GPS Campaign Surveys for Estimating Vertical Land Motion to Inform Coastal Management

NGS Webinar Series

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Outline

- What is Vertical Land Motion (VLM)?
- VLM and sea-level rise
- Techniques to estimate VLM
- Exploring VLM impacts to coastal management

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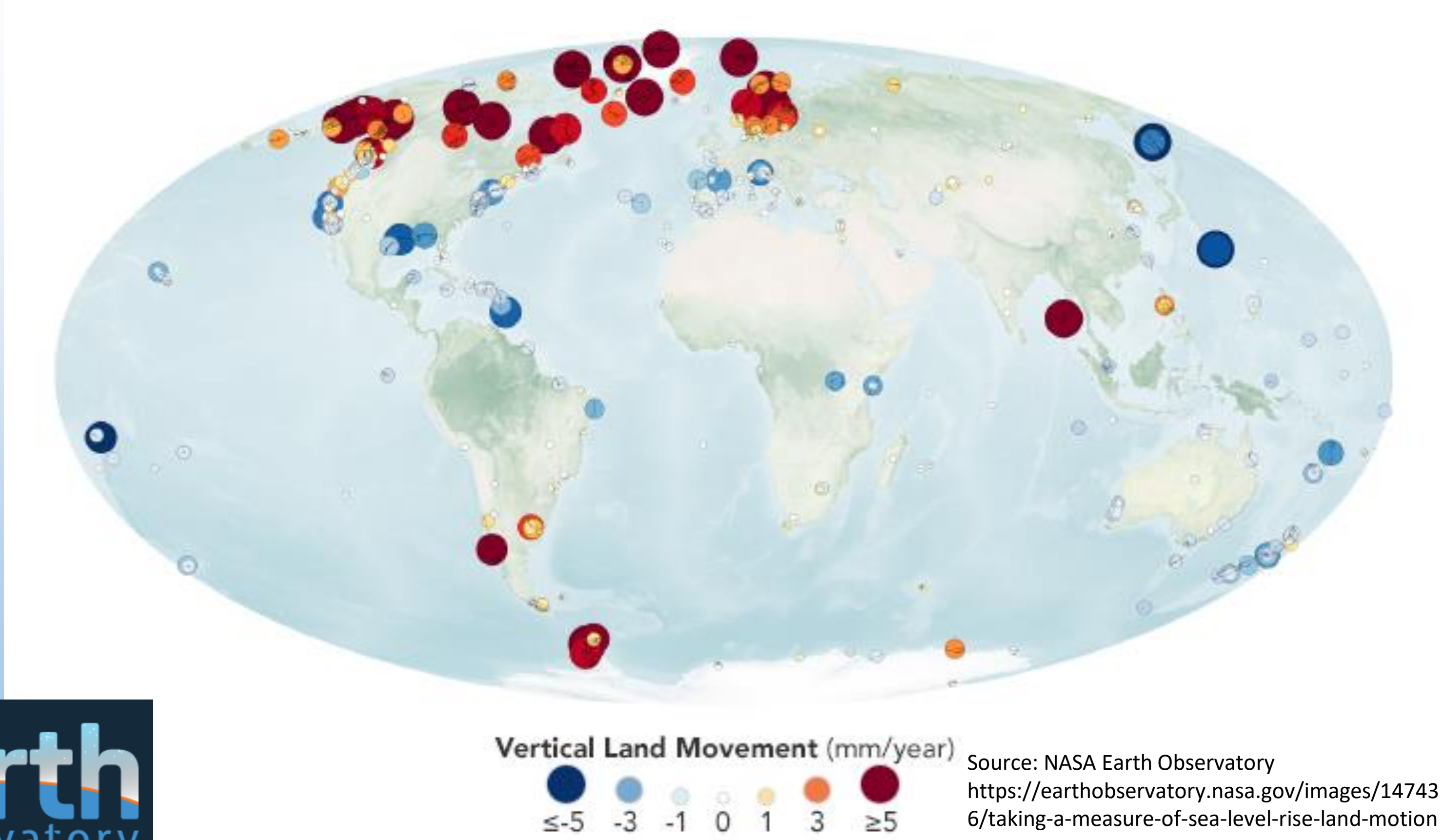
Vertical Land Motion



Source: NASA Earth Observatory
https://earthobservatory.nasa.gov/images/147436/taking-a-measure-of-sea-level-rise-land-motion

Causes of VLM

- Plate tectonics
- Glacial Isostatic Adjustment (GIA)
- Bolide impacts
- Sedimentary processes
- Subsurface fluid withdrawal

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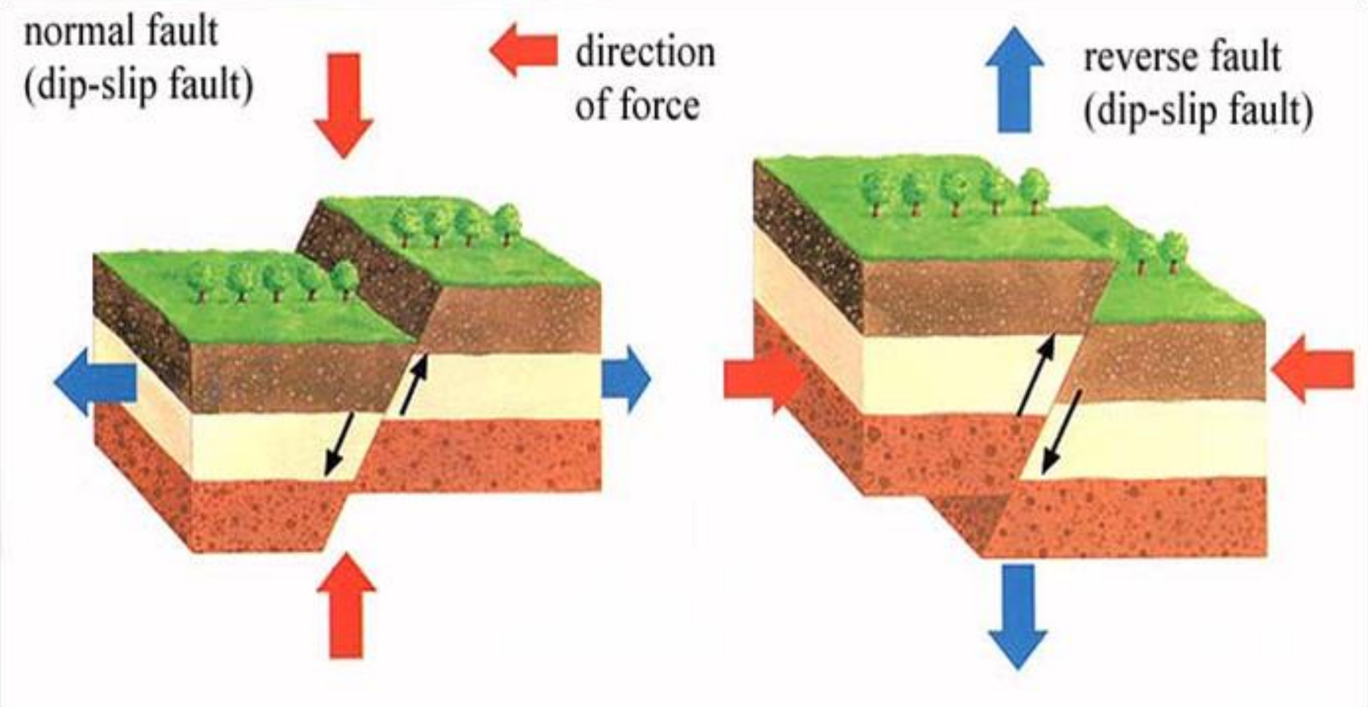
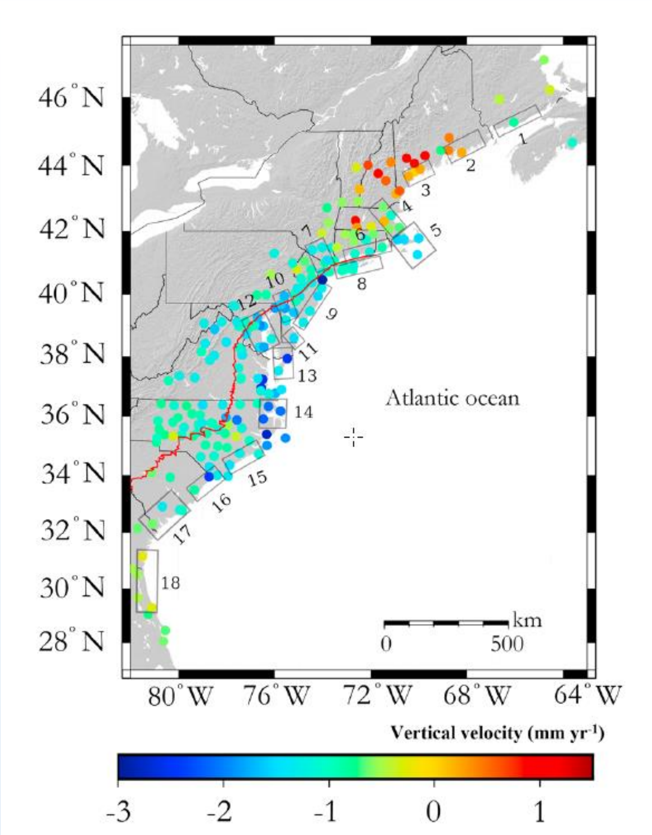
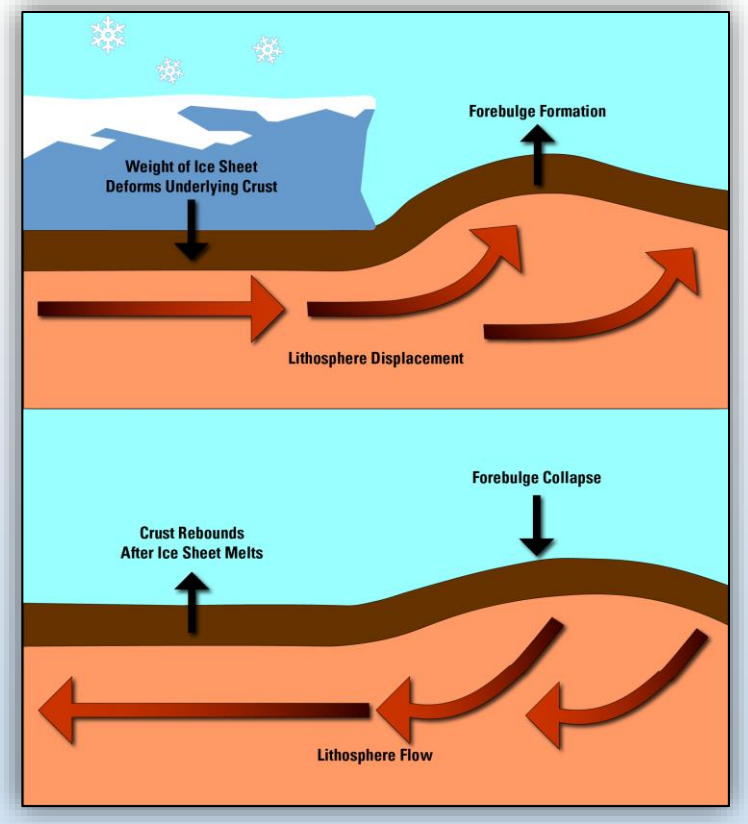
Plate Tectonics



http://blackpoolsixthasgeography.pbworks.com/w/page/23285268/Tectonic%20Uplift

Glacial Isostatic Adjustment (GIA)

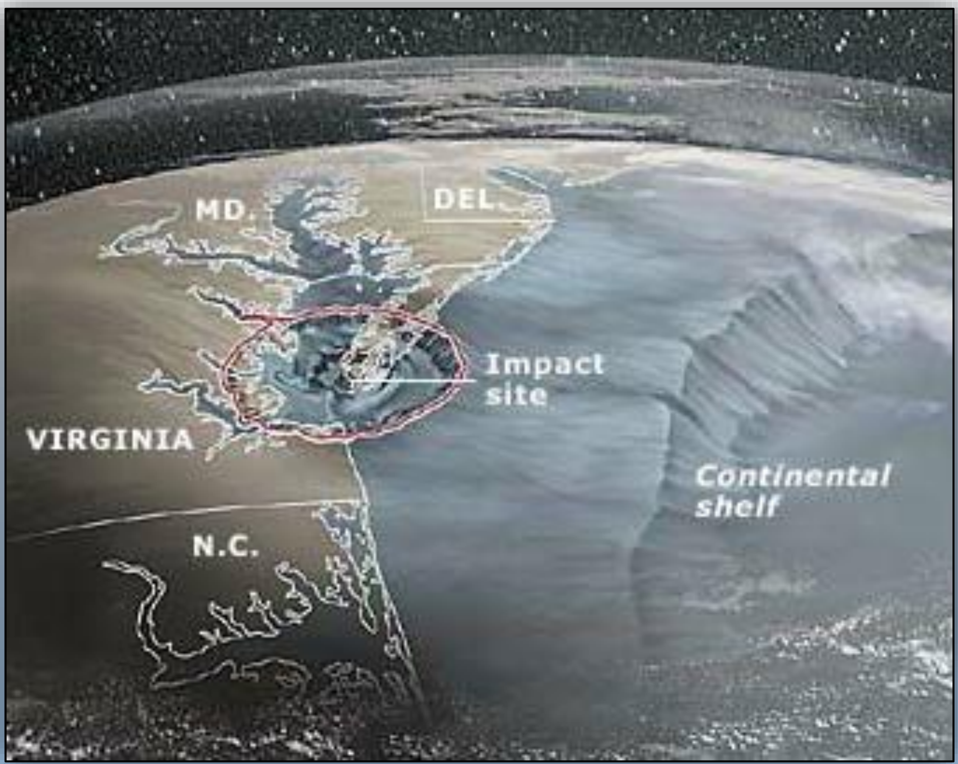




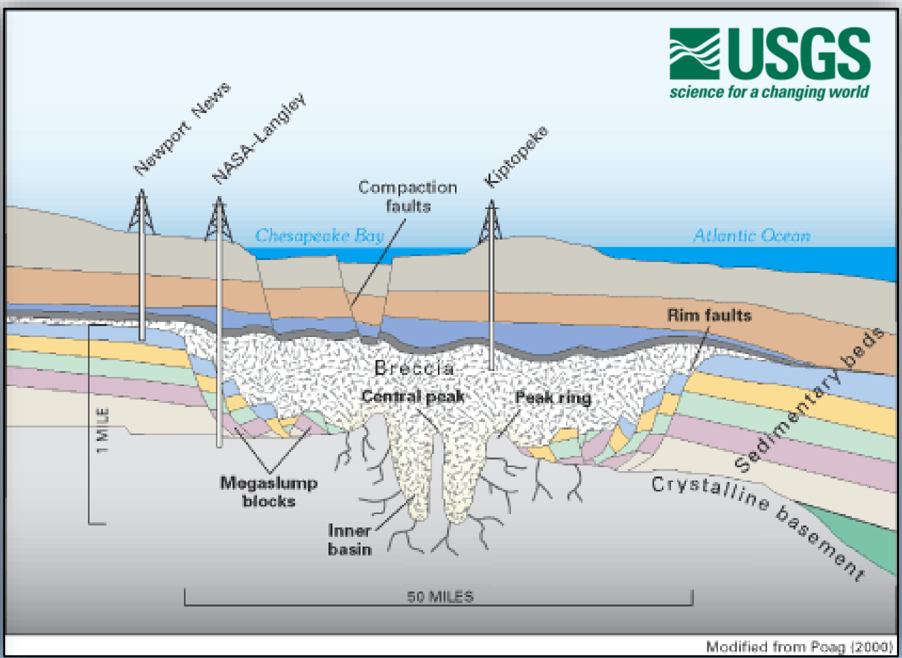
Karegar, M. A., T. H. Dixon, and S. E. Engelhart (2016), Subsidence along the Atlantic Coast of North America: Insights from GPS and late Holocene relative sea level data, Geophys. Res. Lett., 43, 3126–3133

Source: https://www.vims.edu/research/products/slrc/compare/west_coast/index.php

Bolide Impact in the Chesapeake Bay

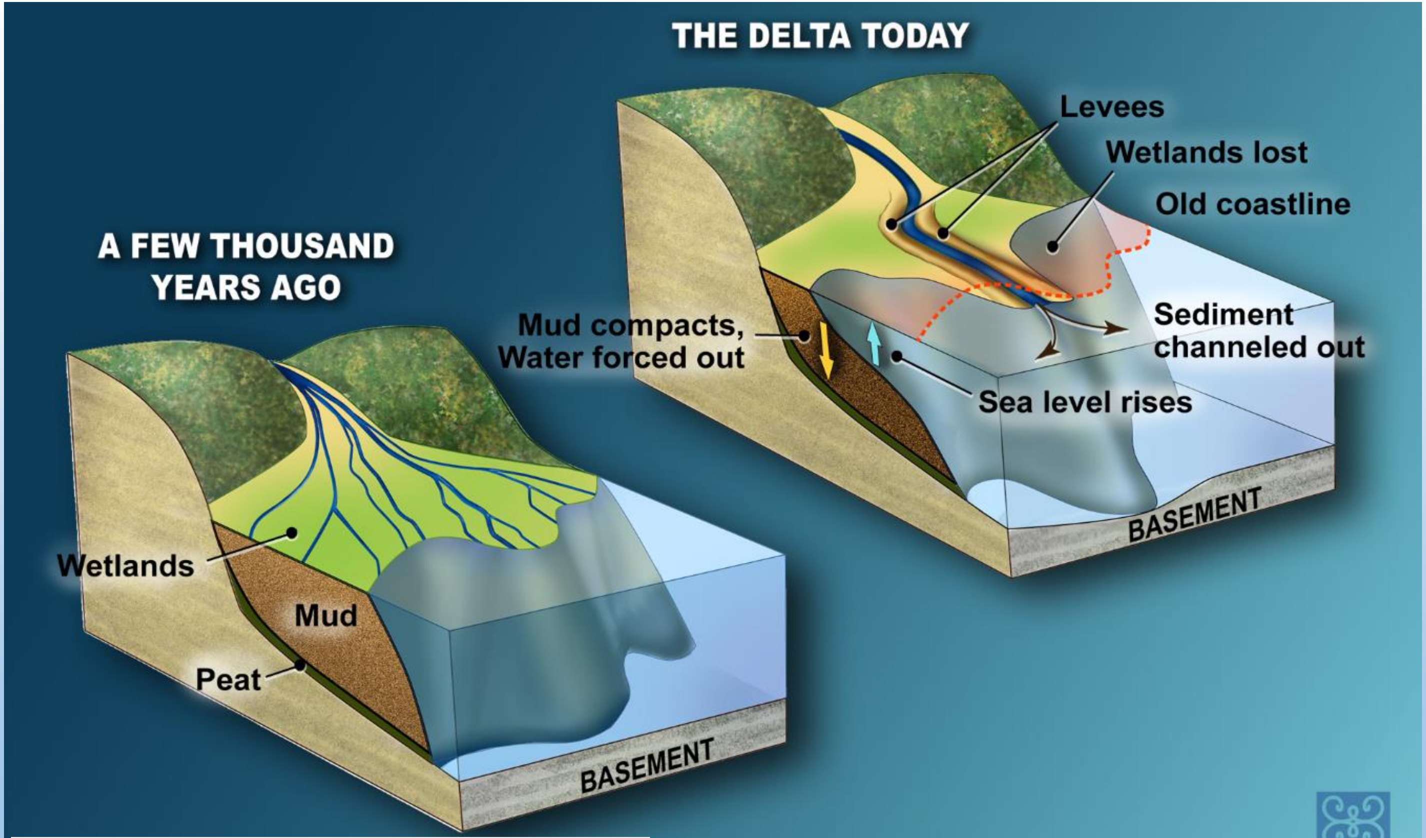


Michael Hall, The Virginian-Pilot, June 25,2001



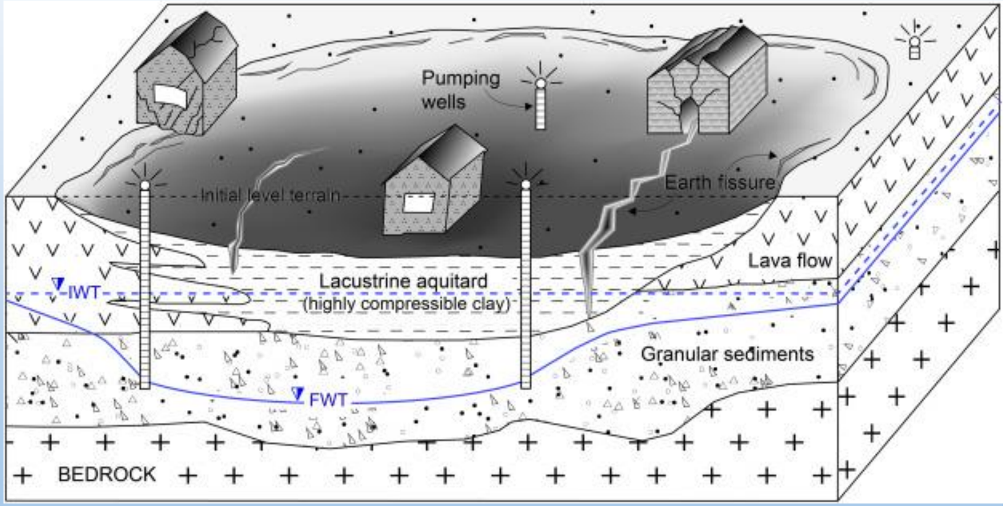
USGS Circular 1262, Barlow, 2003

Sediment Compaction

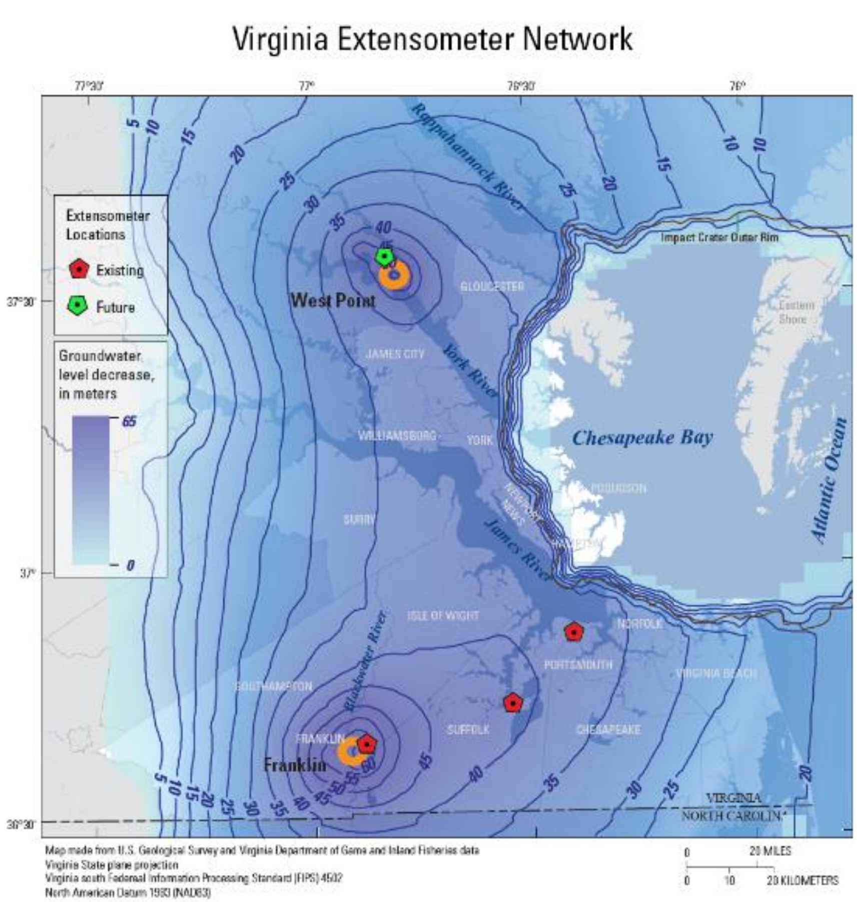


Credit: *Zina Deretsky, National Science Foundation*

Subsurface Fluid Withdrawal



Credit: Figueroa-Miranda et al. 2018



https://va.water.usgs.gov/geonarratives/va-subsidence-geonarrative/

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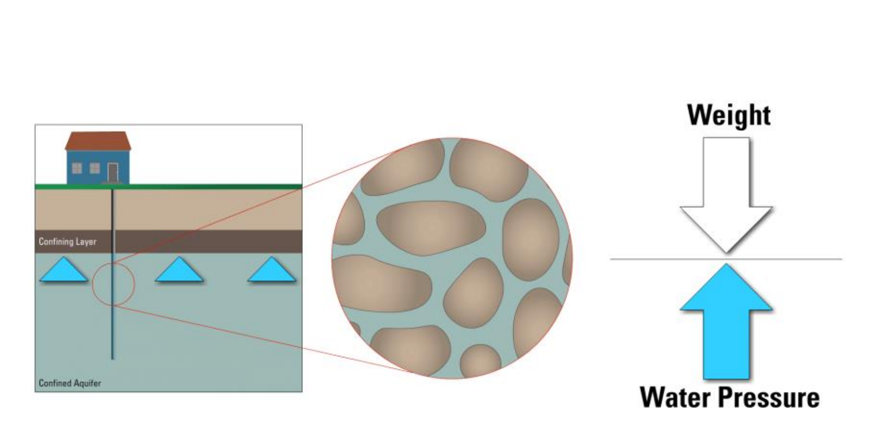
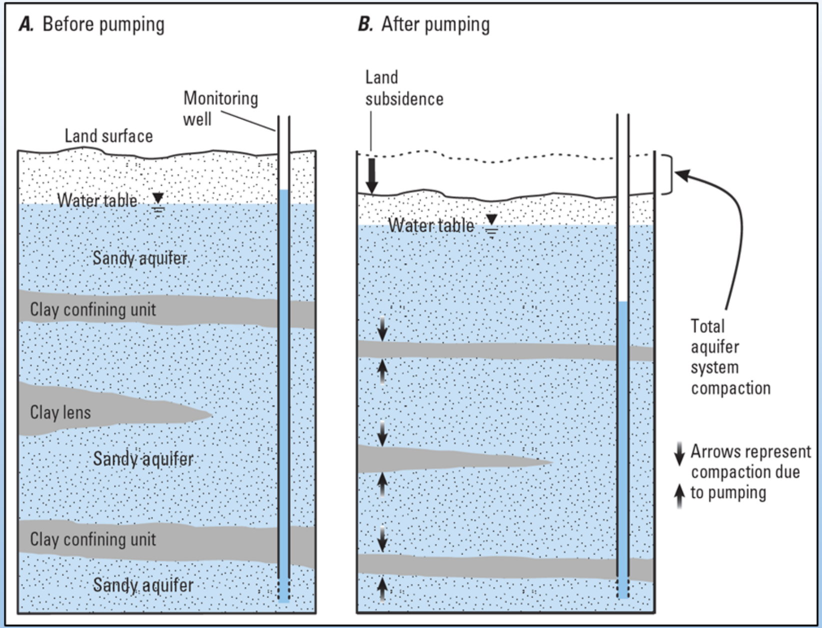
Subsurface Fluid Withdrawal

- Potomac Aquifer historically flowed freely to the surface (artesian)
- Primary regional groundwater source
- Extraction shrinks space between sediments grains



USGS Public Domain

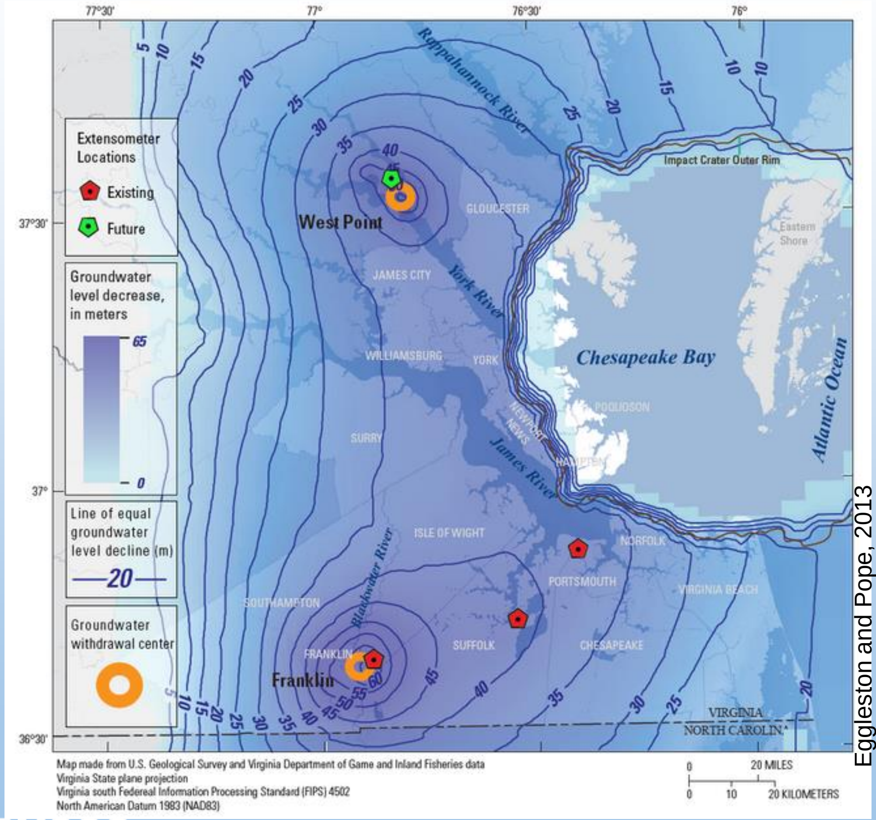
Aquifer-System Compaction (ASC)



Eggleston and Pope, 2013 after Galloway and others, 1999

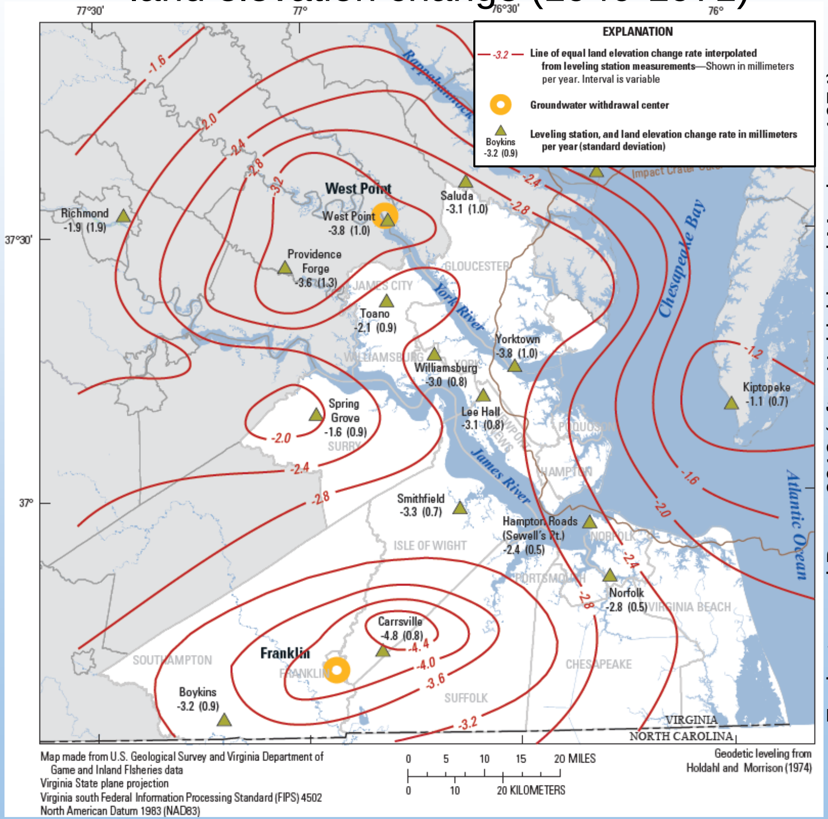
Groundwater levels and VLM across the VACP

groundwater level decline (1900-2008)



Eggleston and Pope, 2013

land elevation change (1940-1971)



Eggleston and Pope, 2013 (after Holdahl and Morrison, 1974)

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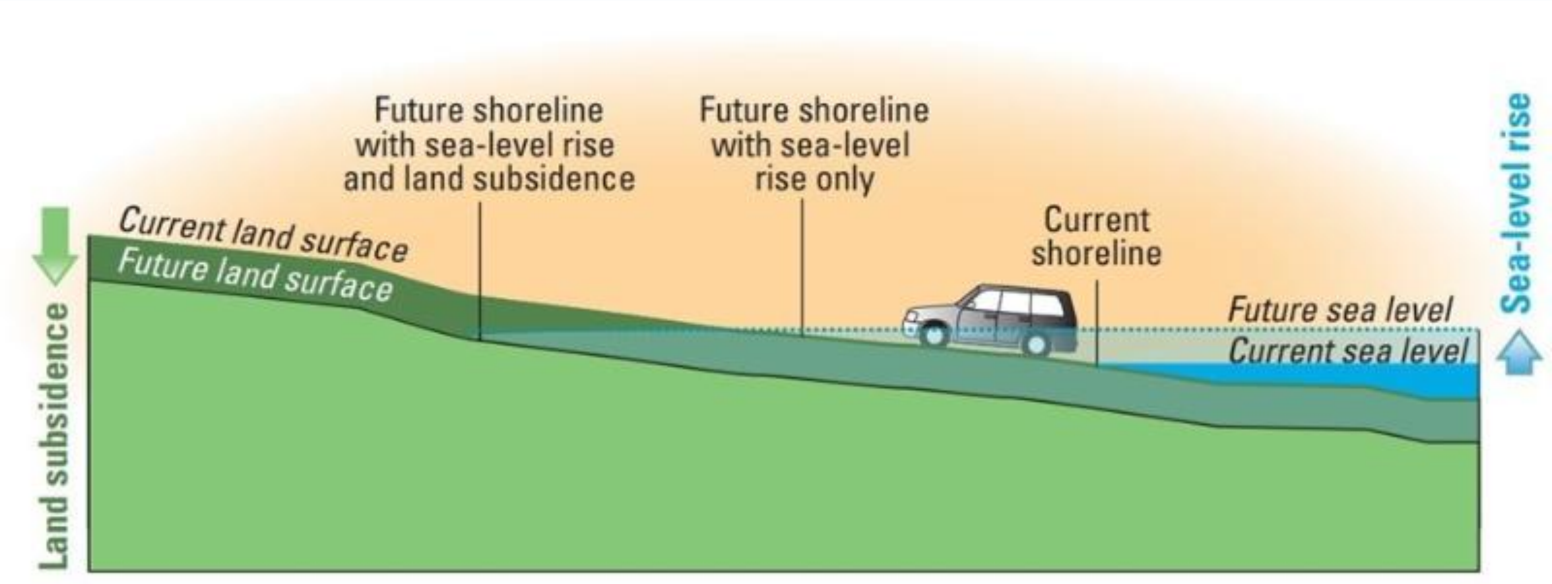
Vertical Land Motion and Sea-Level Rise



Eggleston and Pope, 2013

Relative Sea-Level Rise = Sea-Level Rise + Vertical Land Motion

RSLR = SLR + VLM

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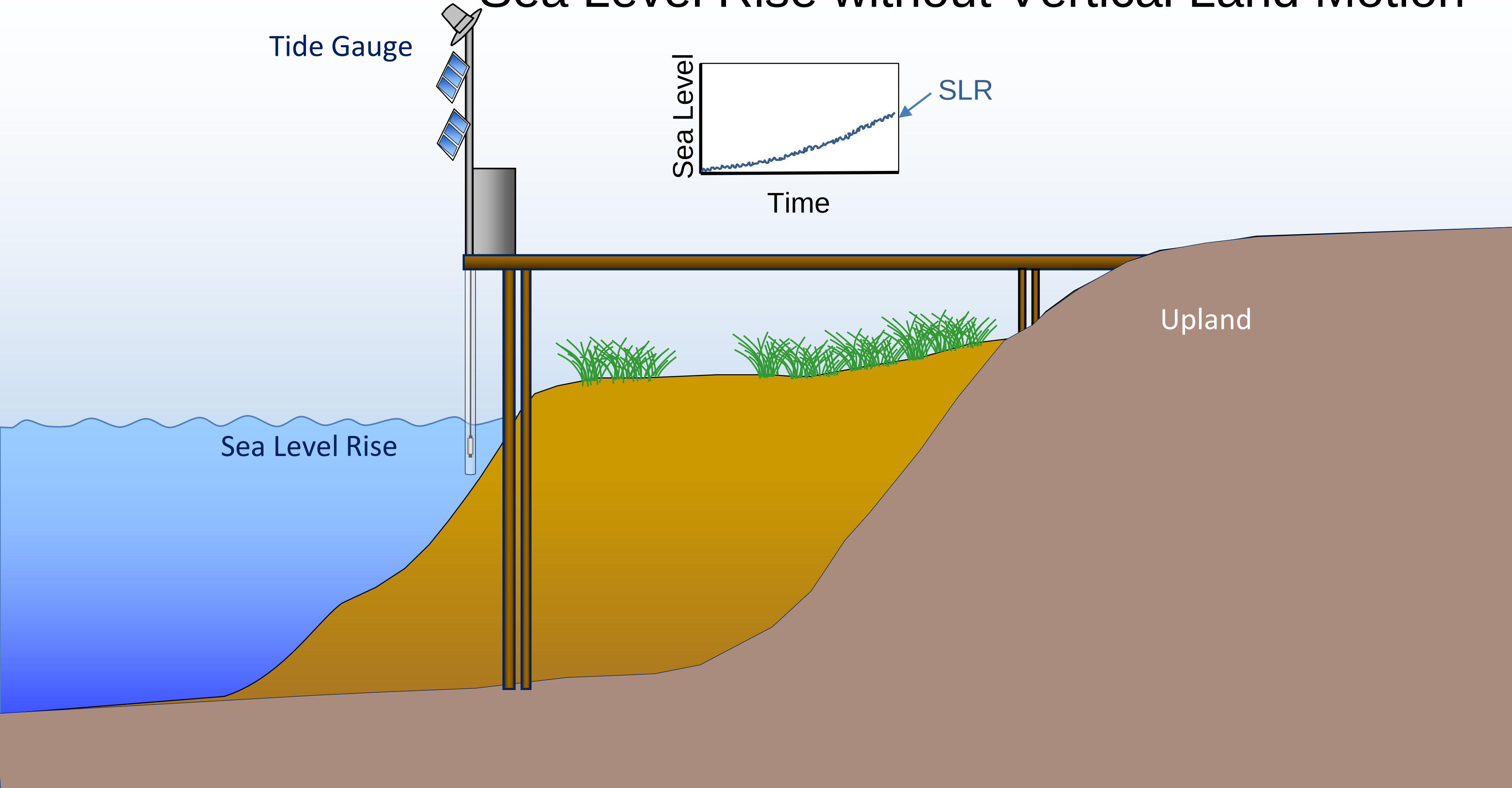
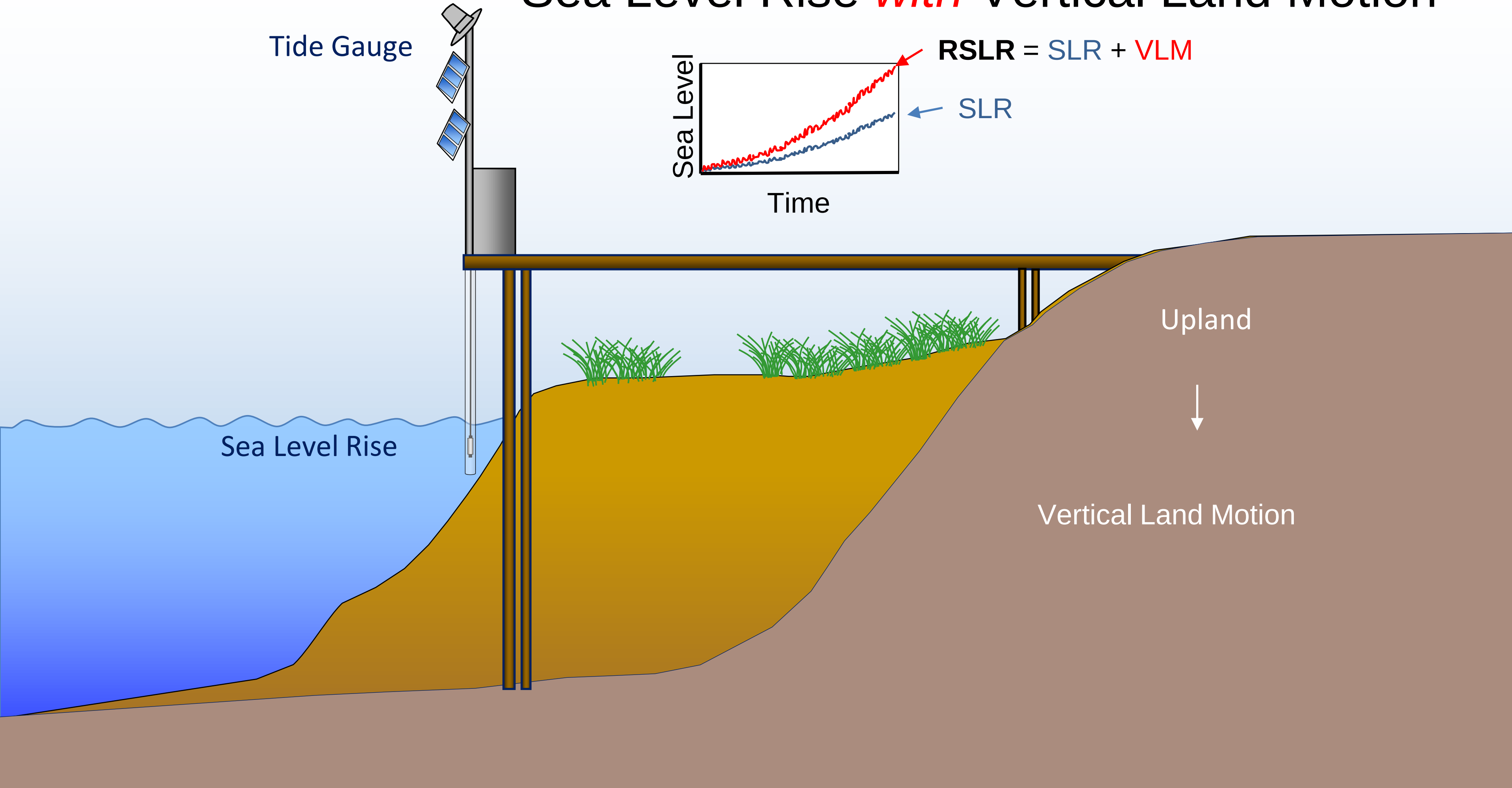
Sea Level Rise without Vertical Land Motion



Sea Level Rise *with* Vertical Land Motion



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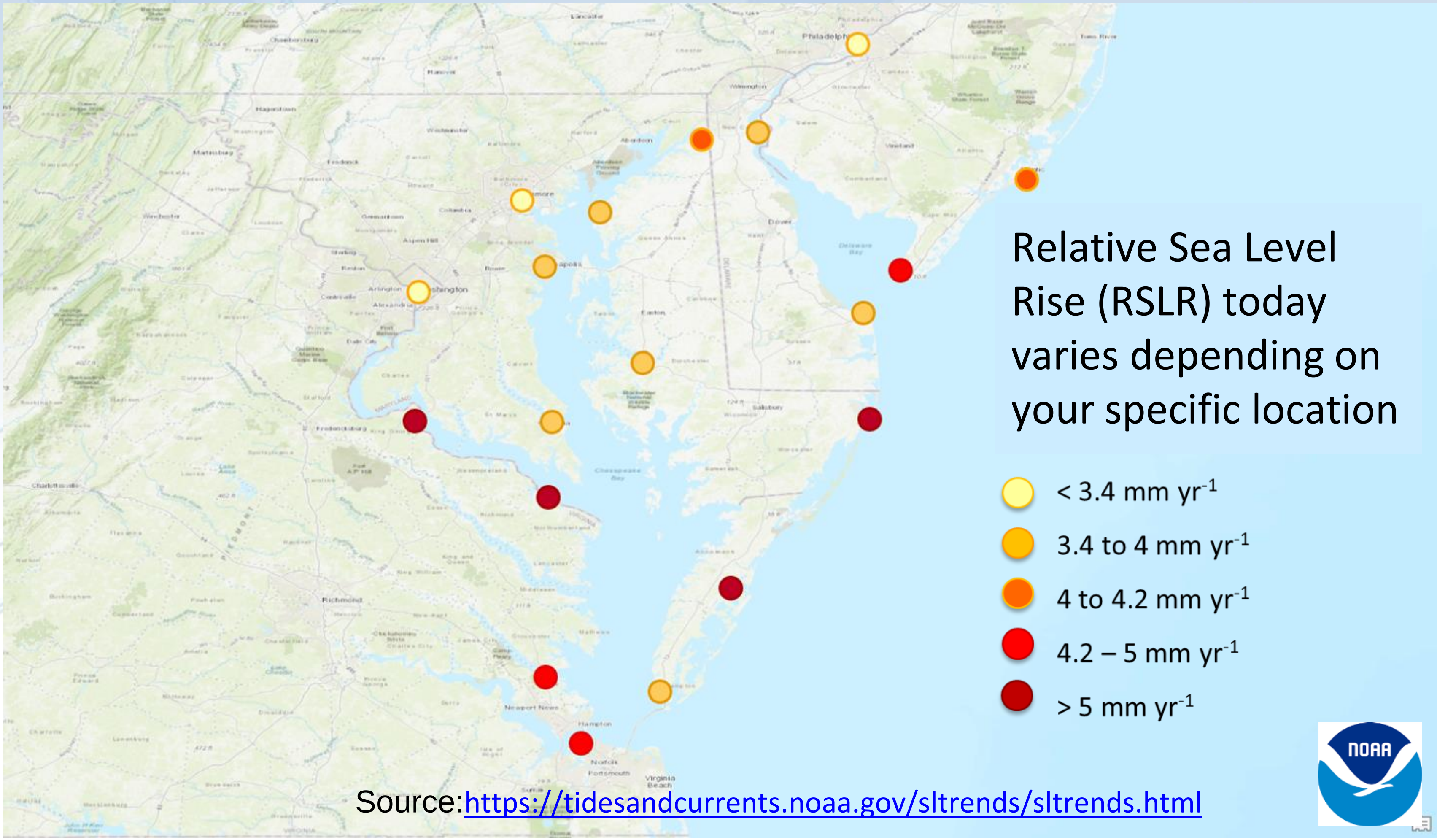
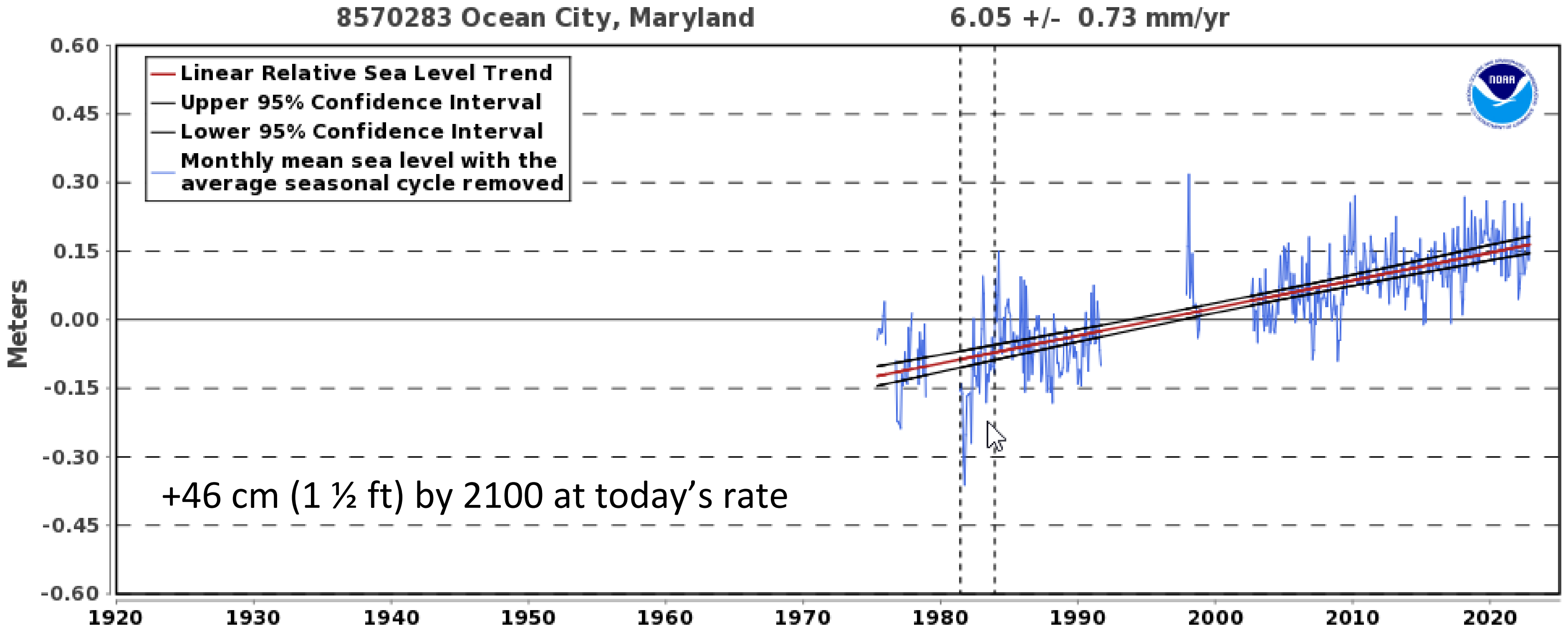


Relative Sea Level Rise (RSLR) today varies depending on your specific location

- < 3.4 mm yr^{-1}
- 3.4 to 4 mm yr^{-1}
- 4 to 4.2 mm yr^{-1}
- 4.2 – 5 mm yr^{-1}
- > 5 mm yr^{-1}

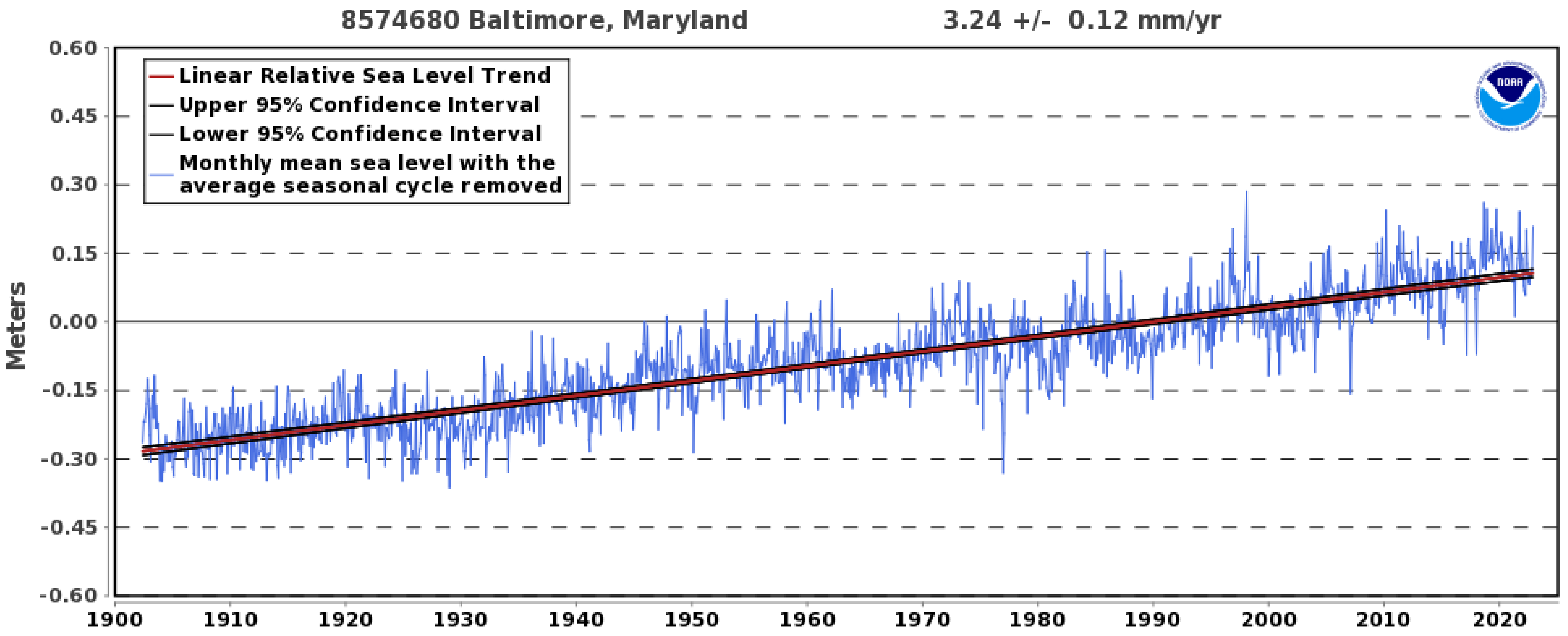
Source:https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

Relative Sea Level Trend
8570283 Ocean City, Maryland



Source: https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

Relative Sea Level Trend
8574680 Baltimore, Maryland



Source: https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

Global Sea-Level Rise

Global Sea-Level Rise rate depends on time scale of computation!

1901-1990 (90 yrs): 1.4 mm yr^{-1} ▲

1970-2015 (45 yrs): 2.1 mm yr^{-1} ▲

1993-2015 (22 yrs): 3.2 mm yr^{-1} ▲

IPCC, 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp. https://doi.org/10.1017/9781009157964.

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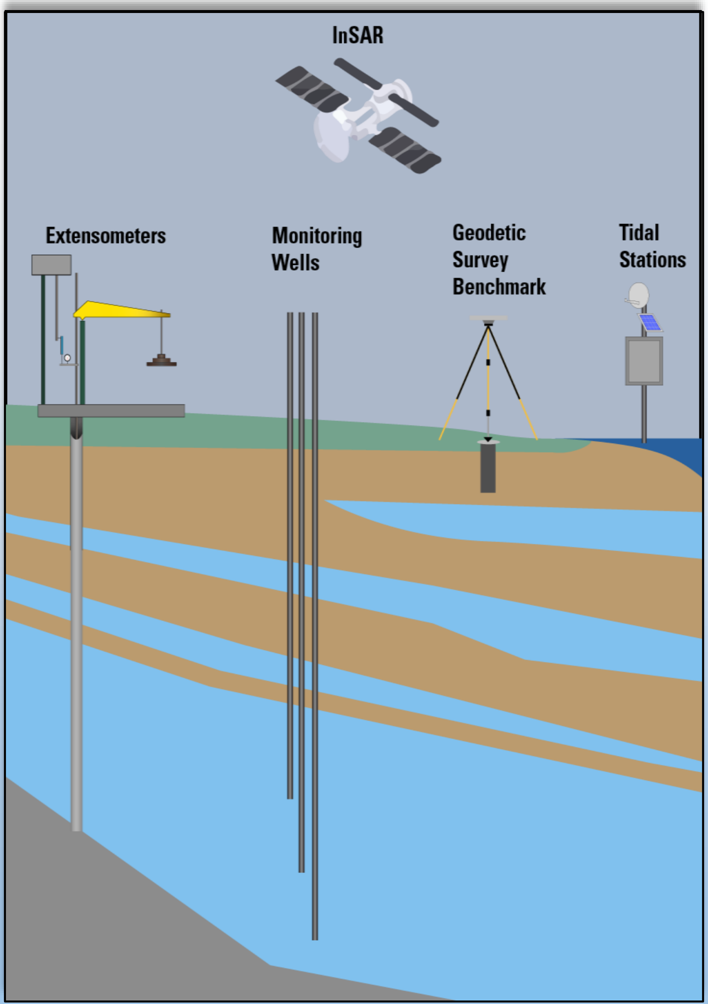
Quantifying VLM

- **Borehole Extensometers**: California, Texas, Virginia
- Geodetic Surveying
  - **GNSS**: Continuous or **discrete**
  - Differential Leveling
- Analyses of long-term tide gauges
- Remote Sensing
  - Synthetic Aperture Radar (SAR)
  - InSAR
  - NiSAR (2024)

Method	Type of data	Measures aquifer-system compaction independently	Spatial coverage	Temporal detail
Borehole extensometer	Aquifer-system thickness at one location, continuous record	Yes	Low	High
Tidal station	Sea elevation at one location, continuous record	No	Low	High
Geodetic surveying	Land elevations at one or several locations, multiple times or continuous record	No	Low to moderate	Low to high
Remote sensing (InSAR)	Land elevations over a wide area, at multiple times	No	High	Moderate



Borehole Extensometer Research Overview

Holdahl and Morrison, 1974 (NOAA)

- Primary source for regional land subsidence rates (1940's to 1970's)
  - ~ 2.0 mm/yr. throughout Hampton Roads
  - largest rates occurring in West Point at -3.2 mm/yr. and Franklin at -4.4 mm/yr.

USGS Borehole Extensometers

- Franklin and Suffolk established in response to Holdahl and Morrison study
  - Active late 1970's through mid 1990's

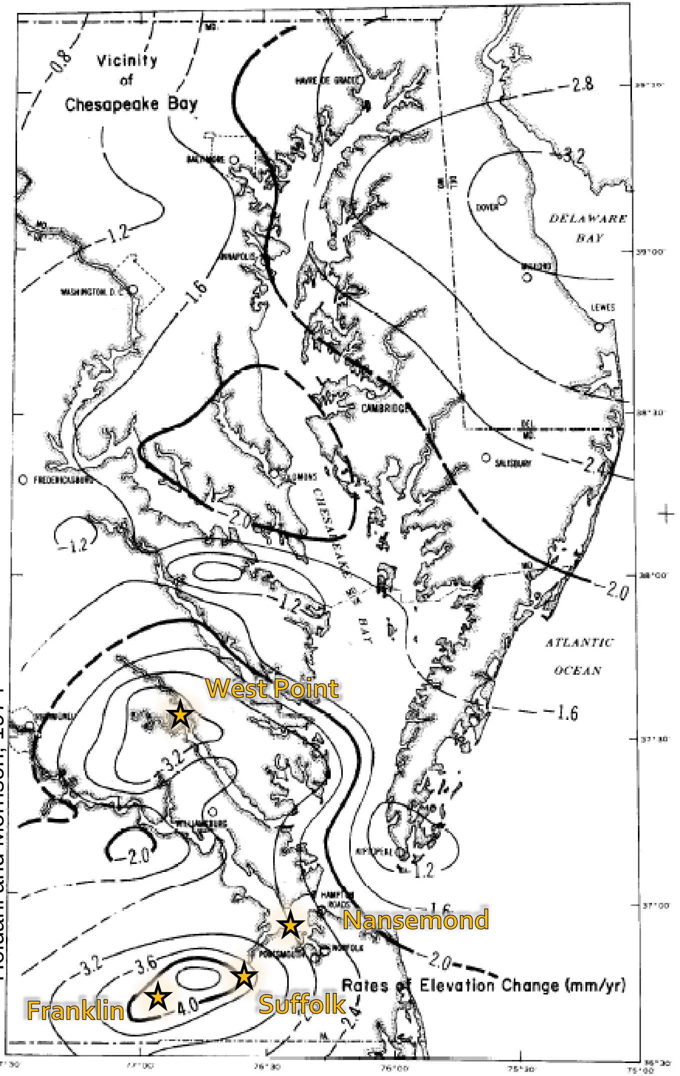
Need new baseline

USGS Borehole Extensometers

- Franklin and Suffolk reactivated in 2016
  - In cooperation with VA Department of Environmental Quality (DEQ)
- Nansemond installed in 2018 at the Nansemond Treatment Plant
  - In cooperation with Hampton Roads Sanitation District (HRSD)
- West Point planned for installation in 2023 in cooperation with DEQ

Global Navigation Satellite Systems (GNSS)

- New baseline study utilizing modern geodetic surveying techniques on passive/discrete benchmark monitoring networks



Holdahl and Morrison, 1974

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The Virginia Extensometer Network

Pictured: Nansemond Extensometer at HRSD's Sustainable Water Initiative for Tomorrow (SWIFT). Source: USGS, Public Domain

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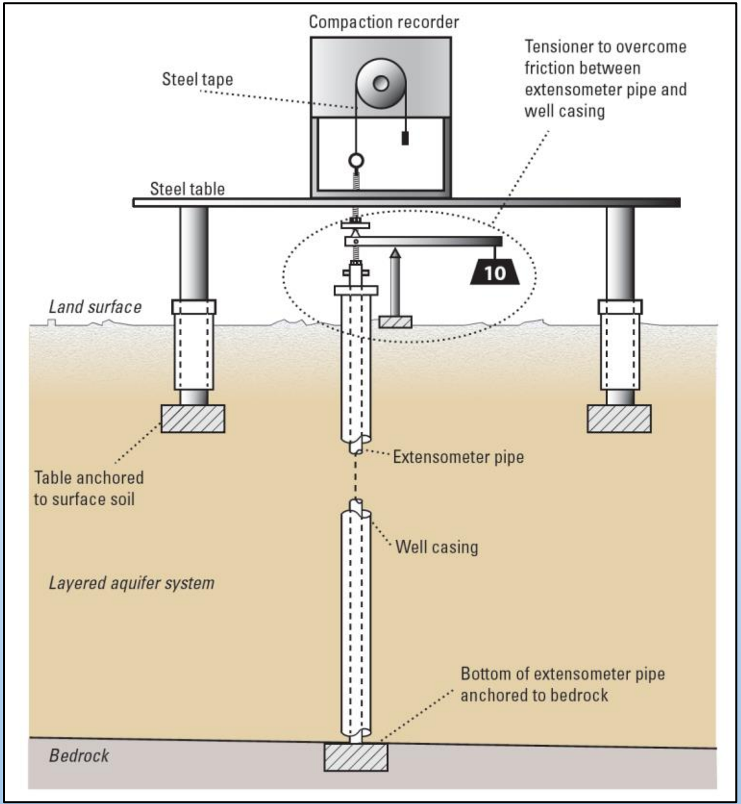
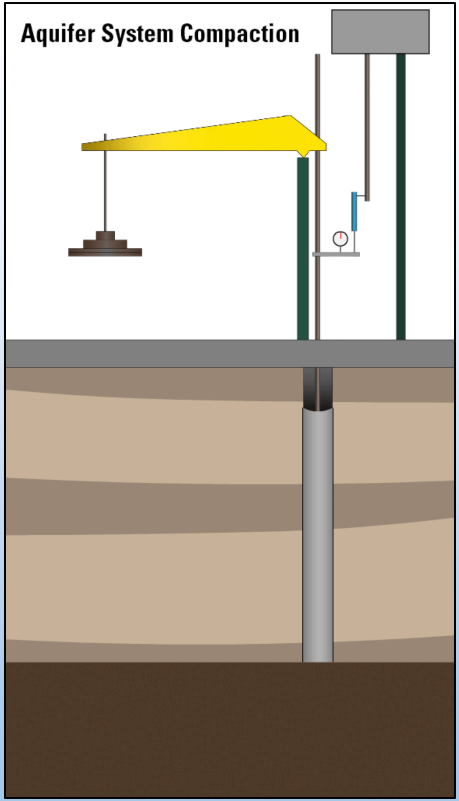
Extensometers and land motion

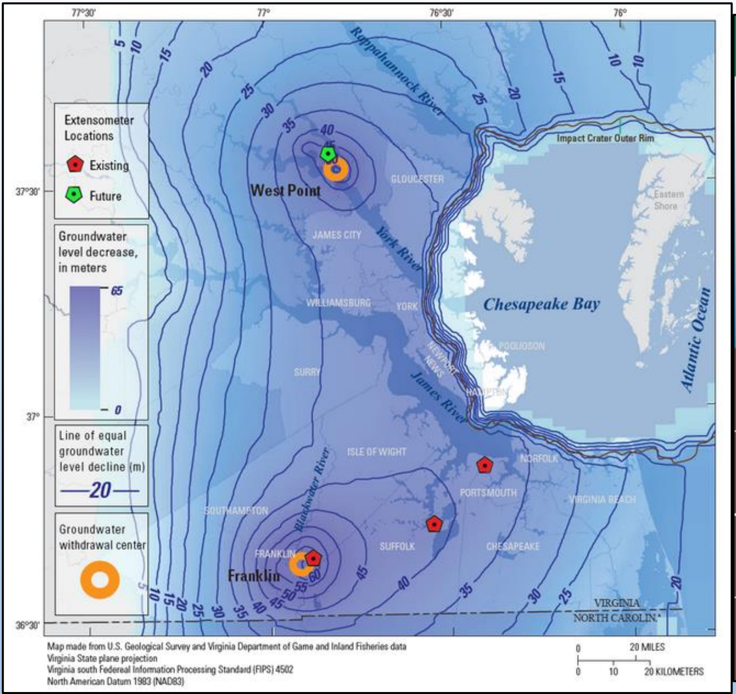


Eggleston and Pope, 2013

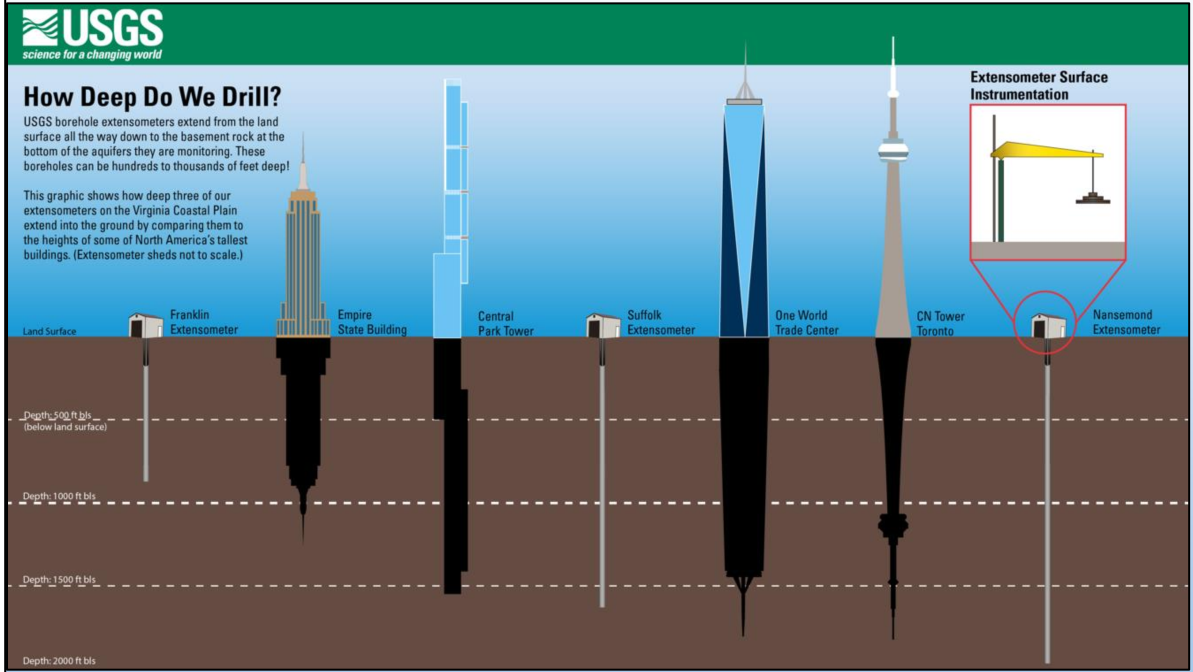


USGS, Public Domain

Virginia Extensometer Network



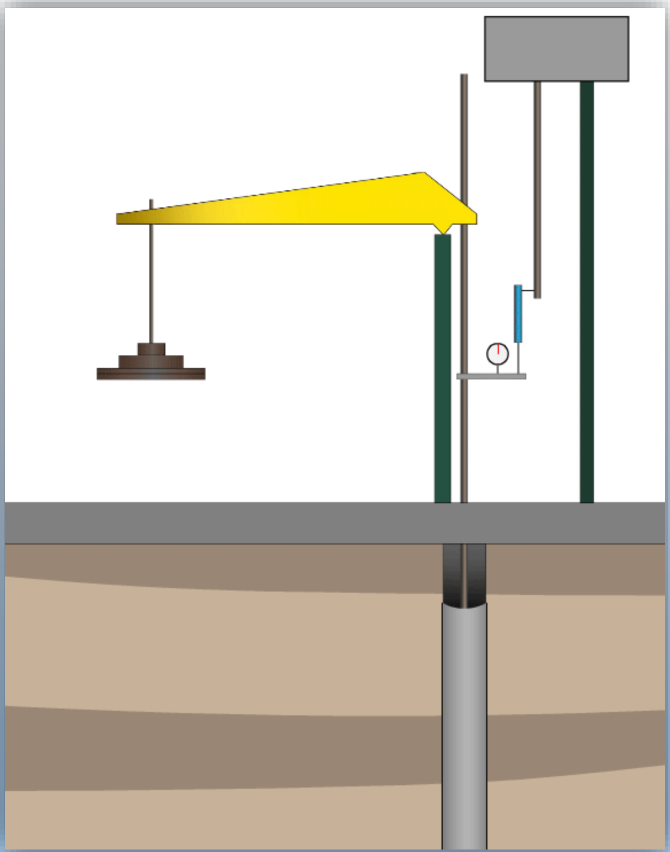
Eggleston and Pope, 2013



USGS, Public Domain

Franklin extensometer

- **Period of record**
  - 1979-1995; 2016-present
- **Depth**
  - 866 ft. bls
- **Location significance**
  - proximal to major pumping center



Franklin extensometer

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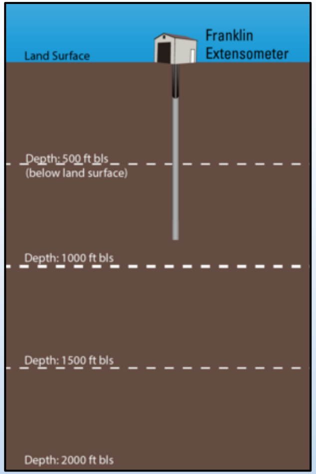
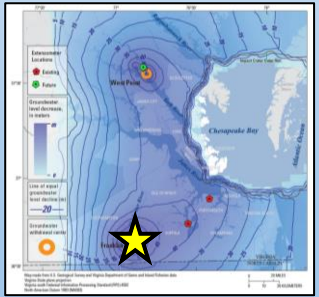
cross section

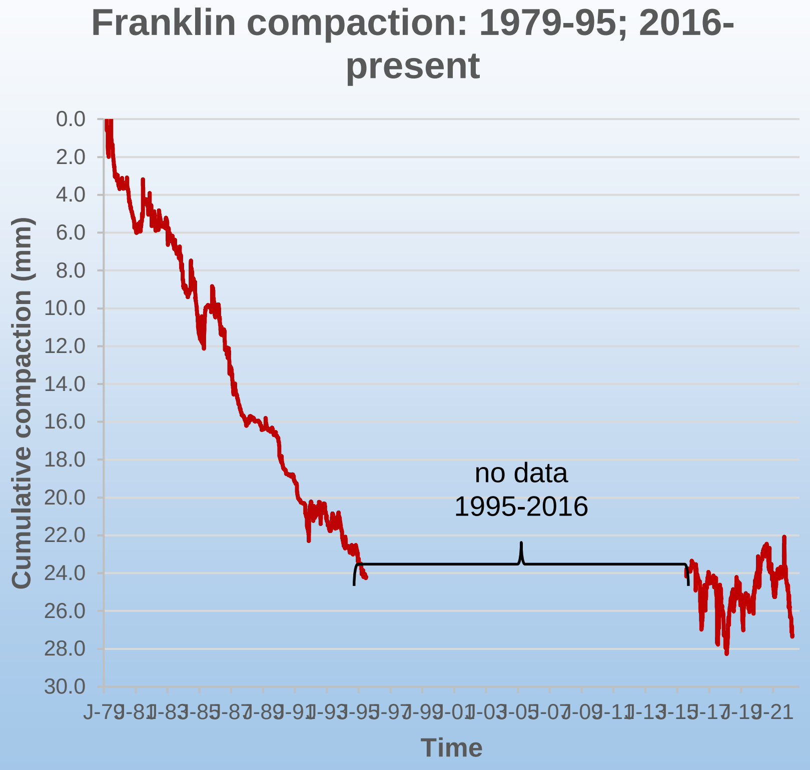


aerial view

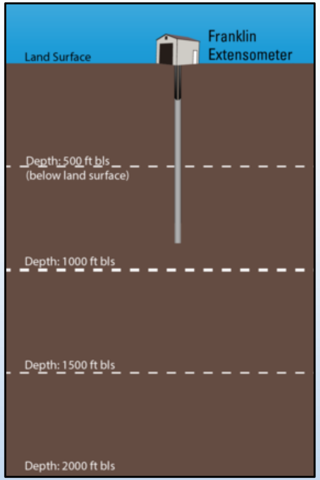


Franklin extensometer

- **Period of record**
  - 1979-1995; 2016-present
- **Depth**
  - 866 ft. bls
- **Location significance**
  - proximal to major pumping center
- **Cumulative compaction**
  - 1979-95: 24.2 mm
    - 1.5 mm/yr



cross section



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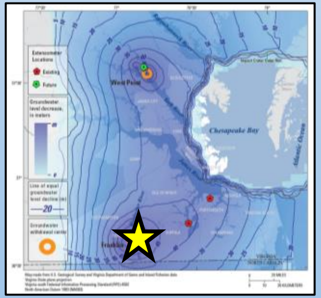


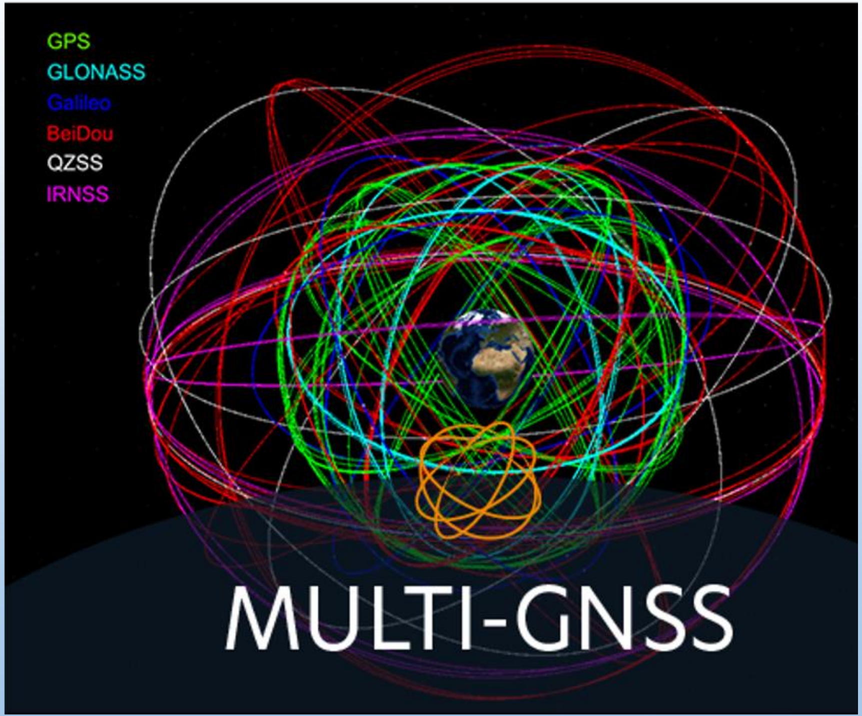
Preliminary Information-Subject to Revision. Not for Citation or Distribution.

USGS

Global Navigation Satellite Systems (GNSS)

- 6 major GNSS systems: GPS (USA), GLONASS (Russia), GALILEO (European), BeiDou (China), QZSS (Japan), IRNSS (India)

- Major transmission signals from all GNSS in the L frequency band (1-2 GHz), but with slightly different frequencies



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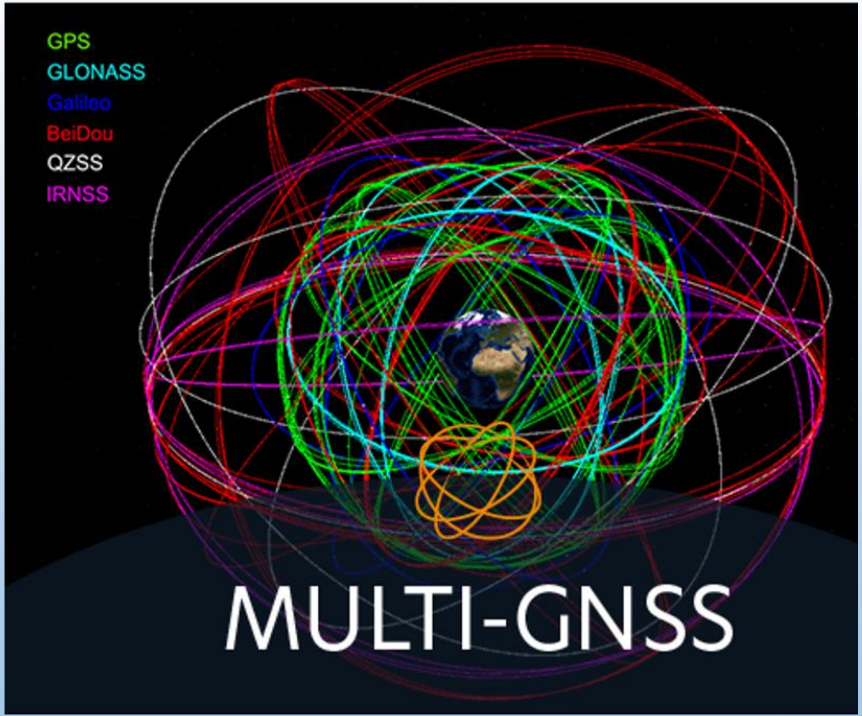
Global Navigation Satellite Systems (GNSS)

- GNSS satellites orbit between 25,000 - 40,000 km away from the Earth’s surface
- All GNSS systems have 3 segments: control, user, and satellite
- 4 satellites need for a position to solve for X,Y,Z, and time



Continuous vs. Episodic/Campaign GNSS/GPS Observations

Continuous GNSS/GPS Observations

- Continuously observing
- Ideally long-time series
- Permanent or semi-permanent installations

Episodic/Campaign GNSS/GPS Observations

- Short observation periods (>=72 hrs for millimeter precision positions)
- Repeated observations
- Benchmarks are observed

S

The monumentation comes in many different styles.

Continuous GPS Observations

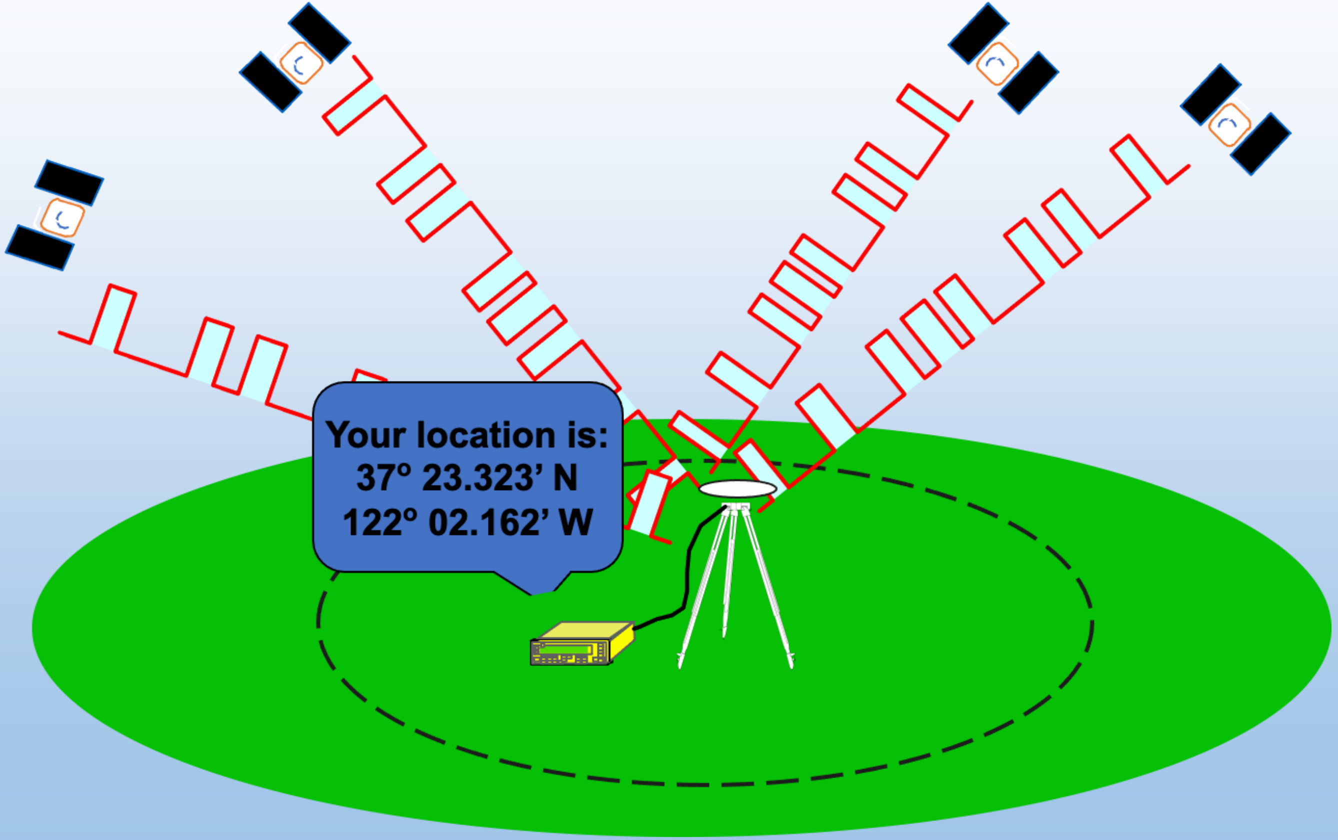
- Continuously observing
- Ideally long-time series
- Permanent or semi-permanent installations

Episodic/Campaign GPS Observations

- Short observation periods (≥72 hrs for millimeter precision positions)
- Repeated observations
- Benchmarks are observed

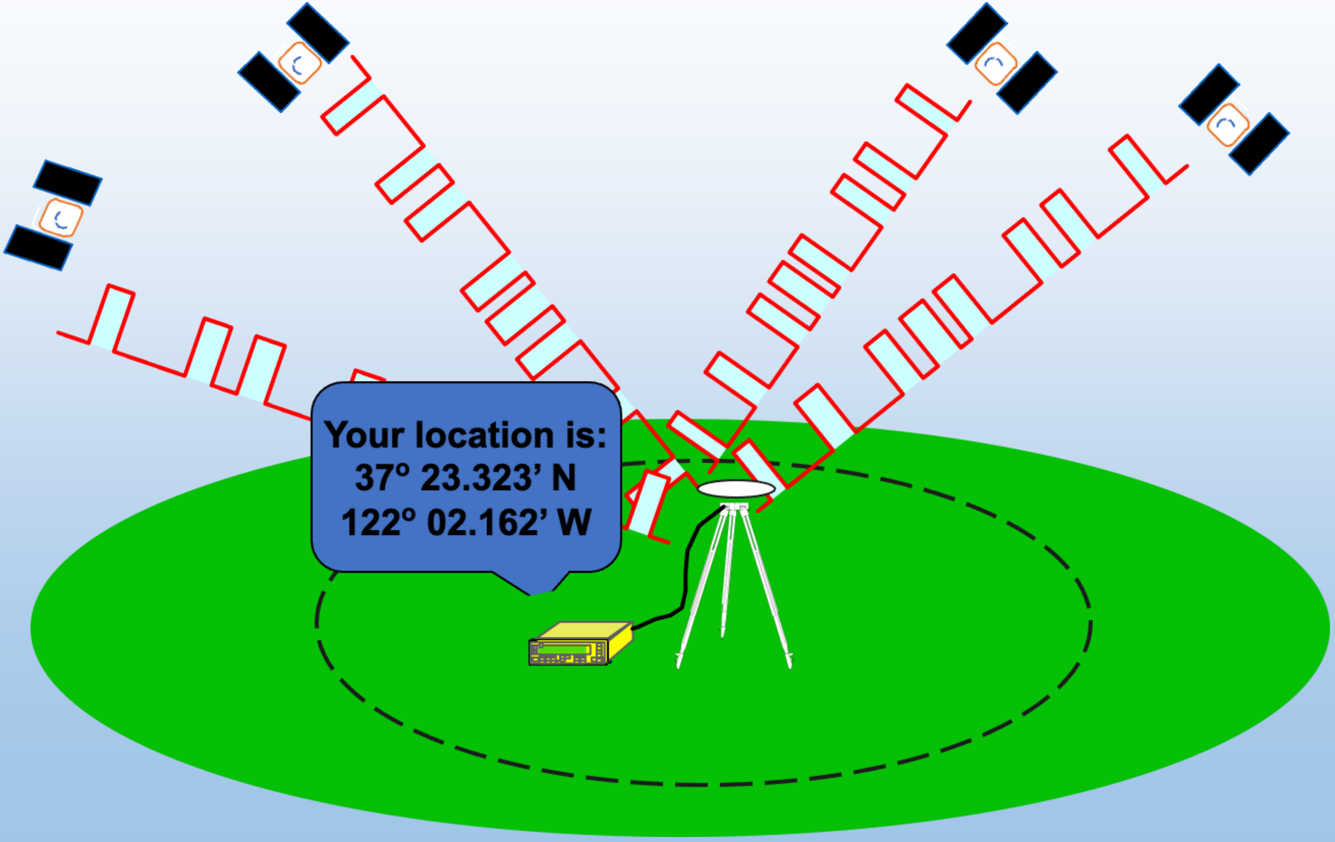
Pseudorange vs. Phase Observables for Positioning

Using the pseudorange allows for instantaneous positions with large uncertainties (1 meter precision at best).



Pseudorange vs. Phase Observables for Positioning

Using the phase of the GNSS signals gets you millimeter precision, but requires advanced post-processing of data using codes like OPUS projects or GAMIT-GLOBK.



Error Budget for GNSS Observations

Satellite-Receiver clocks ≈ 1 m

Satellite ephemeris ≈ 1 m

Troposphere ≈ 1 m

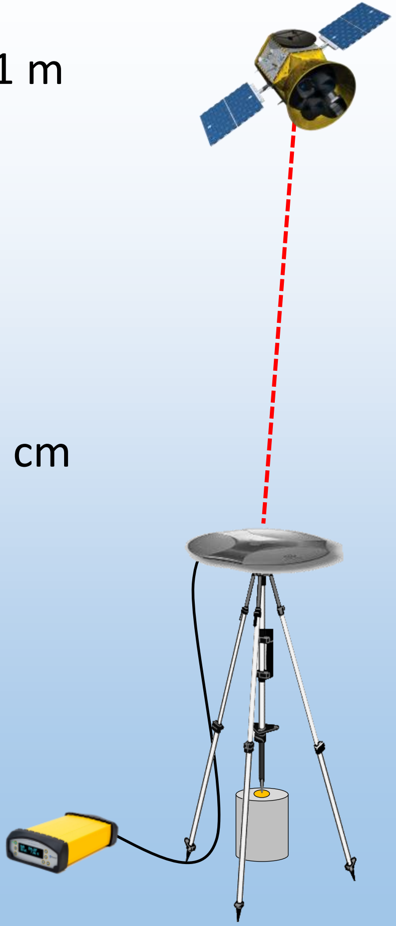
Ionosphere ≈ 5 m

Phase center variations ≈ 1 cm

Multipath ≈ 0.5 m

Pseudorange noise ≈ 1 m

Phase noise < 1 mm



Satellite:
- clocks
- orbits

Signal propagation:
- Ionospheric refraction
- Tropospheric refraction

Receiver/antenna:
- Ant. phase center variations
- Multipath
- Clock
- Electronic noise

Operator errors: up to several km…

Dominant error sources:
- Ionospheric refraction

Best practices for mm-precision

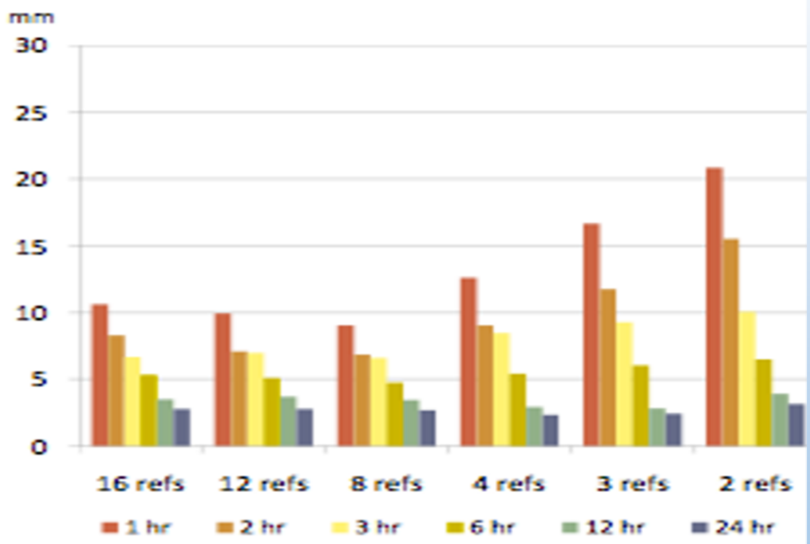
- Given time and personnel constraints, what are the trade-offs between between spatial and temporal density of campaign observations?

- Ideally, you would like for the white noise position uncertainty for an occupation to contribute to the velocity uncertainty at a level less than the usually dominant long-period correlated noise.

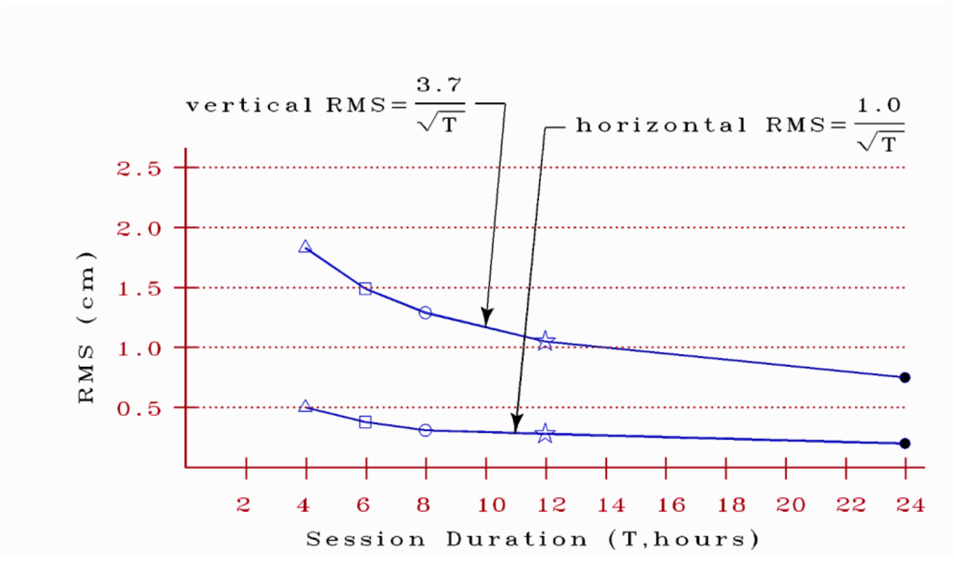
- Typical white noise uncertainties (horizontal and vertical) as a function of occupation time are:
  - 6–8 hrs: 2–2.5 mm (H), 5–10 mm (V)
  - 12–24 hrs: 1.0–1.5 mm (H), 3–5 mm (V)
  - 36–48-hrs: 0.7–1.0 mm (H), 2–4 mm (V)

Precision of Post-Processed GPS

Vertical Precision (GAMIT/GLOBK)



Vertical & Horizontal Precision (OPUS)



GPS/GNSS Reference Stations typically called “CORS” (Continuously Operating GNSS Reference Stations)

Best practices for mm-precision

- ≥ 72 hours GPS time (≥ 5 days best for mm precision)
- Run temporary CORS if in a low-CORS density environment
- No need for simultaneous GPS occupations if in a high-density CORS environment
- Use survey-grade L1/L2 GPS antennas & receivers
- Calibrated tripods
- Antennas pointed North
- Avoid obstructions & multipath
- For repeat observations, observe at same time of year
- Use L1/L2 post-processing software (e.g. GAMIT/GLOBK, OPUS, etc.)

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VLM impacts to coastal management

- Blackwater National Wildlife Refuge
- Hampton Roads pilot project
- Chesapeake Bay Regional Subsidence Monitoring Study

Research Goals

Method Development

- Can utilization of these relatively inexpensive campaign style GNSS techniques get an estimate of VLM rates to help better manage flooding, storm surge, land/habitat loss, etc.?
- How can these methods be expanded into areas outside of our sample?
- How can these data be used in ground truthing of remotely sensed information products?

Explain Variability in VLM Rates

- Can these methods be used to influence local land use decisions rather than implement a statewide or federal one-size-fits-all strategy
- What do individual local communities see as important?

GNSS Occupation on 84TB adjacent to Fort McHenry - Oct. 2021 (Photo Credit: Heather Quinn – MGS)

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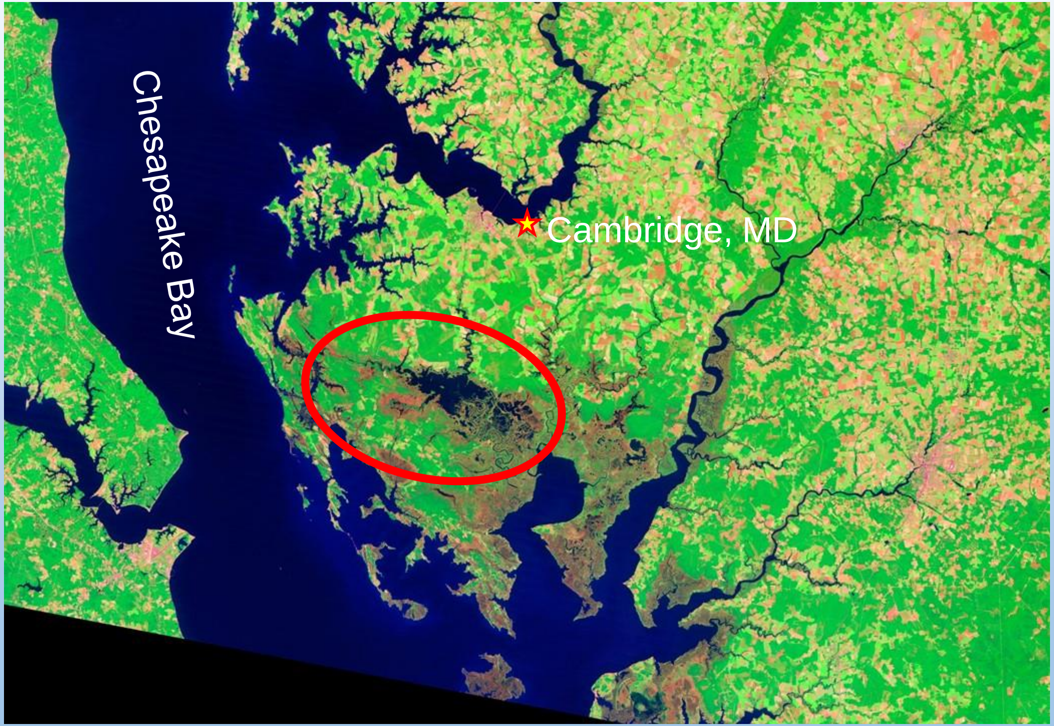
Historic wetland losses in Blackwater



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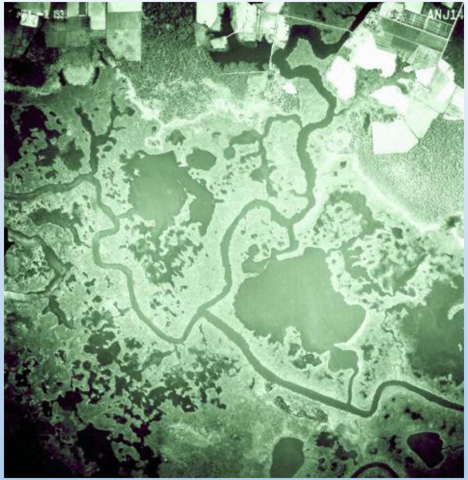
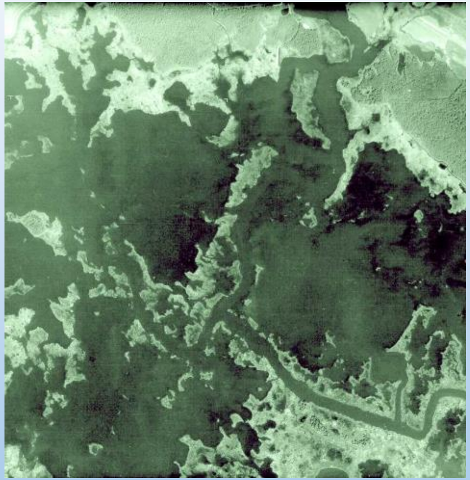


1938



1974

1989

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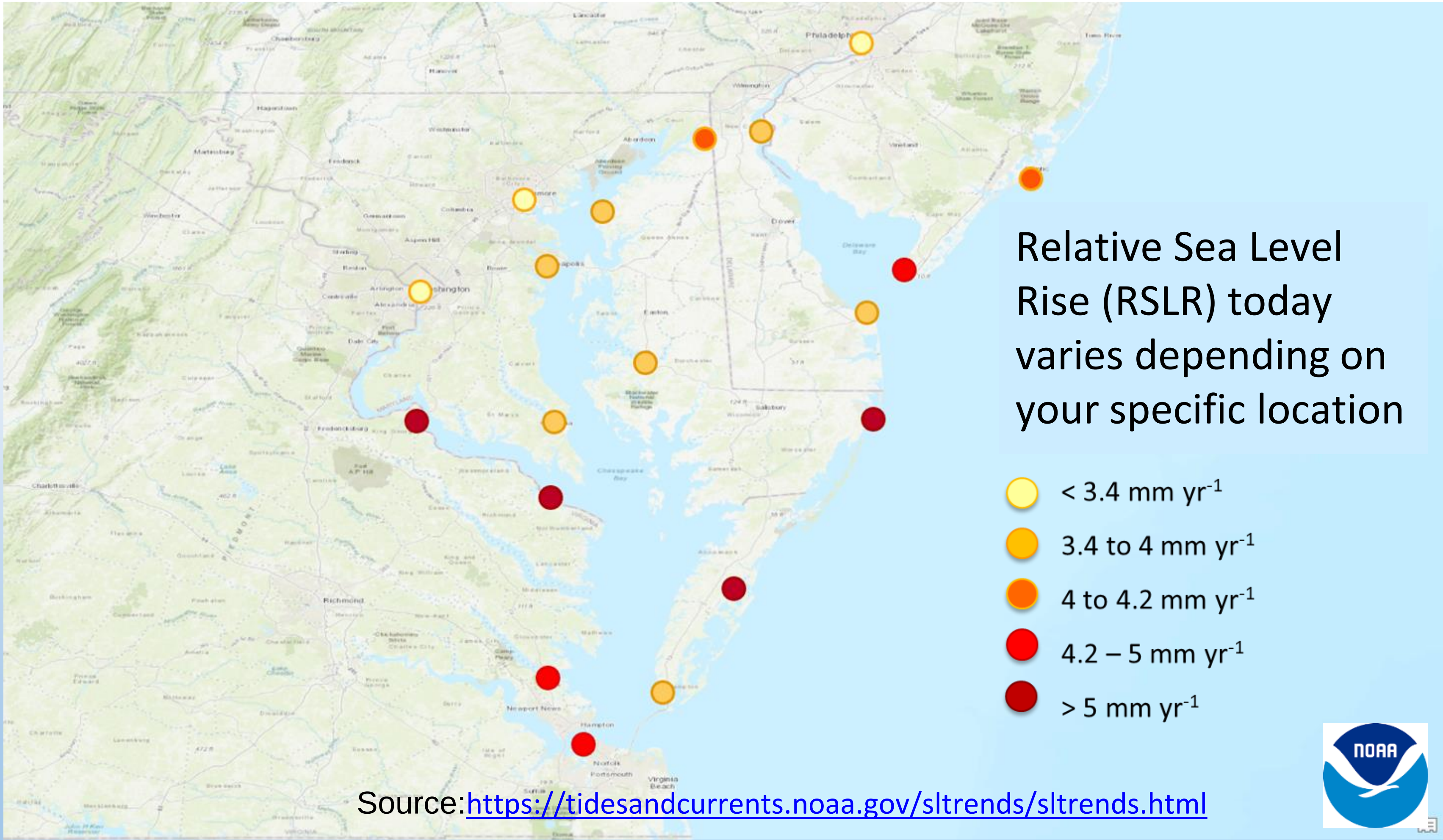
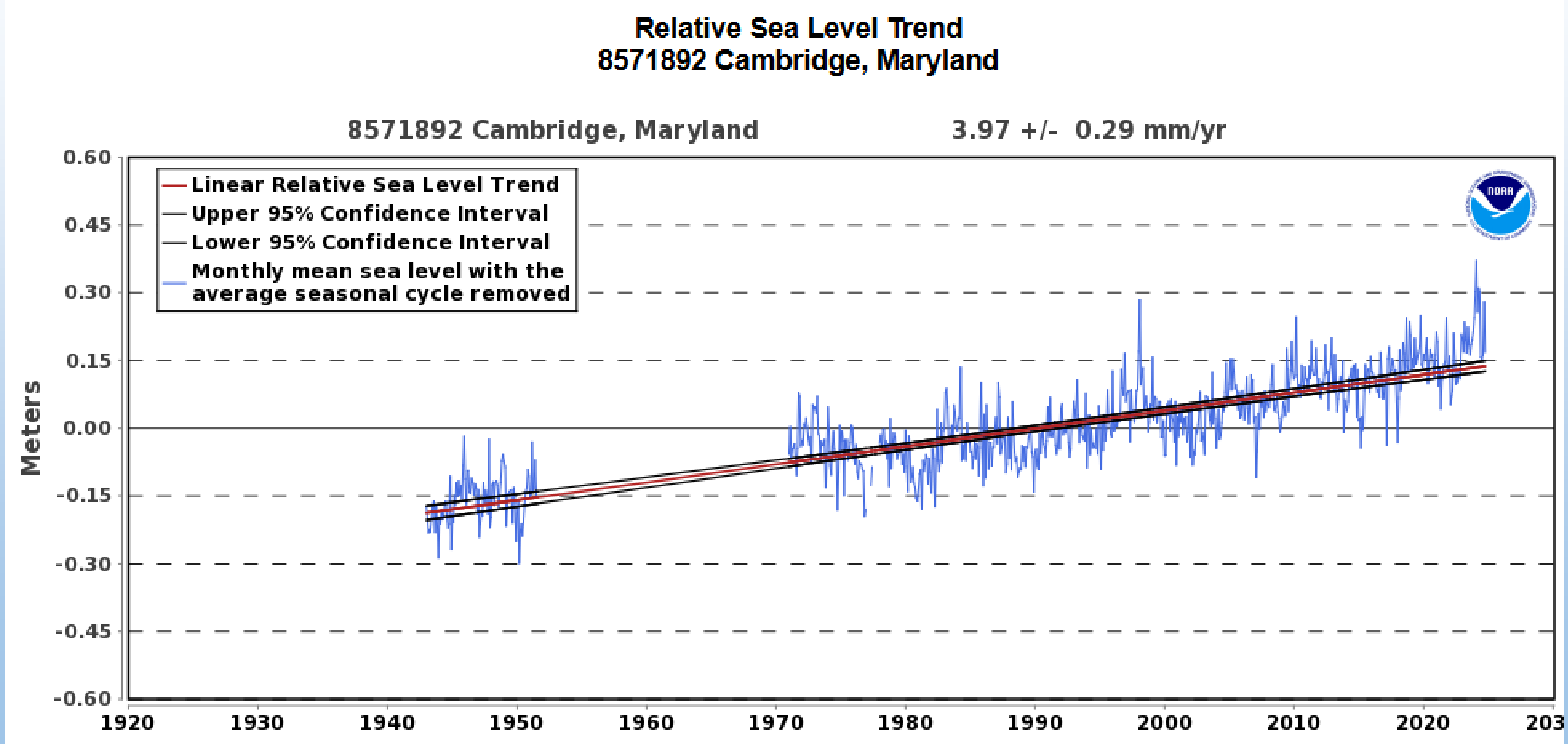
Relative Sea Level Rise (RSLR) today varies depending on your specific location



Source: https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

NOAA

Sea-Level trend at Cambridge MD



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Adaptive Management:

Prescriptive burning to promote marsh productivity

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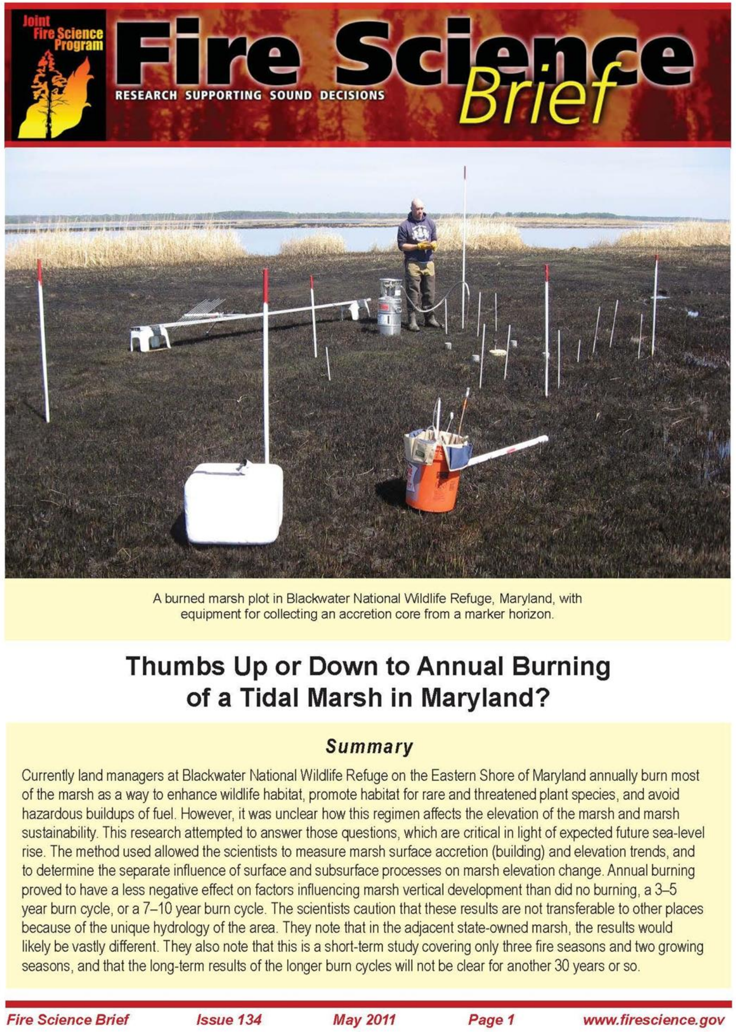
Results from over 100 SET plots


Joint Fire Science Program

Fire Science Brief

RESEARCH SUPPORTING SOUND DECISIONS

A burned marsh plot in Blackwater National Wildlife Refuge, Maryland, with equipment for collecting an accretion core from a marker horizon.

Thumbs Up or Down to Annual Burning of a Tidal Marsh in Maryland?

Summary

Currently land managers at Blackwater National Wildlife Refuge on the Eastern Shore of Maryland annually burn most of the marsh as a way to enhance wildlife habitat, promote habitat for rare and threatened plant species, and avoid hazardous buildups of fuel. However, it was unclear how this regimen affects the elevation of the marsh and marsh sustainability. This research attempted to answer those questions, which are critical in light of expected future sea-level rise. The method used allowed the scientists to measure marsh surface accretion (building) and elevation trends, and to determine the separate influence of surface and subsurface processes on marsh elevation change. Annual burning proved to have a less negative effect on factors influencing marsh vertical development than did no burning, a 3–5 year burn cycle, or a 7–10 year burn cycle. The scientists caution that these results are not transferable to other places because of the unique hydrology of the area. They note that in the adjacent state-owned marsh, the results would likely be vastly different. They also note that this is a short-term study covering only three fire seasons and two growing seasons, and that the long-term results of the longer burn cycles will not be clear for another 30 years or so.

- No clear trend among fire treatments
- Overall rates of wetland elevation change positive 7 mm yr^{-1}
- Elevation Capital deemed best indicator of resilience
- Recommendation to monitor elevations (“*elevation capital*”) throughout refuge

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SET stations within Blackwater NWR

Very clustered distribution
Small area sampled despite large # SET sample stations

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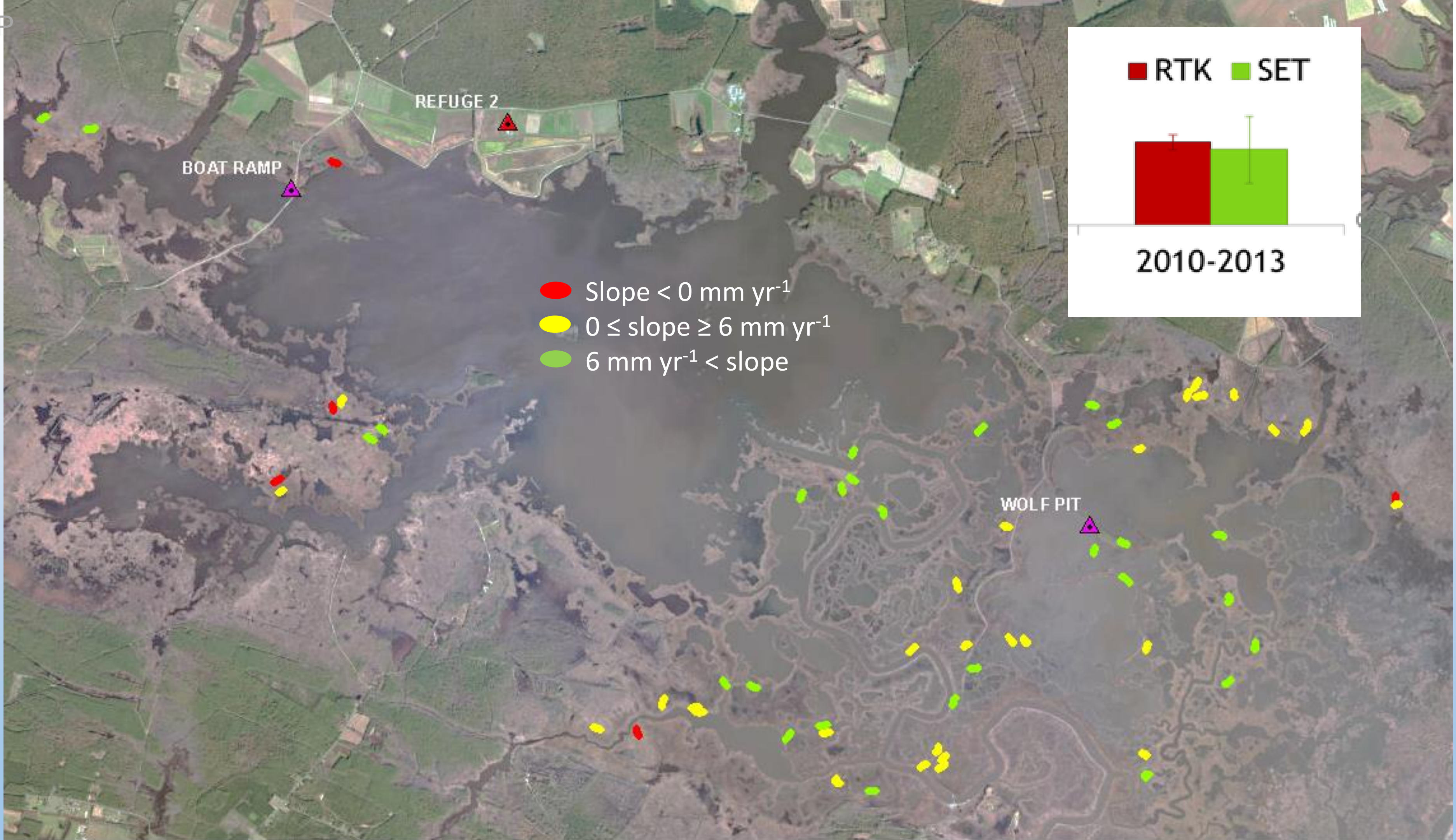
Single Base RTK GPS campaign (2010-2012)

Two rovers, matching Trimble R8's

Per 2005 Height Mod campaign

Base on known point:
38 24 27.81686 (N)
076 03 02.20737 (W)
NAVD 88 0.22 (m)



REFUGE 2
BOAT RAMP
WOLF PIT
Slope < 0 mm yr-1
0 ≤ slope ≥ 6 mm yr-1
6 mm yr-1 < slope
RTK
SET
2010-2013

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What’s going on?

Wetlands are gaining elevation at ~6 $mm\ yr^{-1}$

SLR at Cambridge MD is 3.5 $mm\ yr^{-1}$

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The geodetic control marks are moving vertically too!

GPS-based coordinate comparisons 2005 - 2015

Mark	Δ Northing (m)	Δ Easting (m)	Δ Ellipsoid Ht (m)
Boat Ramp	-0.002	-0.023	-0.043 ± 0.007 (P=0.099)
Refuge 2	-0.007	-0.005	-0.061 ± 0.007 (P=0.07)
Wolf Pit	-0.011	-0.006	-0.069 ± 0.007 (P=0.062)

P

The geodetic control marks are moving vertically too!

GPS-based coordinate comparisons 2005 - 2015

Mark	Δ Northing (m)	Δ Easting (m)	Δ Ellipsoid Ht (mm/yr)
Boat Ramp	-0.002	-0.023	-4.4 ± 0.7 (P=0.099)
Refuge 2	-0.007	-0.005	-6.5 ± 0.7 (P=0.07)
Wolf Pit	-0.011	-0.006	-7.1 ± 0.7 (P=0.062)

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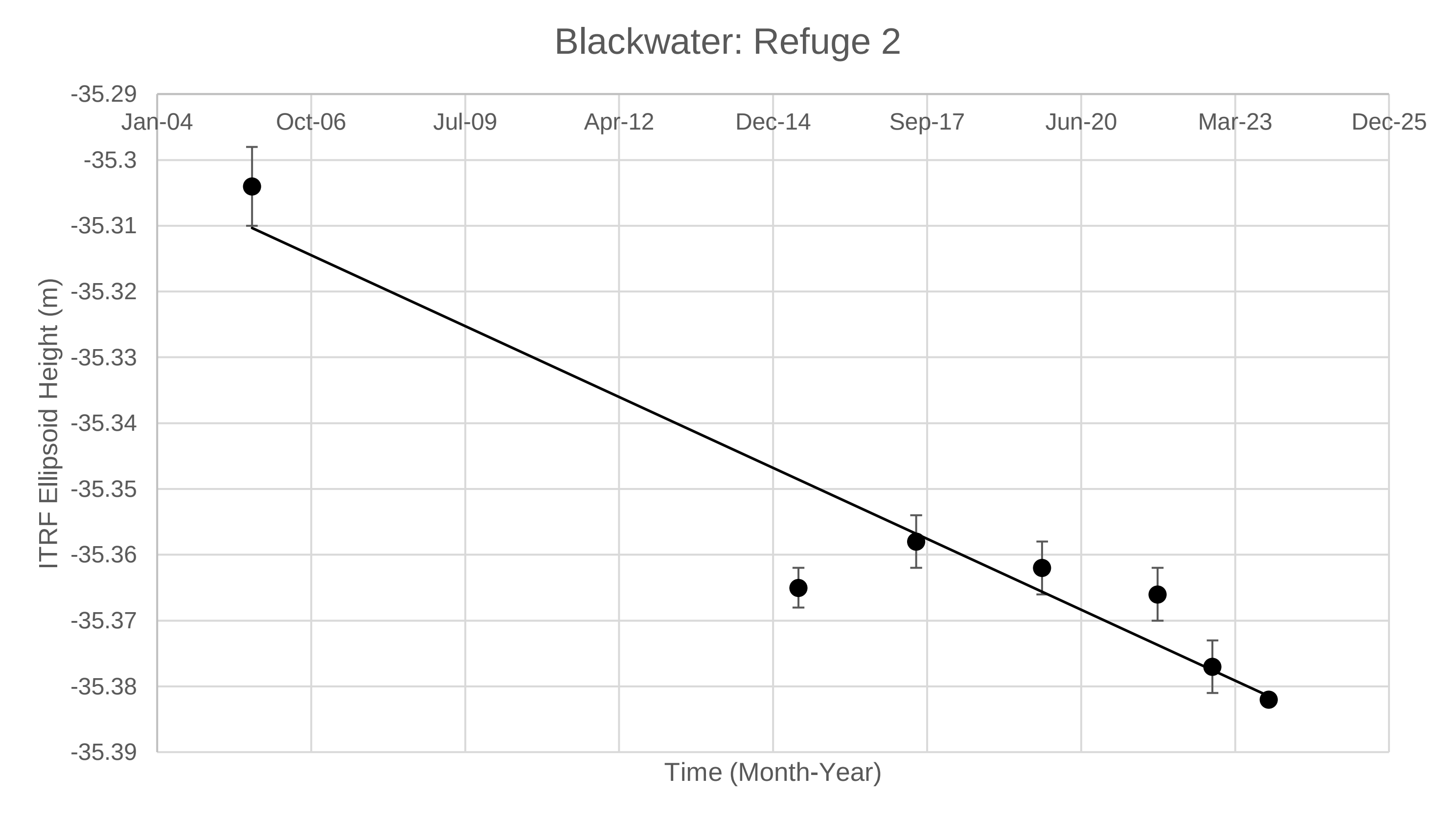
Conclusions from Blackwater NWR



2005 – 2023 VLM at Refuge 2:

-3.9 ± 0.7 SE mm year^{-1}

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Conclusions from Blackwater

- Wetland vertical dynamics need to take into account VLM occurring below the reference marks
- The nearest long-term tide station may not be in the same VLM environment as your area of interest
- Episodic GPS/GNSS measurements can, over time, provide very good estimates of VLM at the mm/yr scale

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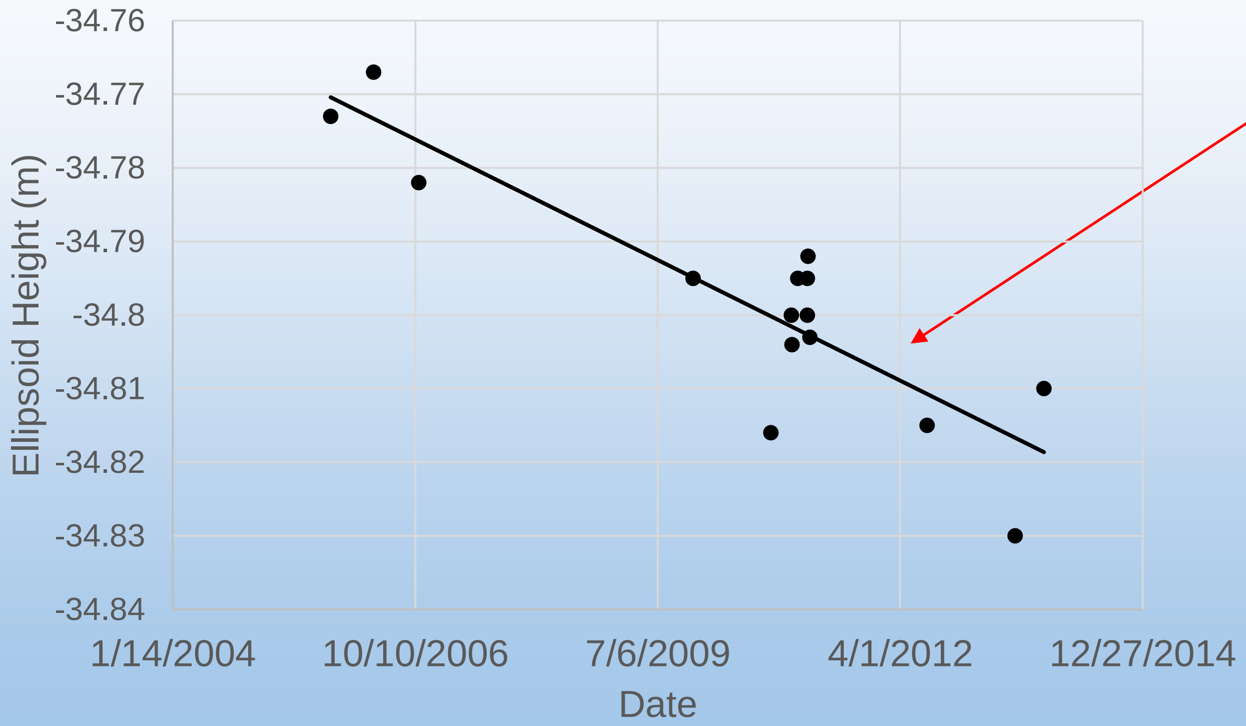
Monitoring coastal VLM with GPS: Assateague Island National Seashore



$y = -0.006x - 34.77$

$R^2 = 0.7772$

6 mm yr^{-1}

Unverified National Park Service Data; Credit: Neil Winn, National Park Service

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Hampton Roads Benchmark Network

Project Objectives

1) Establish a network of Class B, or greater

Original Holdahl and Morrison marks were attempted to be recovered, but none could be found

   - Been in place for a minimum of 20 years
   - Suitable for GNSS surveying
   - Remaining gaps filled with deep rod installations

- Final Network Configuration: 26 benchmarks
   - 4 subsidence piers (NASA LaRC)
   - 6 concrete surface monuments of importance
   - 16 deep rods

2) Occupy the benchmarks with GNSS

- Annual campaigns consisting of ≥ 24-hour deployments
- Winter timeframe to reduce seasonal noise

3-D Deep Rod Installation at Jamestown, VA

Methods from: “Attachment V: Setting an NGS 3D Monument” by: National Geodetic Survey. September 30, 2004, Updated October 27, 2009

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Project Objectives Cont.

3) Compute land relative differences

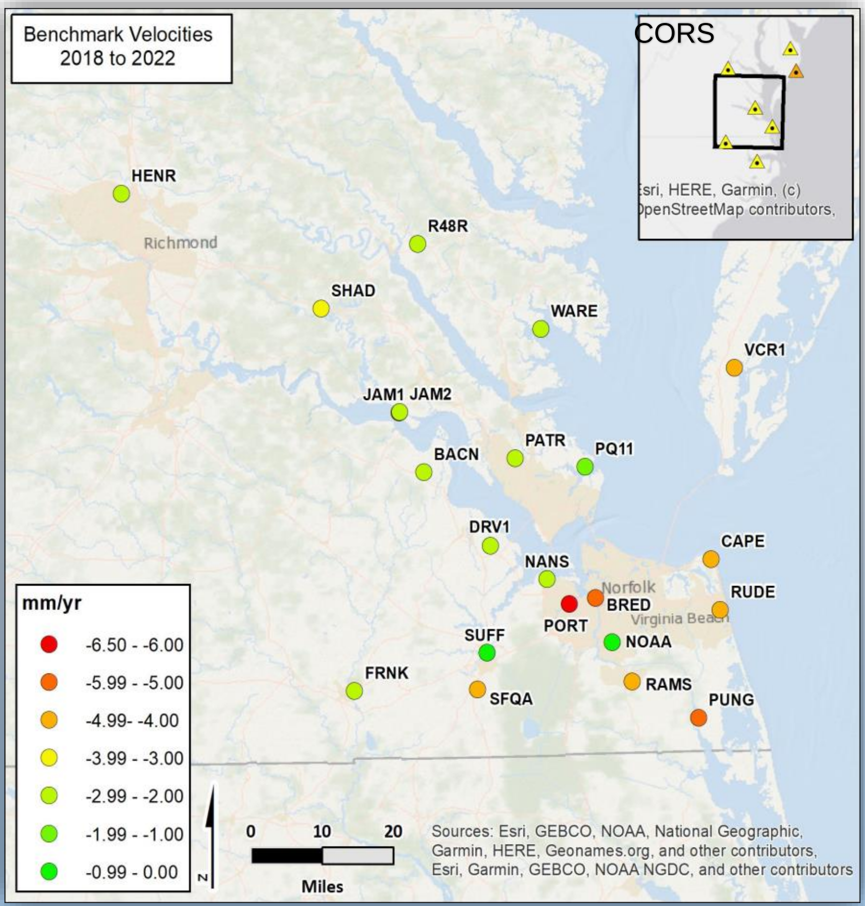
USGS ScienceBase Data Release:

- RINEX files
- CSV with benchmark/survey information and computed ellipsoid heights in ITRF2014
- Metadata

Data Processing in OPUS-Projects

- Piecewise linear with normal constraints
- HUB: VAGP (2007) -centrally located and within 100 km
- Constrained CORS: CORB, DED2, LS03, NCCR, NCJA
- TROPO: vary year to year
- *In 2018 VAGP was not available so LS03 was used

How much does the CORS network configuration affect results?



Lotspeich and Duda, 2022

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Chesapeake Bay Regional Subsidence Monitoring Study

<u>Interagency Steering Committee</u>
US Geological Survey
VA-WV WSC: Jim Duda
EESC: Joel Carr
Virginia Tech
D. Sarah Stamps, Gabbi Troia, Karen Williams, & Madeline Kronebusch
Maryland Geological Survey
Andy Staley, Thomas Ulizio, & Heather Quinn
National Geodetic Survey
Observation and Analysis Division: Philippe Hensel
Field Operations Branch: Ryan Hippenstiel
Corbin Testing and Training Center: Charlie Geoghegan

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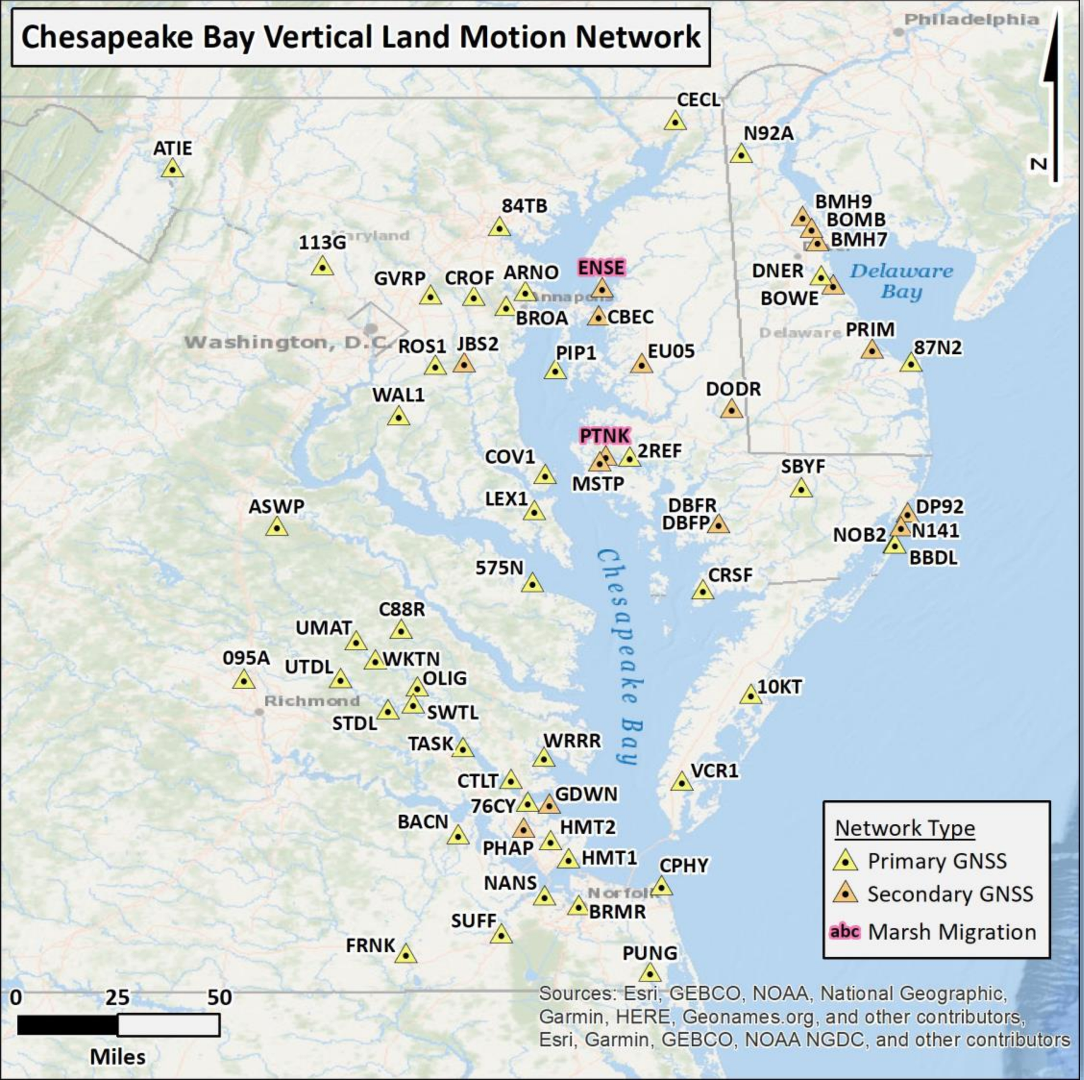
NASA Jet Propulsion Laboratory - Brett Buzzanga
Hampton University - Bill Moore
Delaware Geological Survey - Tom McKenna
US Fish and Wildlife Service - Scott Covington
VA Institute for Marine Science - Scott Lerberg
National Park Service – Neil Winn & Jim Lynch
Chesapeake Bay National Estuarine Research Reserve – Kyle Derby
Numerous surveyors and field operations personnel



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Chesapeake Bay Network

- 62 survey marks monitored yearly (October) since 2019
- Chesapeake Bay, Delaware Bay
- Atlantic Barrier Islands, Delmarva peninsula, Coastal Plain, Piedmont
- Variety of monumentation types

QUESTIONS?
Thank you!

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