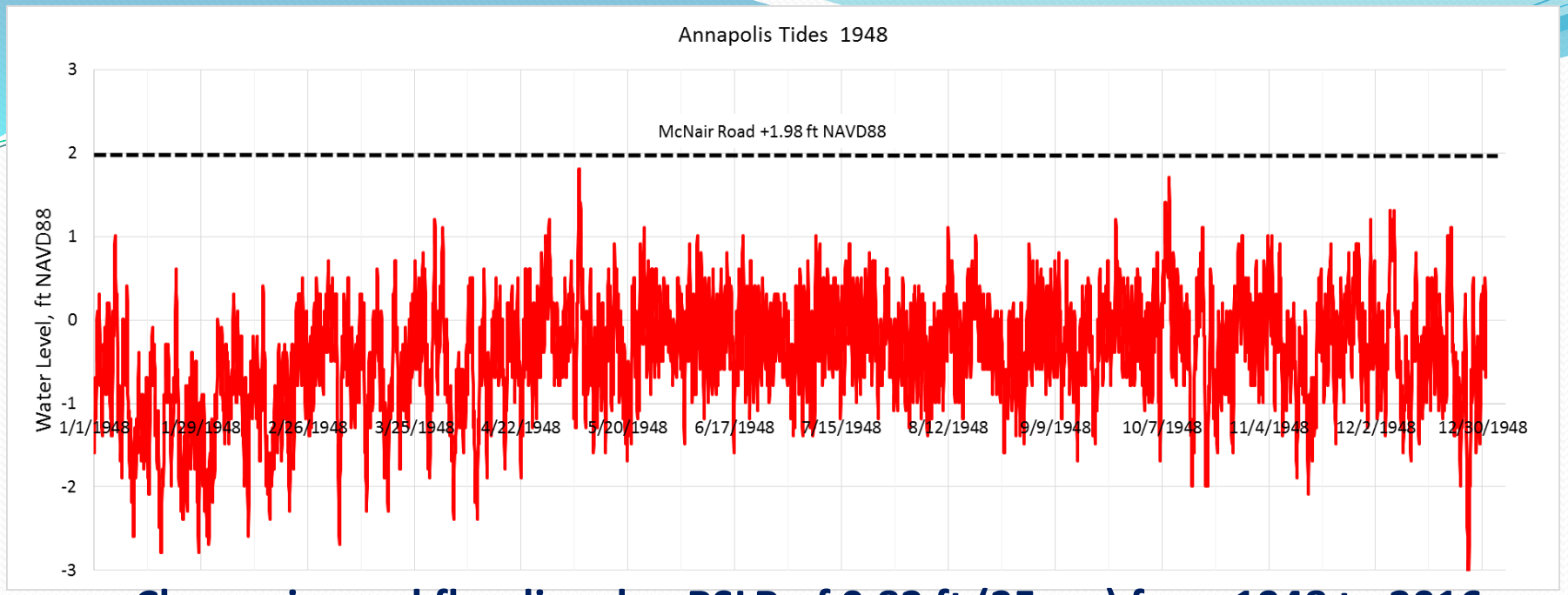


- **Not predicted:**
  - All predicted tides were more then 1 ft (30 cm) below road
  - Only 1 of 12 flood events occurred same day as new or full moon
- **So What Causes Flooding?**
  - Minor meteorological events (wind, barometric pressure)
  - Superimposed on high astronomical tides
  - Shifted upward by long term, decadal, and seasonal sea level change plus ground subsidence

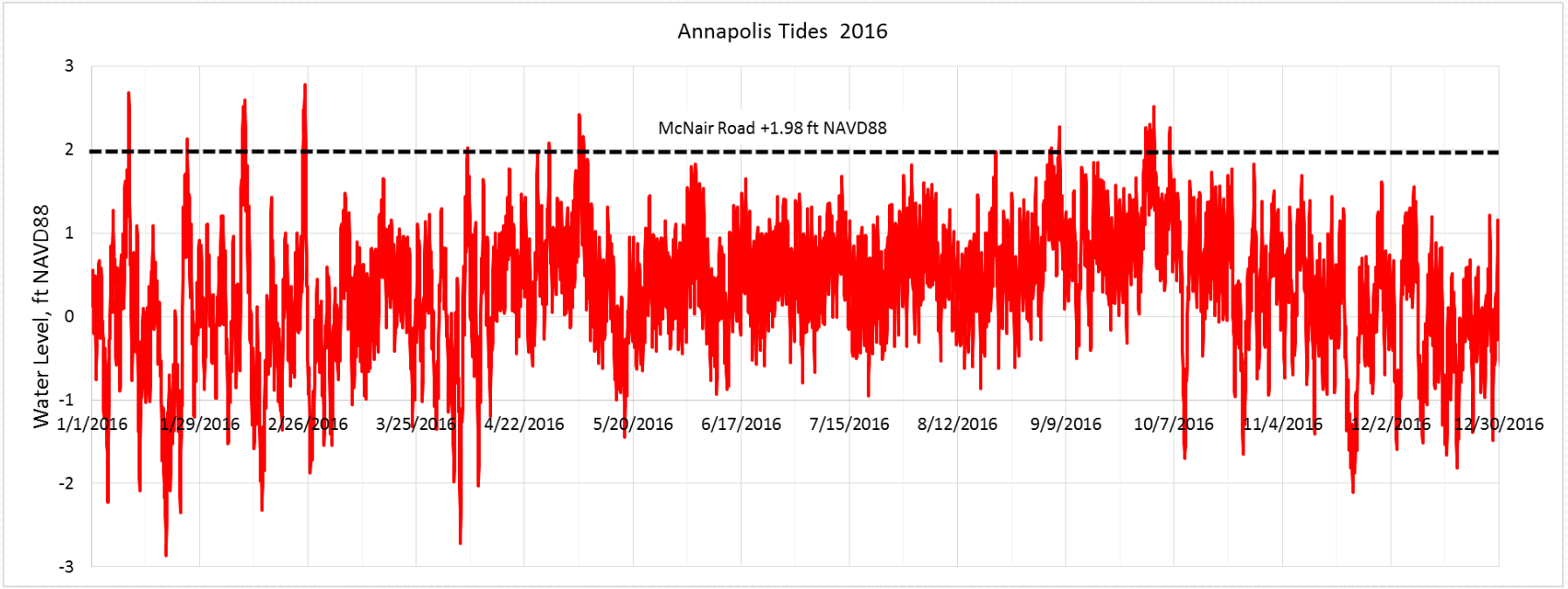
Annapolis Relative Sea Level Rise (RSLR) Including Vertical Land Movement (VLM) (not accounted for in tide prediction)



Current tidal datums (official MSL, MLLW, MHHW, etc) and tide predictions are based on last National Tidal Epoch 1982-2001 centered on 1992

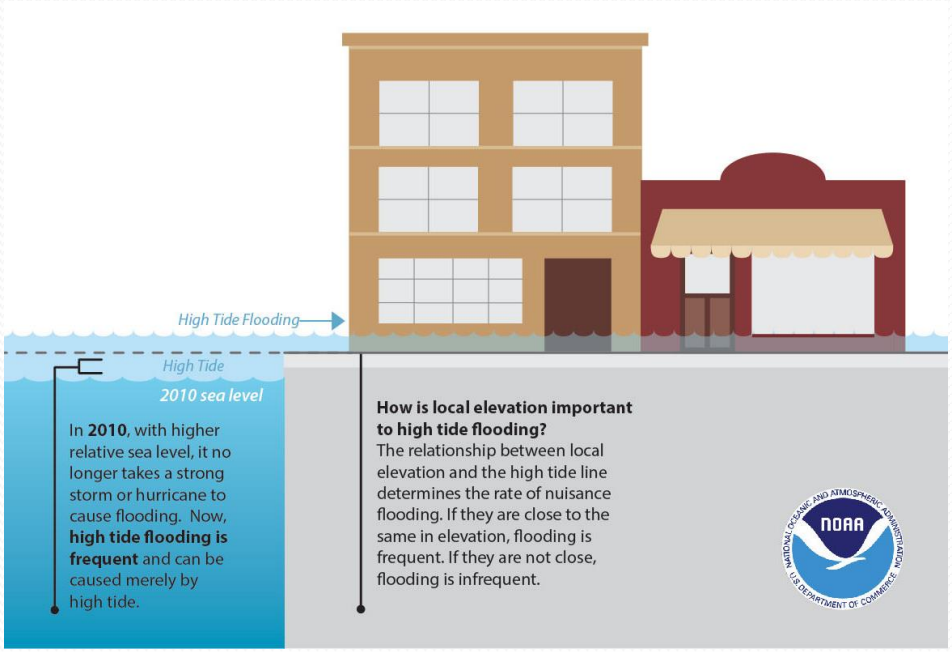


Change in road flooding due RSLR of 0.82 ft (25 cm) from 1948 to 2016



Flooding Occurs when High Tide Exceeds some Flood Threshold

- **Flood Threshold is elevation of infrastructure above Datum**
  - Road, Building, Storm drain if connected to tidal waters
- **Flood Threshold is site specific**
  - Can vary building to building, block to block, or within a lot or parcel
  - Best to use local topographic survey or lidar data
- **Can also define "Generic" flood thresholds for community**
  - Typical flood "stages" for community

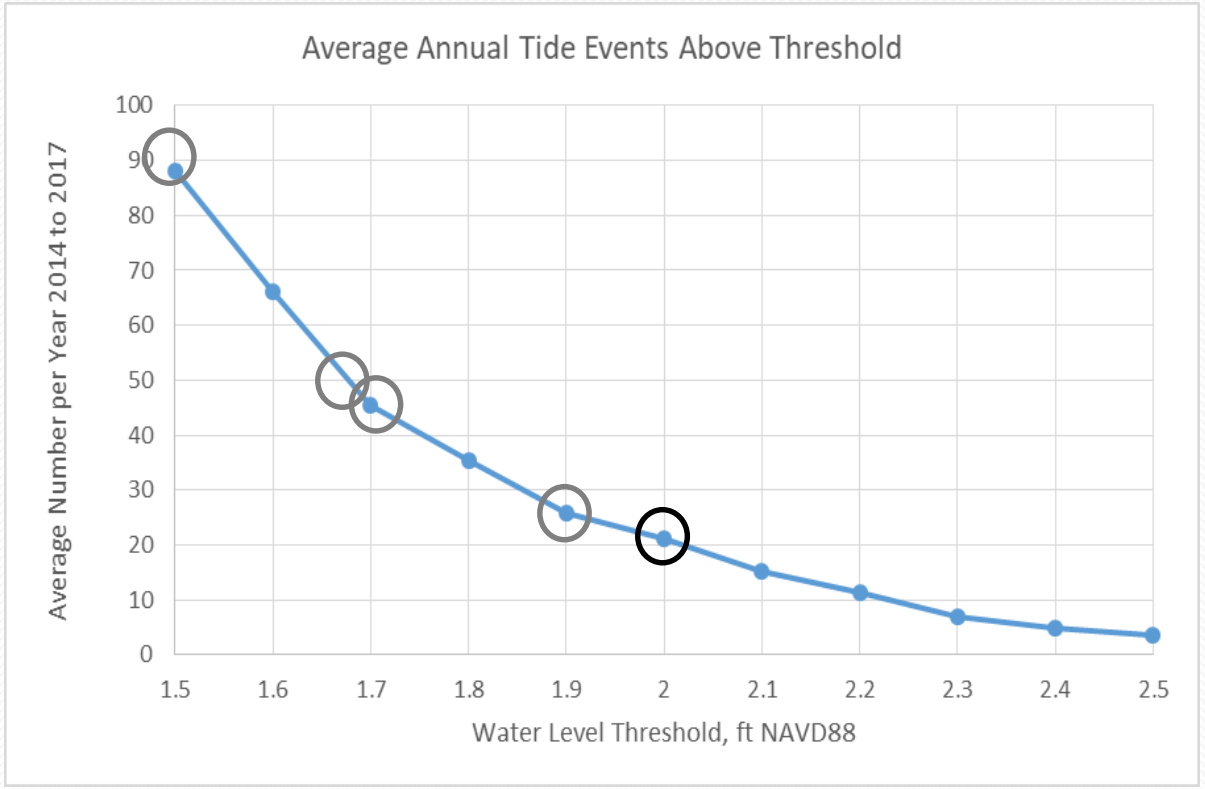


Site Specific Elevations of Storm Drains around Annapolis City Dock

Number of High Tide Flood Events changes dramatically with just a few inches (or a few centimeters) of elevation

Some troublesome Annapolis threshold elevations (all from NAVD88):

USNA McNair Rd 1.98 ft
Dock St Storm Drain 1.90 ft
City Dock Storm Drain 1.71 ft
Compromise St Storm Drain 1.67 ft
Newman Street Storm Drain 1.44 ft



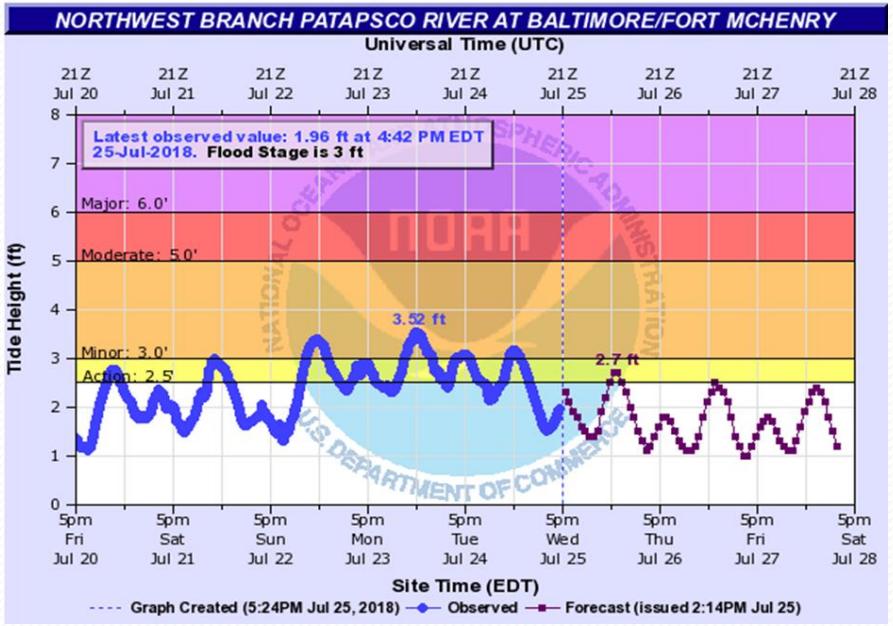
1 foot or 30 cm

National Weather Service
Advanced Hydrological Prediction Service

Generic Coastal Flood Stages

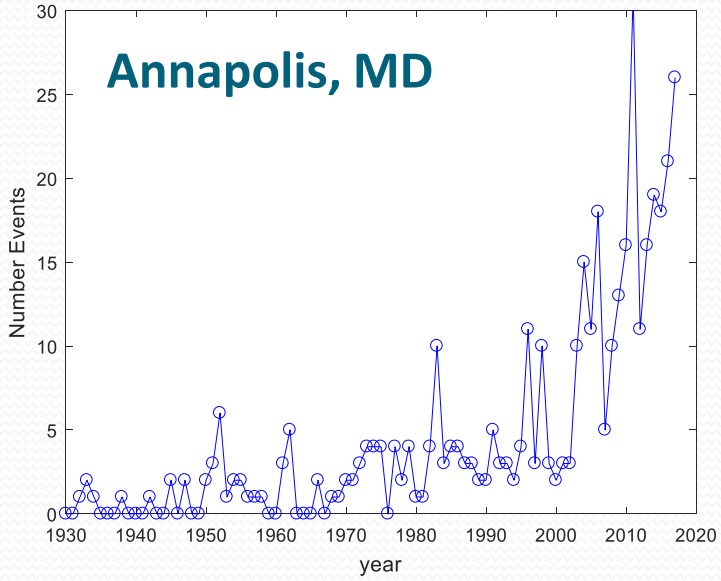
Example from Baltimore, MD (using MLLW datum)

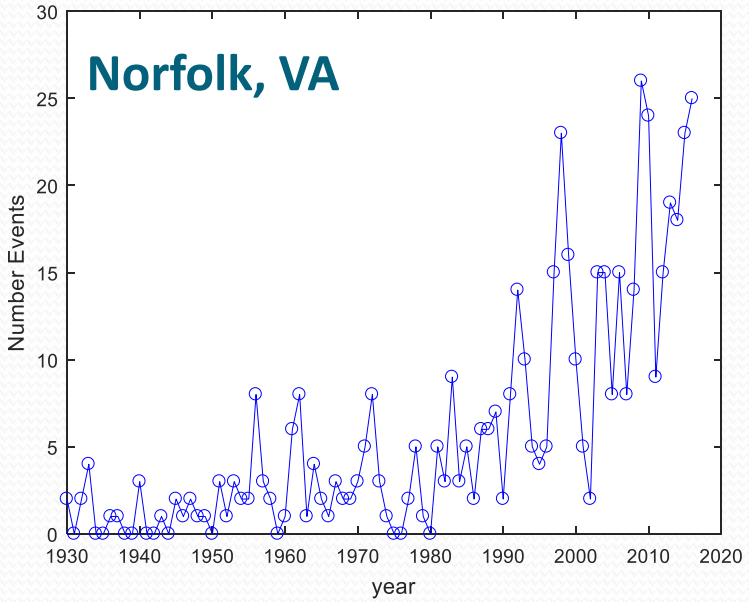
6	Water reaches the corner of Ann Street and Thames Street.
5.5	Water begins to cover the Pier 4 promenade on the west side and Pier 5 on the west side.
5.25	The boardwalk at Fells Point begins to flood. Water also begins to cover low spots in the promenade at the end of Broadway Street.
5	Water begins to cover the Pier 4 promenade on the east side.
4.5	The end of Ann Street begins to flood.
4.25	The concrete promenade at Fells Point begins to flood. Water also begins to cover the boardwalk at the Maritime Park water taxi stop.
3.5	Water begins to cover the promenade at the Inner Harbor at the electric boat dock west of the World Trade Center.
3	Flooding is occurring at the end of Thames Street. Water also nearly covers the promenade at the dragon boat dock in the Inner Harbor.
2	Water begins to cover the lower promenade at the Harbor Place water taxi stop.

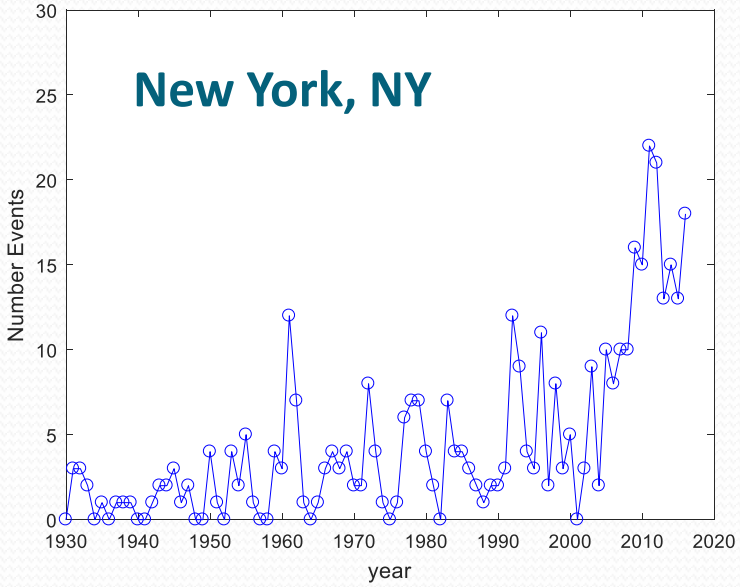


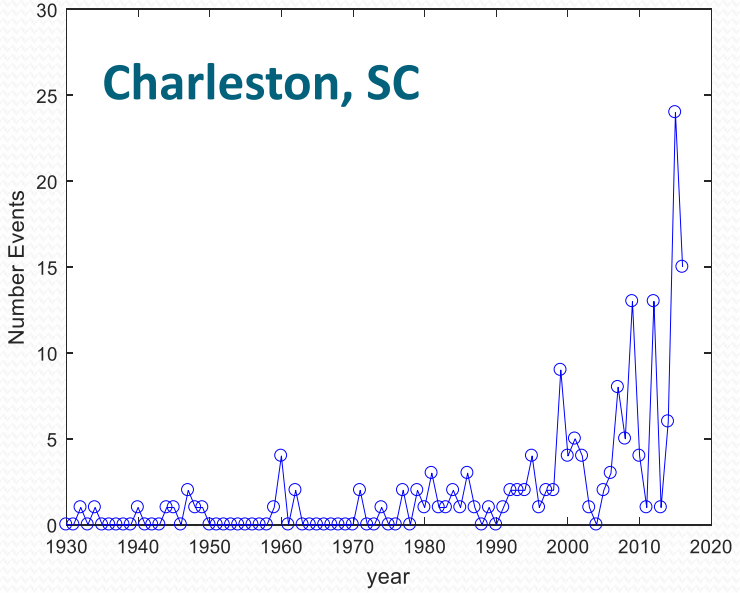
Minor Stage – used to issue public flood warnings/advisories
Moderate Stage – some inundation of roads and structures
Major Stage – extensive inundation, significant evacuation needed

Number of Tides per Year Exceeding Minor Flood Threshold



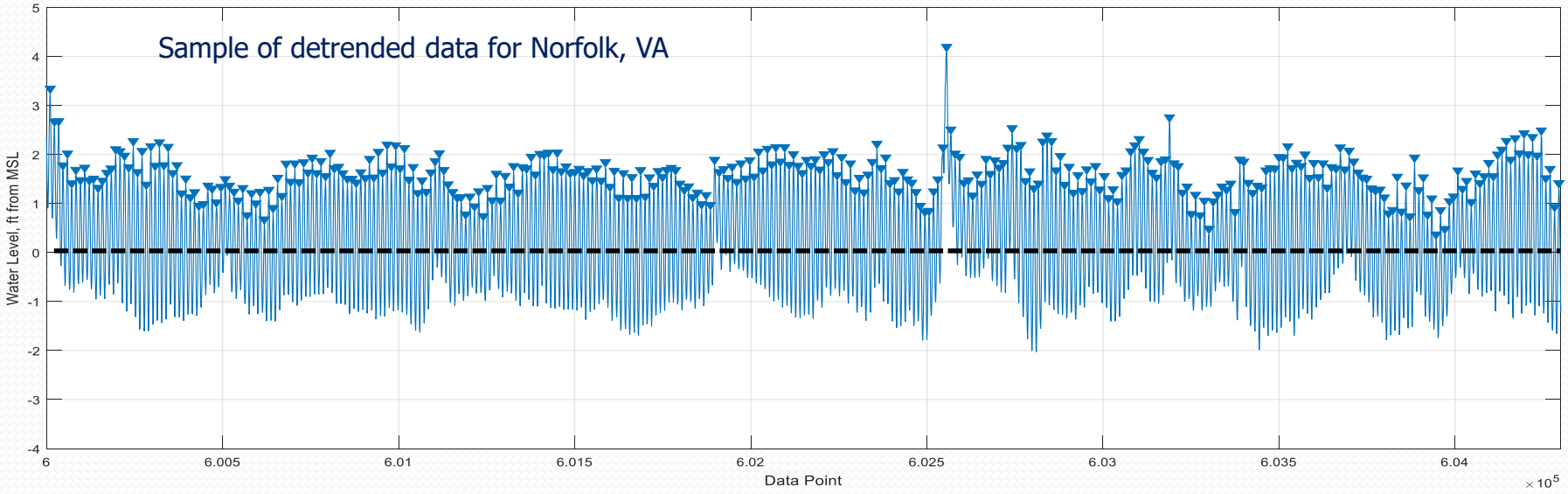




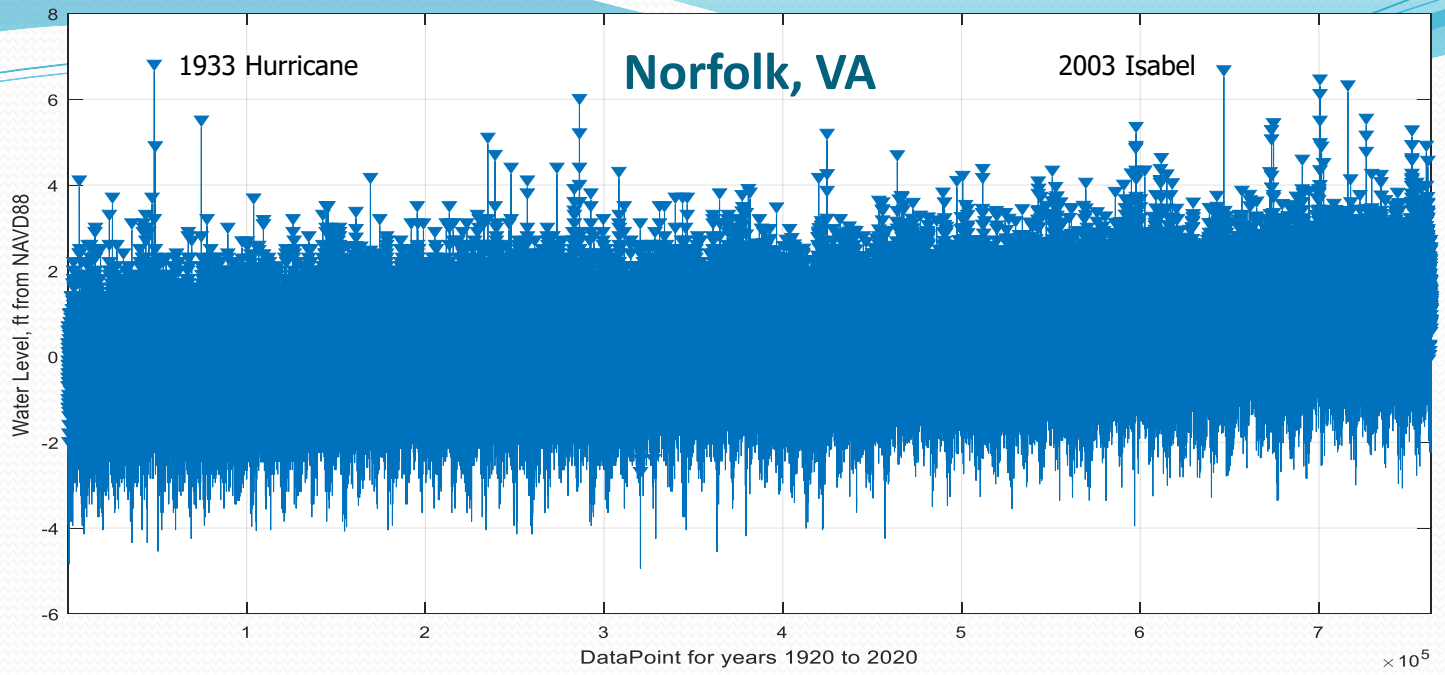


Nuisance or Recurrent Flooding Analysis

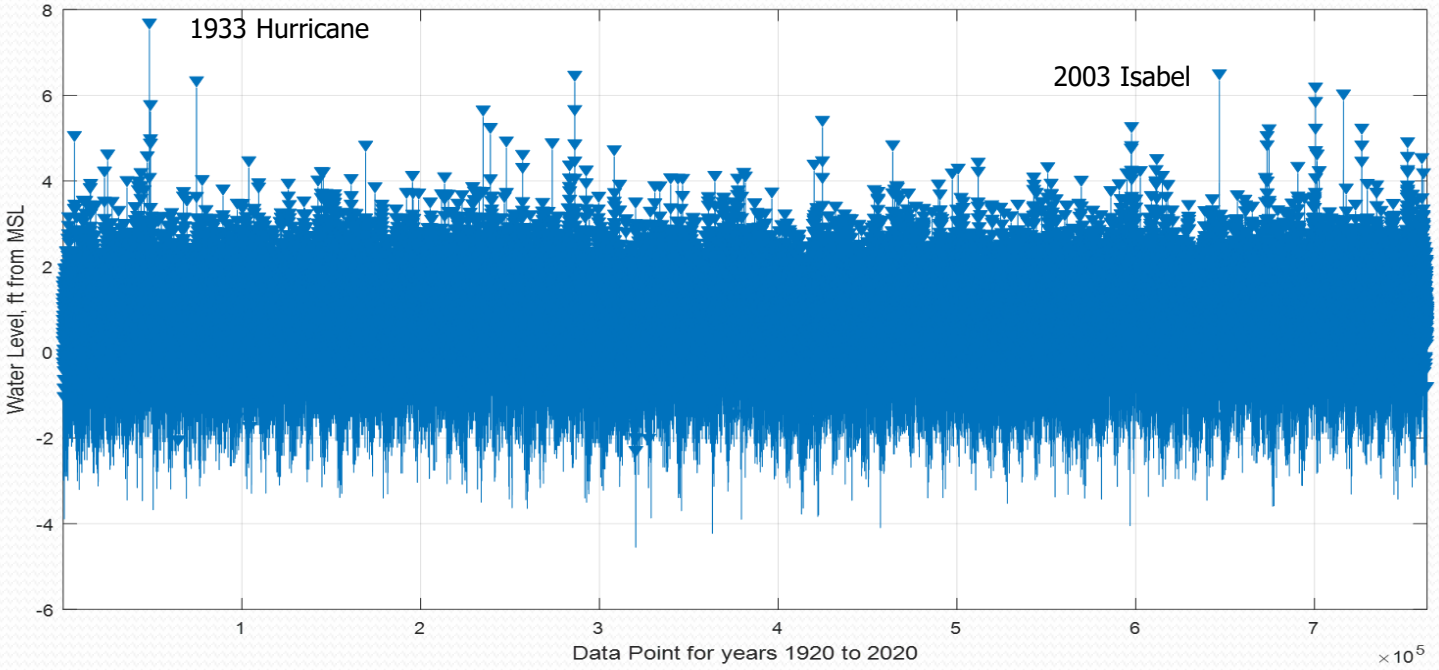
- Start with hourly water levels from NOAA tide gage
- De-trend to remove linear trend in relative sea level rise
  - Remove historic sea level change and subsidence
  - Retain astronomical tides, seasonal mean sea level, decadal sea level anomalies, and meteorological events
- Identify high tide peaks or high tide amplitudes
  - Relative to “flat” mean sea level
  - Used matlab *findpeaks* function



Original Data plotted to NAVD datum

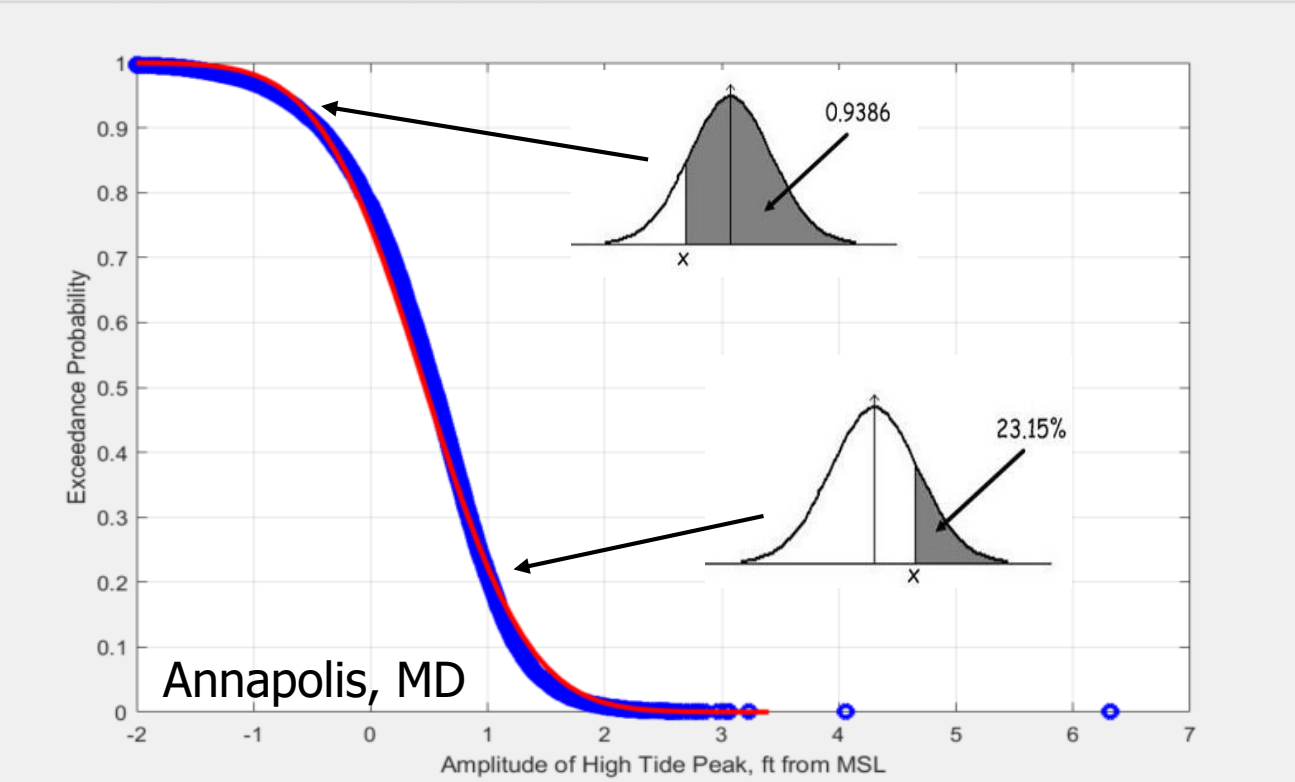


De-Trended Data plotted to flat MSL datum



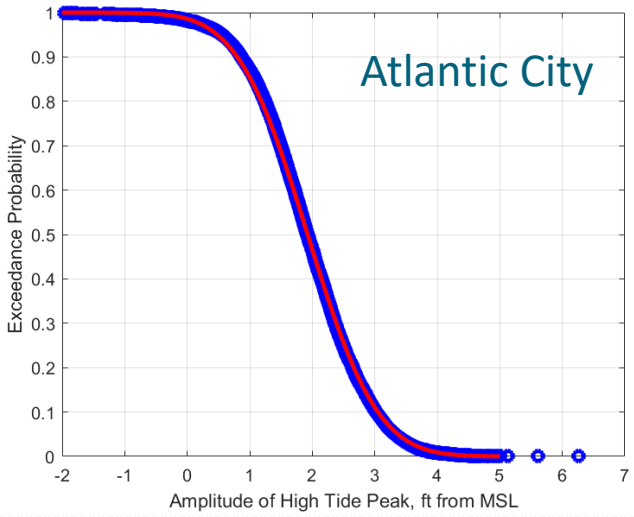
Nuisance Flooding Analysis - Continued

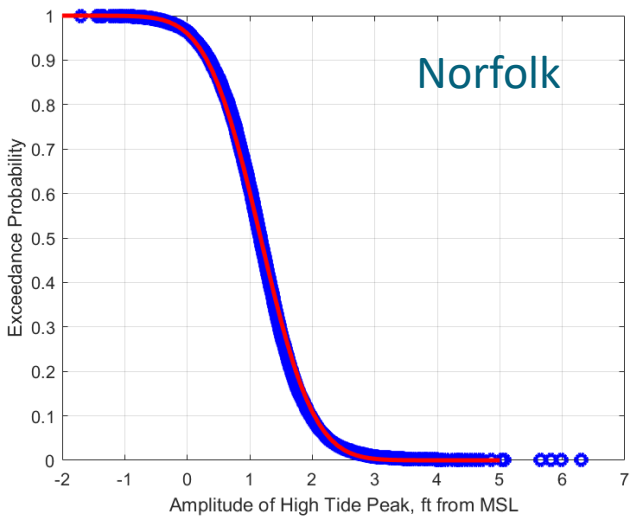
- **Develop empirical probability distribution of high tide amplitudes**
  - Probability of Exceedance of high tide amplitudes relative to flat mean sea level using historic data
- **Most data closely follow Gaussian or Normal probability curve**
  - Dimensionless similarity among most US east coast tide gage sites

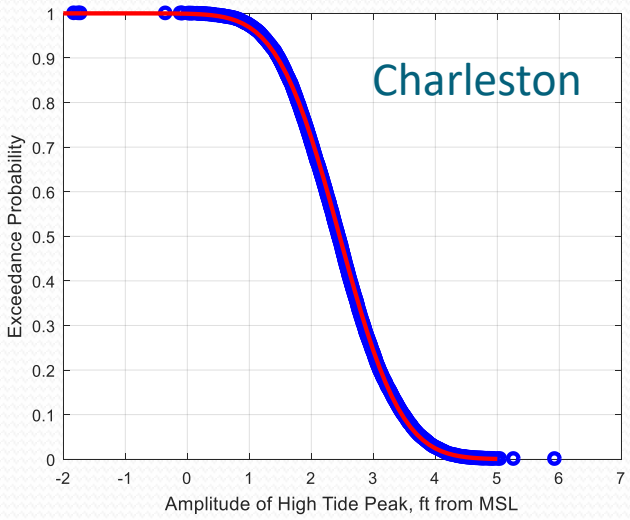


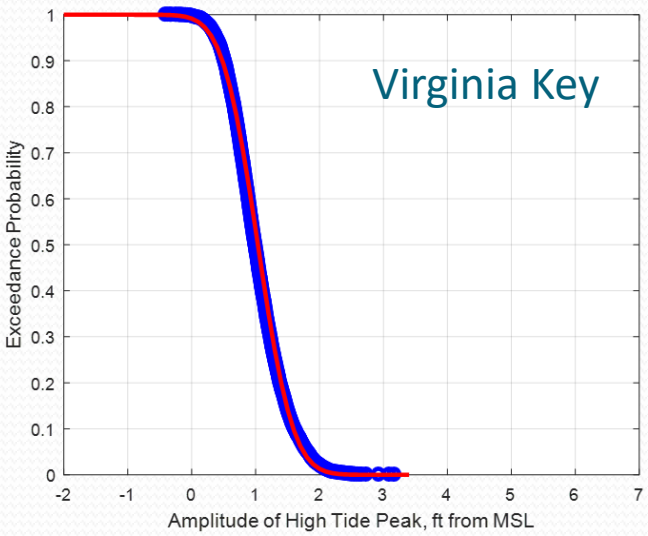
High Tide Amplitudes of other Cities 1996-2016

Empirical distribution (blue) vs Normal distribution (red)



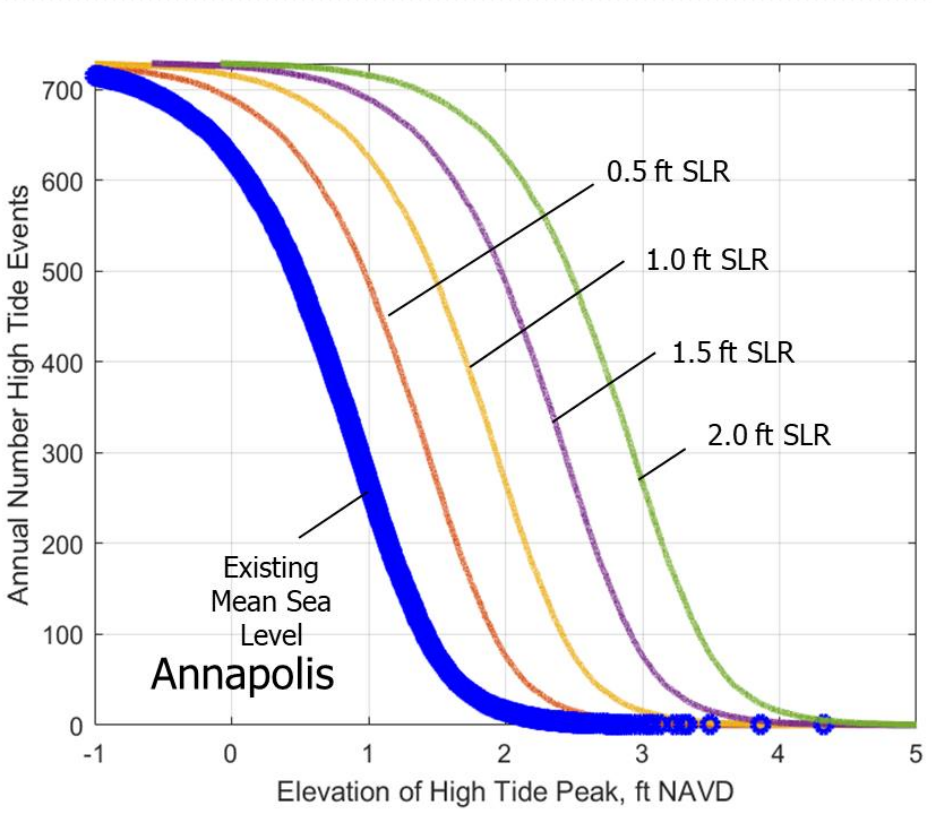






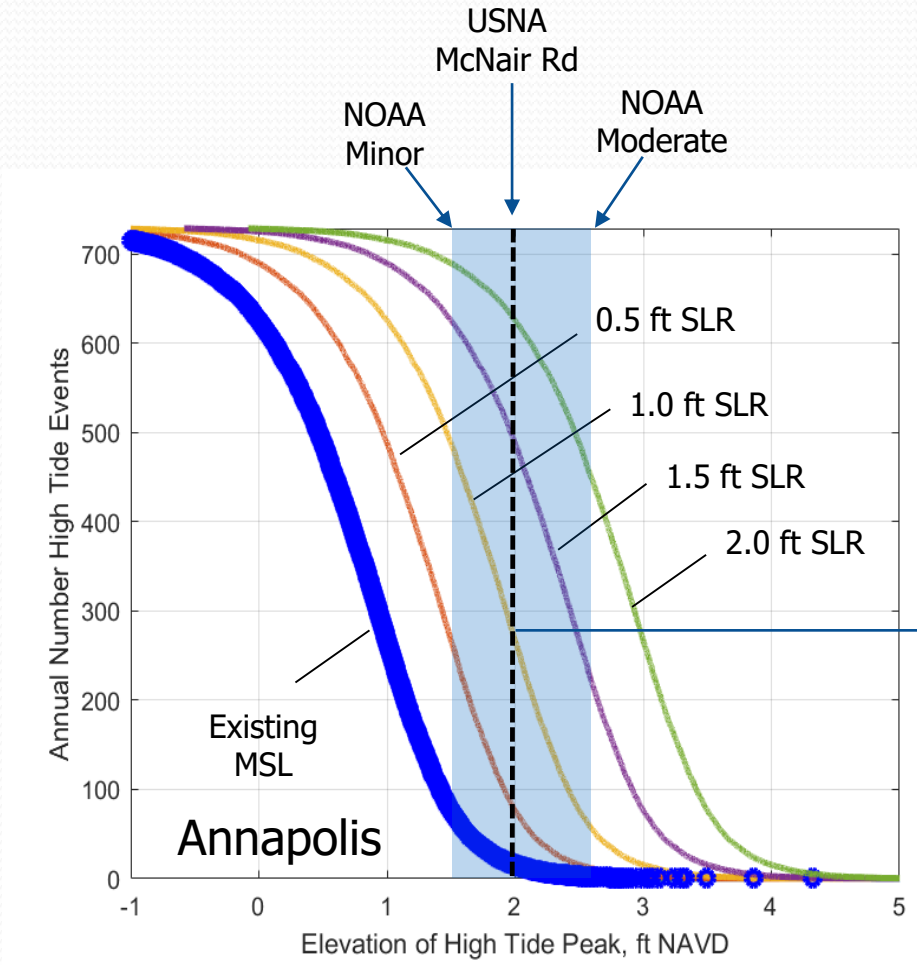
High Tide Amplitudes with Sea Level Rise

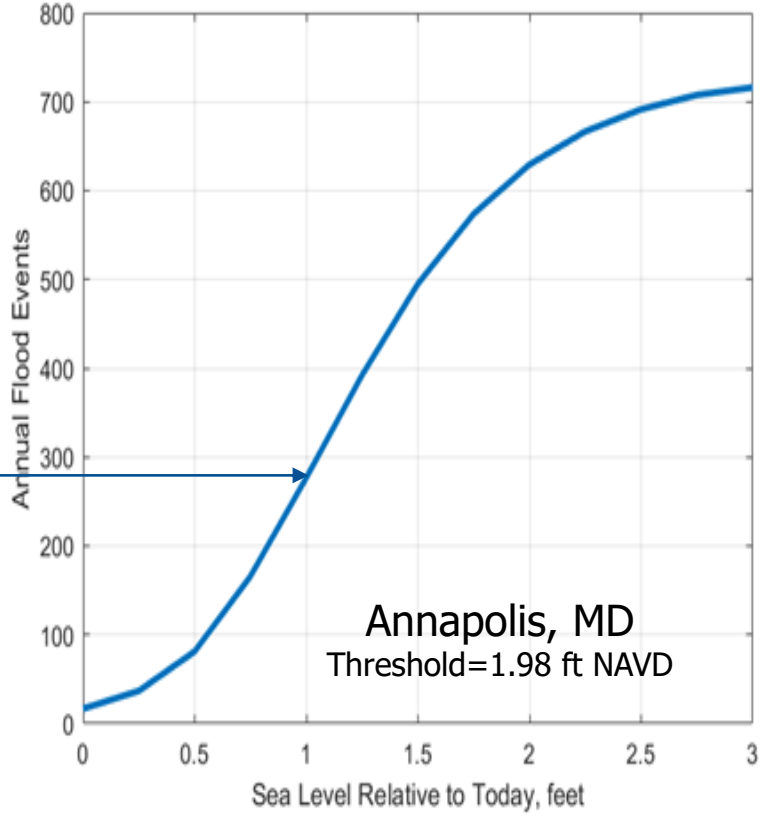
- **Convert probability, Q, to annual number of events, N**
  - N = Q * 2 tides/day * 365 days/yr
- **Shift data upward to present MSL**
  - Extend linear RSLR trend from 1992 Tidal Epoch to present
- **Shift from MSL to NAVD88**
  - To compare to land, road, and building elevations
- **Add relative sea level rise**
  - Example shows RSLR of 0.5, 1.0, 1.5, and 2.0 ft (0.15, 0.30, 0.45, 0.60 cm)
  - *Assume shape of probability curve does not change with future SLR*
- **Then… analyze tide elevations above some flood threshold**



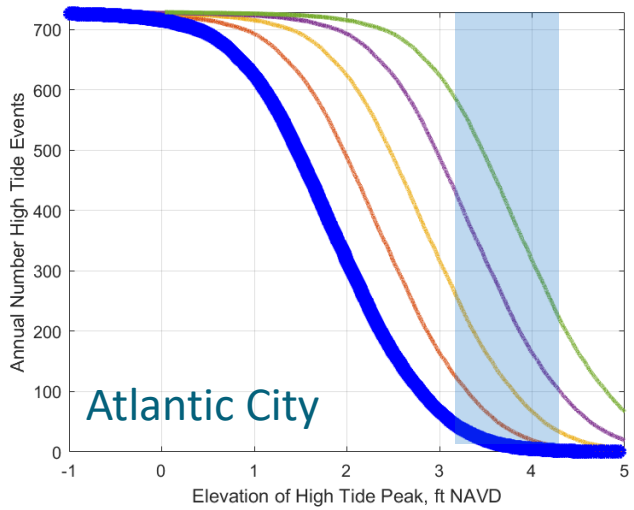
Conversion: 1 foot = 30 cm

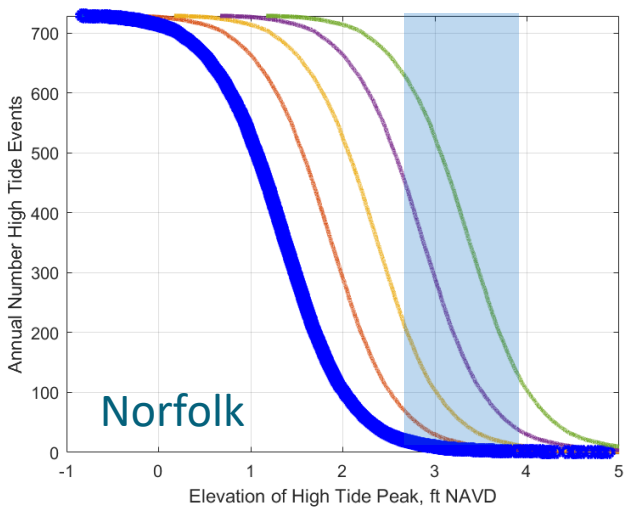
Apply Flood Stage
To Probability Curves for High Tide Events

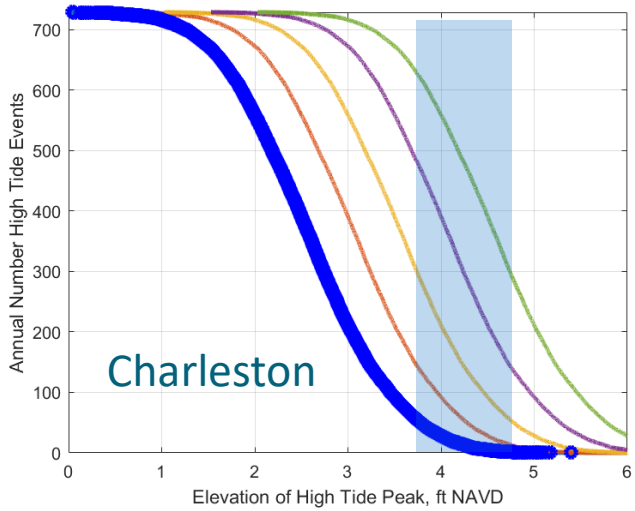


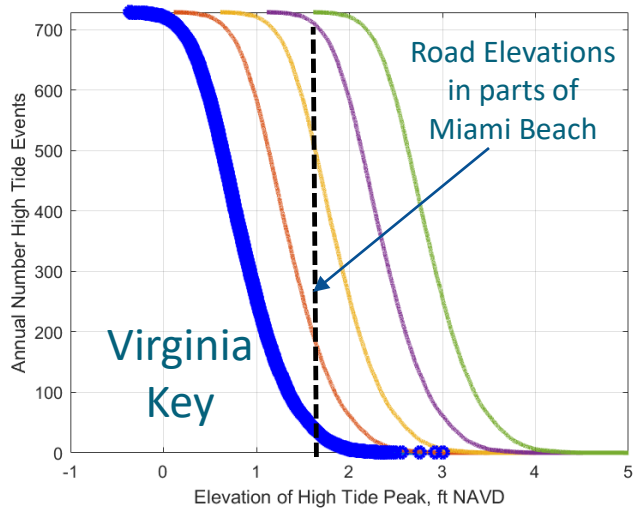


Existing trend (blue) plus 0.5, 1.0, 1.5, and 2.0 ft relative sea level rise

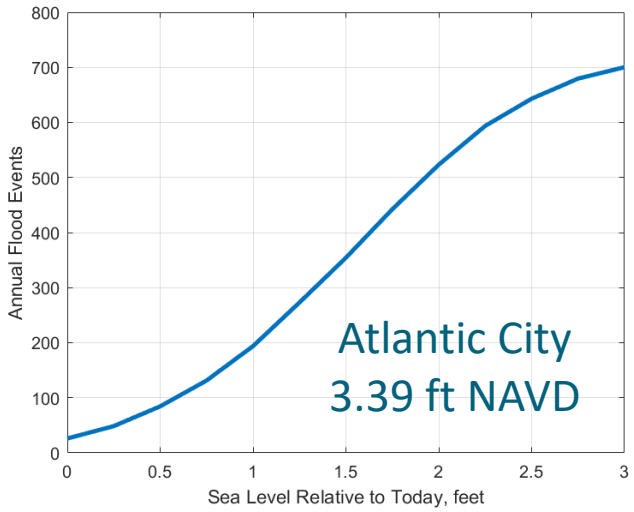


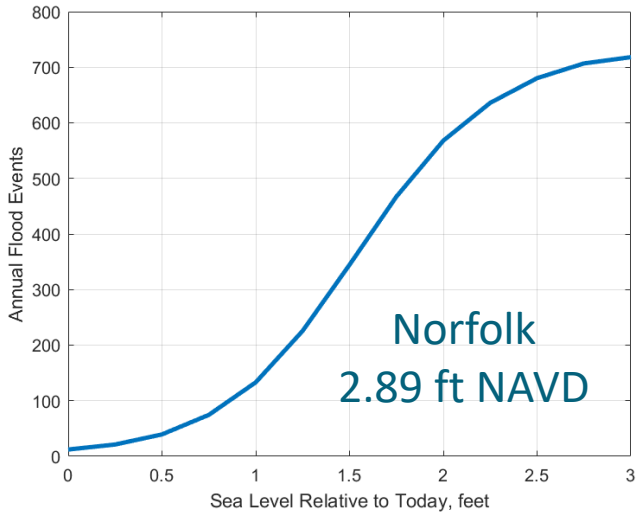


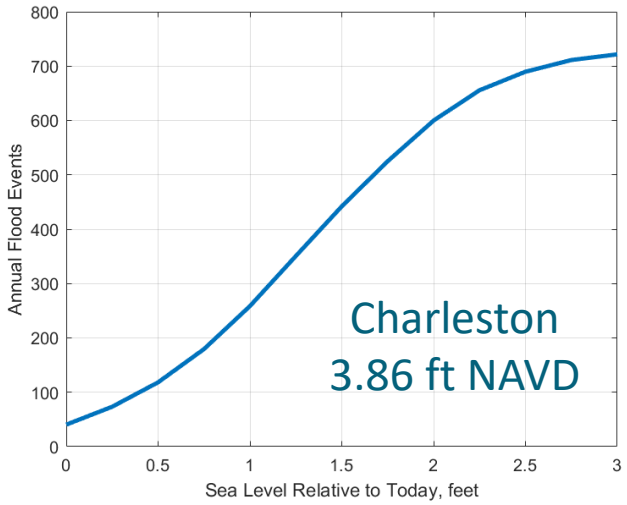


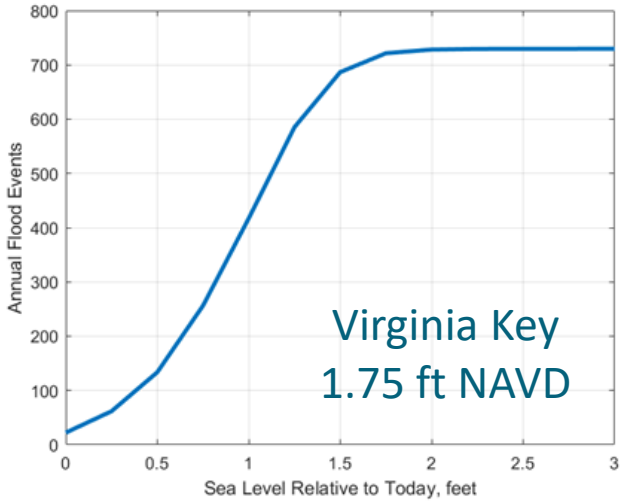


Existing and Future Flood Events above NOAA Minor Flood Stage



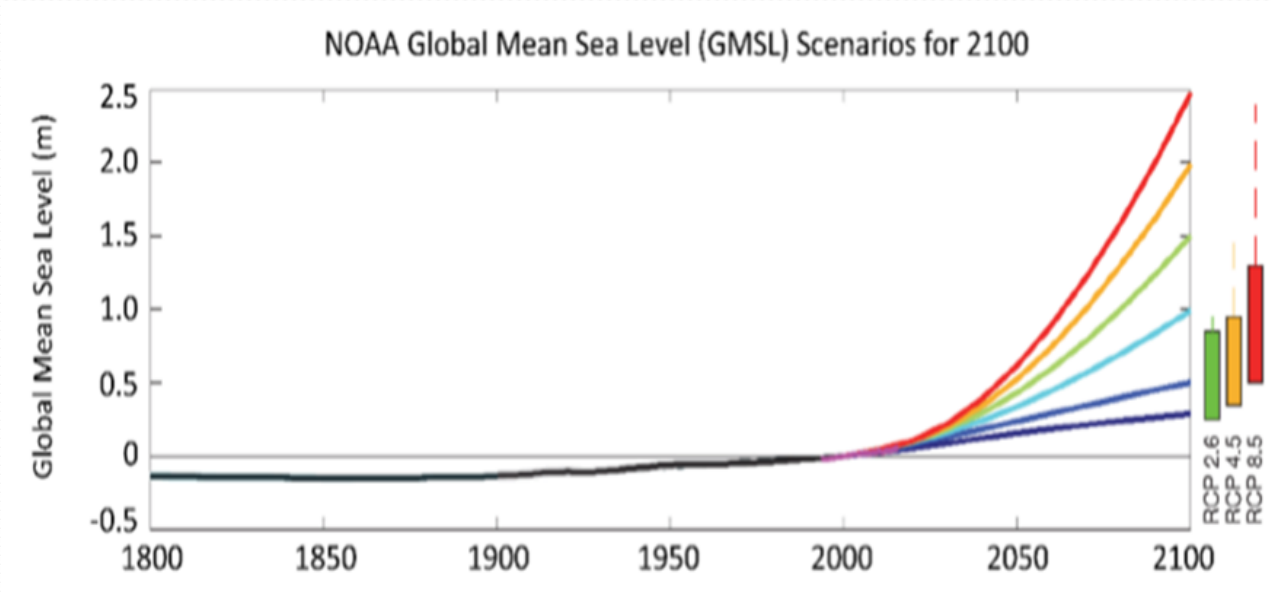


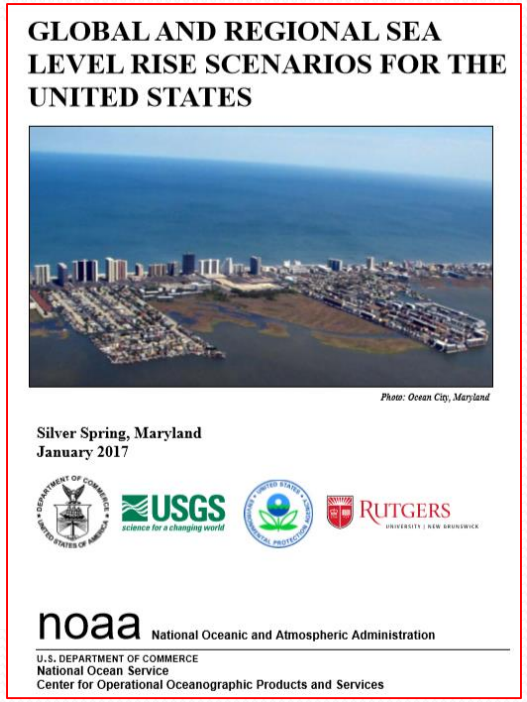




Projections with Future Sea Level Rise by Year

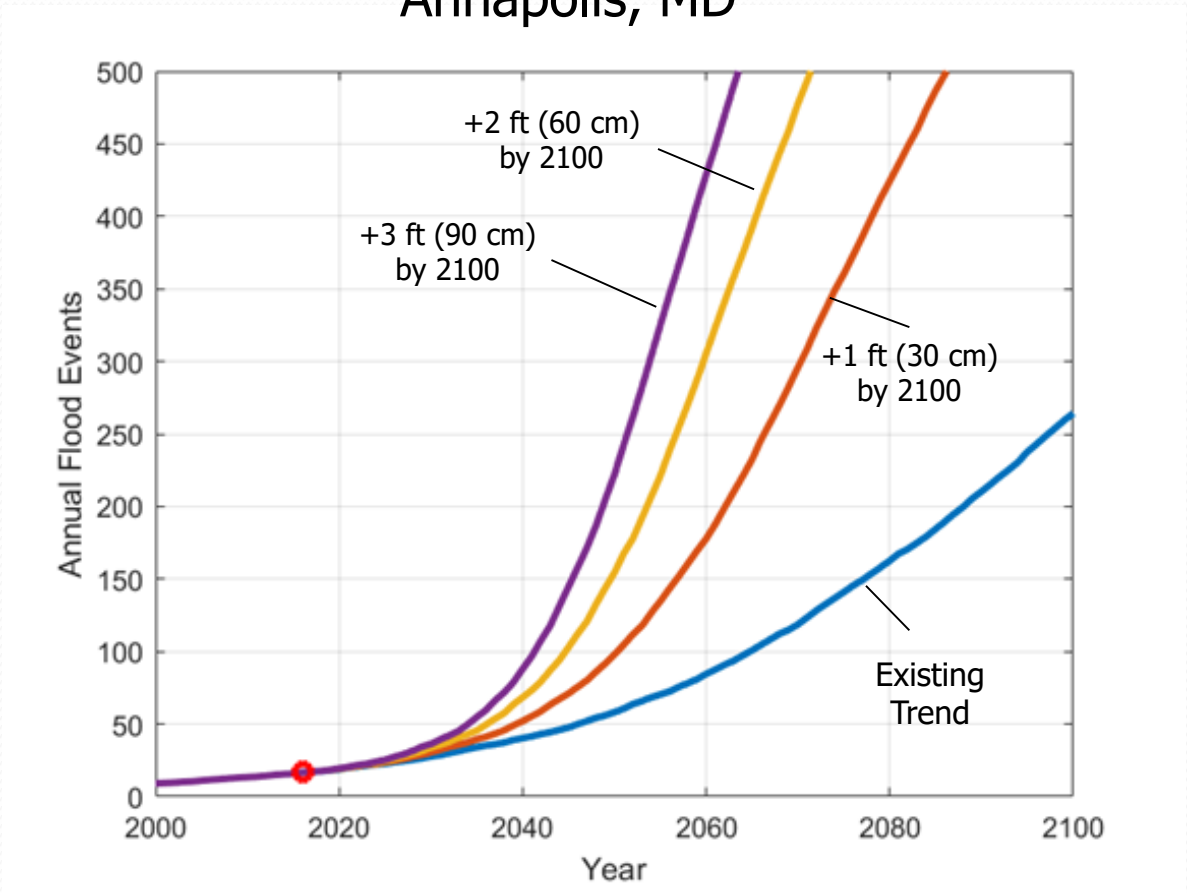
- Apply future sea level rise scenarios over time to year 2100
- Use existing trend plus 1 ft (0.3m), 2 ft (0.6m), or 3 ft (0.9m) to illustrate
  - Low to Medium range below following IPCC
- Determine number of flood events in any future year



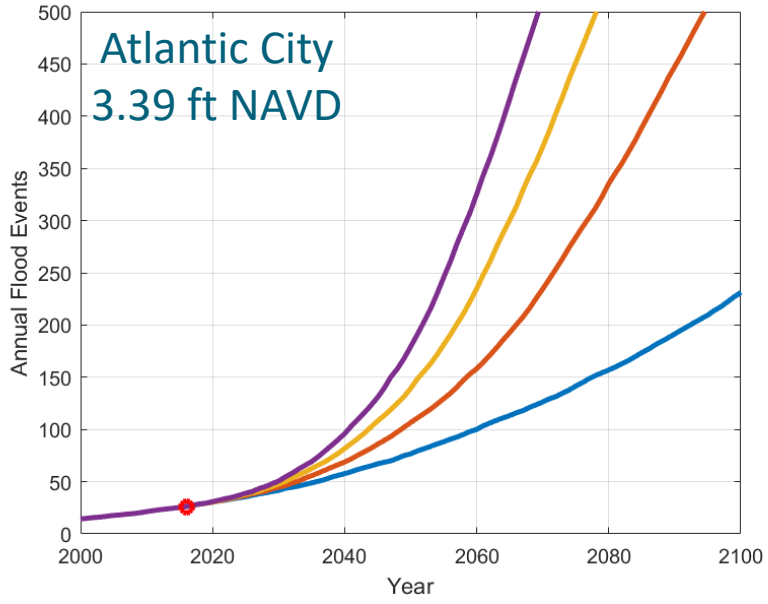


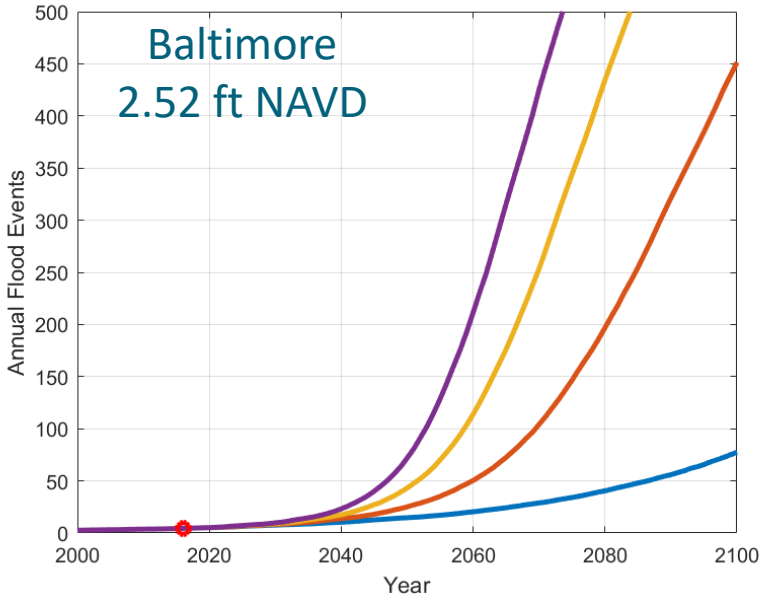
Number of Flood Events with Future Sea Level Rise Scenarios

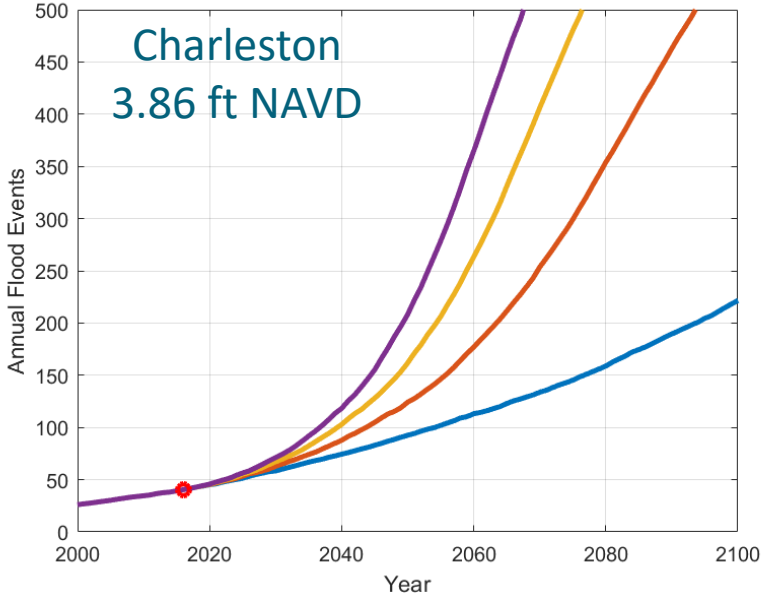
for Existing Trend (GSLR + VLM) then
Trend + 1 ft, Trend + 2 ft, Trend + 3 ft

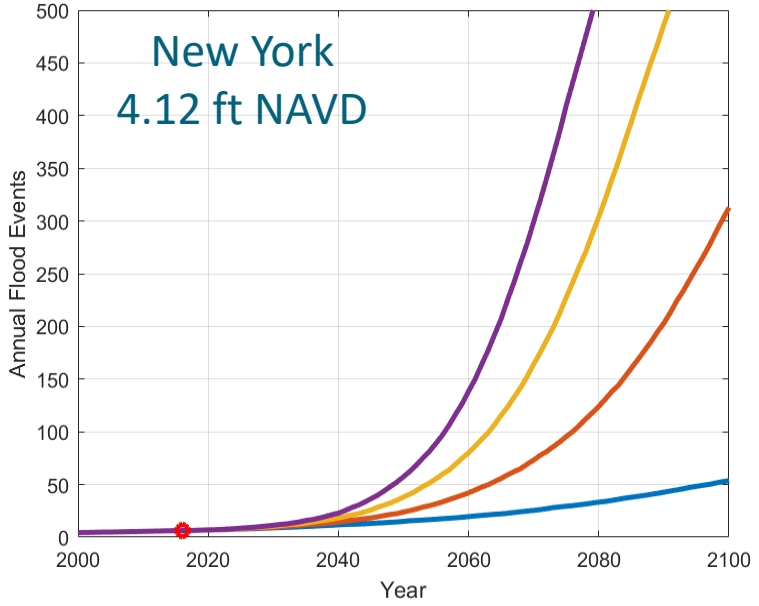


Future Flood Events above NOAA Minor Flood Stage





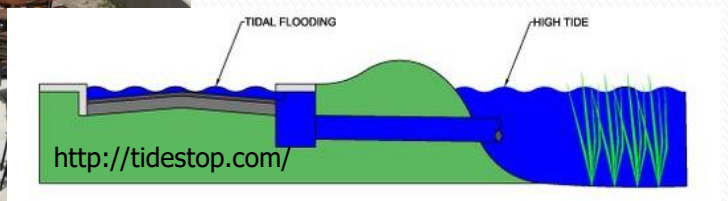




To Reduce Nuisance Flooding…

Increase Flood Threshold!

- Raise Roads
- Raise Buildings
- Raise Bulkheads/Seawalls
- Install Floodwall
- Install door dams or barriers
- Install tidal check valves



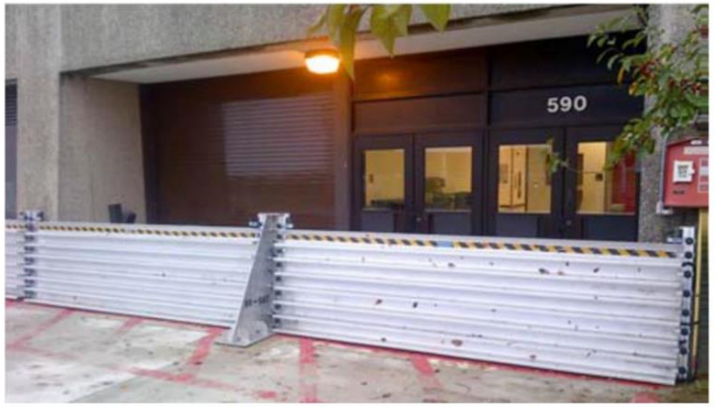
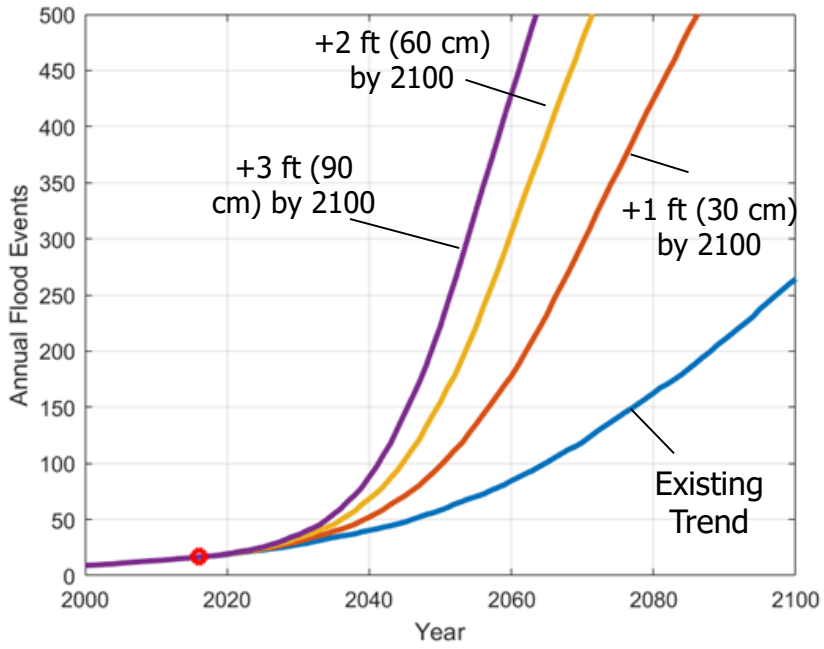


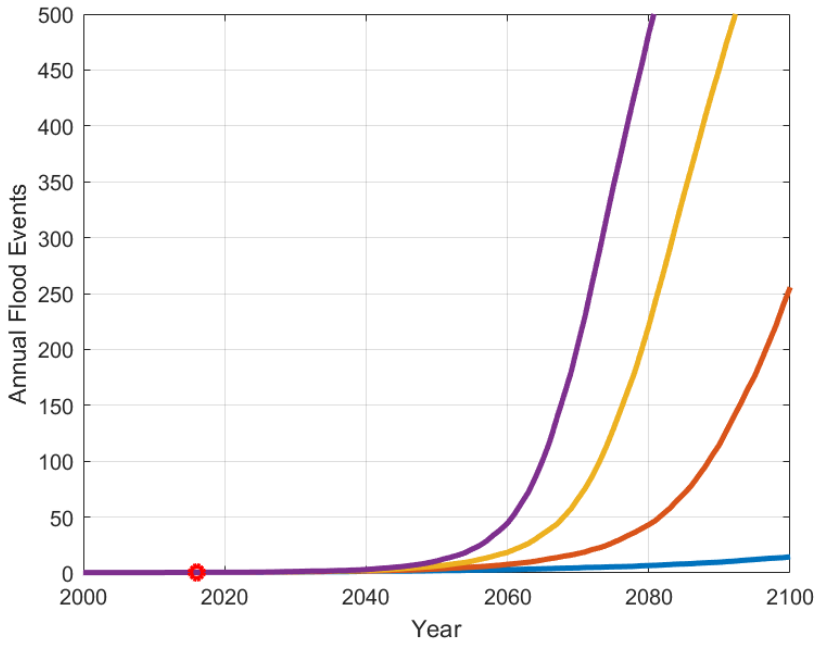
Figure 6: Temporary flood protection stoplogs installed at the U.S. Naval Academy
(Source: U.S. Navy)

Hypothetical Effect of Raising Roads (Raising Threshold) in Annapolis

USNA
McNair Rd
Existing Condition



USNA
McNair Rd
Raised 1 ft



In Conclusion

We have two choices…