

Maryland Geological Survey



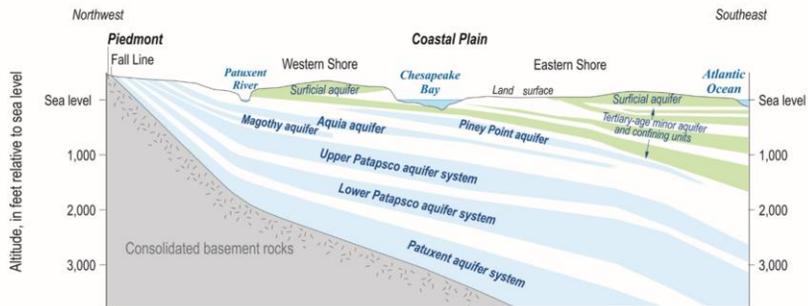
**MONITORING NETWORK TO ASSESS LAND
SUBSIDENCE CAUSED BY GROUNDWATER
WITHDRAWALS**

To what degree are GW withdrawals causing
land subsidence in MD's Coastal Plain aquifers?

Funding support from
Anne Arundel County DPW and
Dominion Cove Point LNG

A relatively small network of seven 3d marks and yearly GPS measurements

Maryland's Coastal Plain aquifers



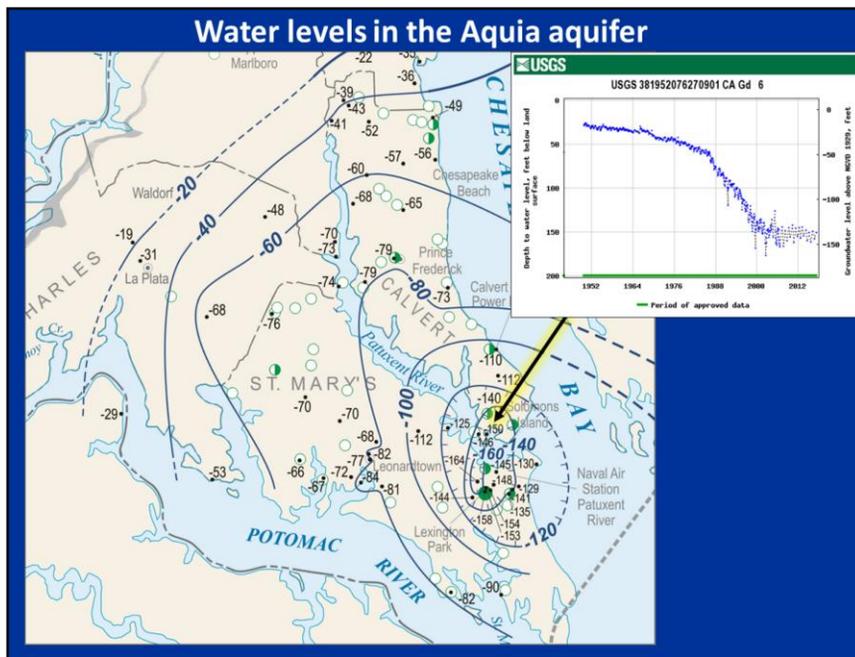
Generalized schematic cross section showing the major aquifer systems in Maryland's coastal plain. The Piney Point and Aquia aquifers are used extensively in Calvert County with the potential for additional supply from the deeper units.

Groundwater Withdrawals (million gallons per day)

| County | Public Supply | Domestic | Total | Projected? |
|-----------------|---------------|----------|-------|------------|
| Anne Arundel | 35.5 | 11.1 | 46.6 | ~78 |
| Calvert | 3.4 | 2.9 | 6.3 | ~9 |
| Charles | 9.0 | 2.8 | 11.5 | ~22 |
| Prince George's | 2.2 | 2.1 | 4.3 | ~4.3 |
| St. Mary's | 5.3 | 2.7 | 7.7 | ~13 |
| Total | | | 74.7 | ~126 |

Calvert, Charles, and St. Mary's figures based on MGS RI 76 (projected values are from high scenario 2b). Anne Arundel and Prince George's figures from

Maupin, M.A., Kenny, J.F., Hutson, S.S., Lovelace, J.K., Barber, N.L., and Linsey, K.S., 2014, Estimated use of water in the United States in 2010: U.S. Geological Survey Circular 1405, 56 p. (AA Co projected from AADPW buildout of ~67 Mgal/d).



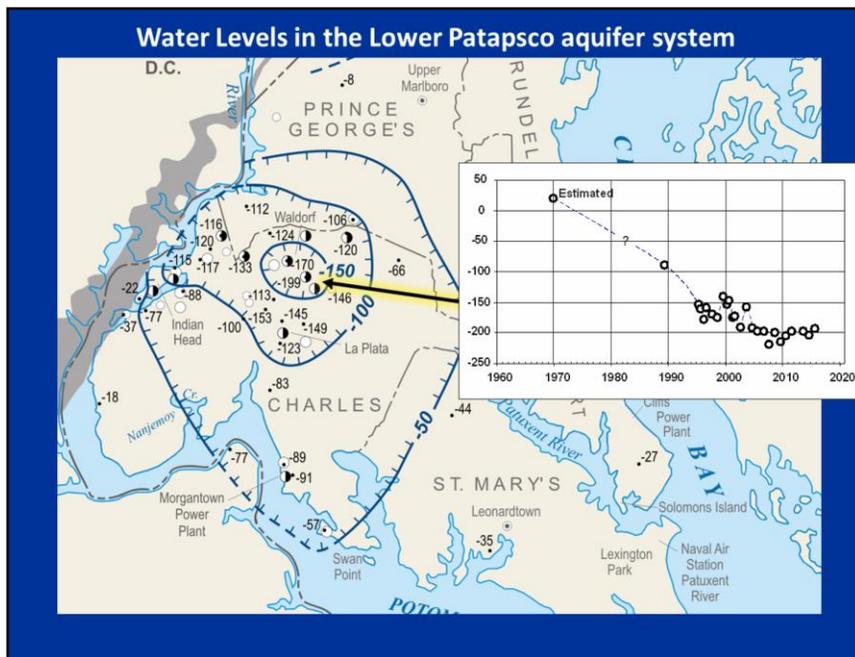
A long history of declining waters in the Aquia aquifer caused by withdrawals. Water levels have stabilized post ~2002 after some public water system withdrawals were shifted from the Aquia to the Upper Patapsco aquifer system in St. Mary's County to avoid naturally-occurring arsenic concentrations in the Aquia.

Map:

Staley, A.W., Andreasen, D.C., and Curtin, S.E., 2016, Potentiometric surface and water-level difference maps of selected confined aquifers in Southern Maryland and Maryland's Eastern Shore, 1975-2015: Maryland Geological Survey Open-File Report 16-02-02, 30 p. http://www.mgs.md.gov/publications/report_pages/OFR_16-02-02.html

Hydrograph:

CA Gd 6 at Solomons was nearly flowing (water level at land surface) when well was drilled in 1942 (Bennion, V.R., Dougherty, D.F., and Overbeck, R.M., 1951, The water resources of Calvert County: Maryland Geological Survey Bulletin 8, 100 p.) https://nwis.waterdata.usgs.gov/nwis/gwlevels/?site_no=381952076270901



Some of the deepest water levels in Maryland's coastal plain aquifers.

Map:

Staley, A.W., Andreasen, D.C., and Curtin, S.E., 2016, Potentiometric surface and water-level difference maps of selected confined aquifers in Southern Maryland and Maryland's Eastern Shore, 1975-2015: Maryland Geological Survey Open-File Report 16-02-02, 30 p. http://www.mgs.md.gov/publications/report_pages/OFR_16-02-02.html

Hydrograph: Observation well CH Be 64

https://nwis.waterdata.usgs.gov/nwis/gwlevels/?site_no=383553076562002

Land subsidence related to GW withdrawals Classic Examples

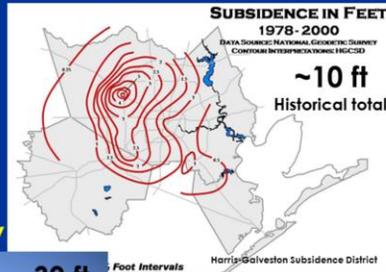
California Central Valley



Mexico City



Houston-Galveston

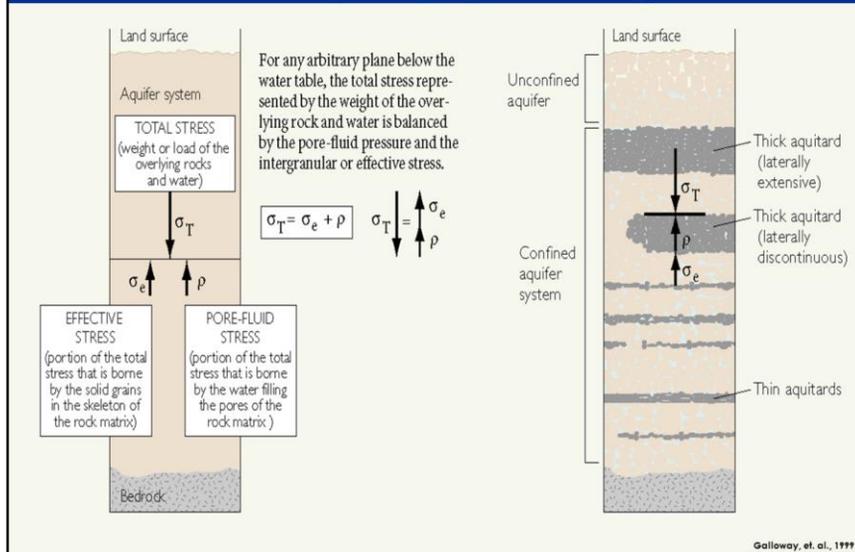


- Extreme examples (meter scale)
- Contrasts with the relatively minor (mm to cm scale) potential in MD coastal plain

Three classic examples of land subsidence related to large-scale groundwater withdrawals. These examples show the process of groundwater-related subsidence at the extreme (meter scale), contrasting with the relatively minor (millimeter to centimeter scale) potential in the Maryland coastal plain.

Mechanics of Compaction

- Recoverable (elastic) compaction in aquifers
- Non-recoverable (inelastic) compaction in confining beds



Most compaction occurs in fine-grained sediment. Must exceed pre-consolidation for inelastic deformation. In the Atlantic Coastal Plain, the preconsolidation stress equivalent is about 65 ft below sea level (Davis, G.H., 1987, Land subsidence and sea level rise on the Atlantic Coastal Plain of the United States:

Environmental Geology and Water Science, vol. 10, no. 2, p. 67-80.)

**Nuisance flooding has increased rapidly
along the U.S. Mid-Atlantic Coast**

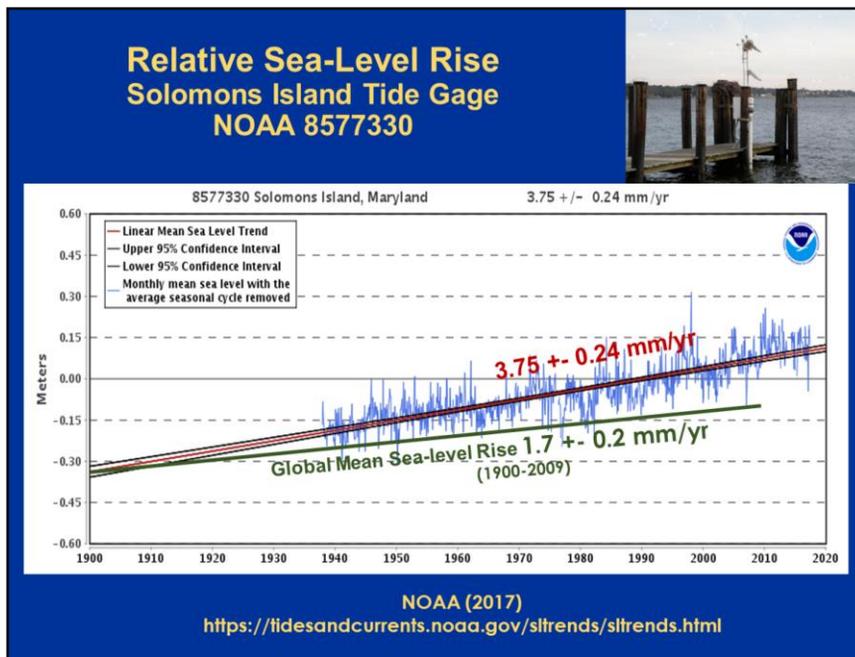


NUISANCE FLOODING IS 300%-900% MORE FREQUENT THAN IT WAS 50 YEARS AGO.

NOAA (2016)

Nuisance flooding is occurring more frequently

<https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level>



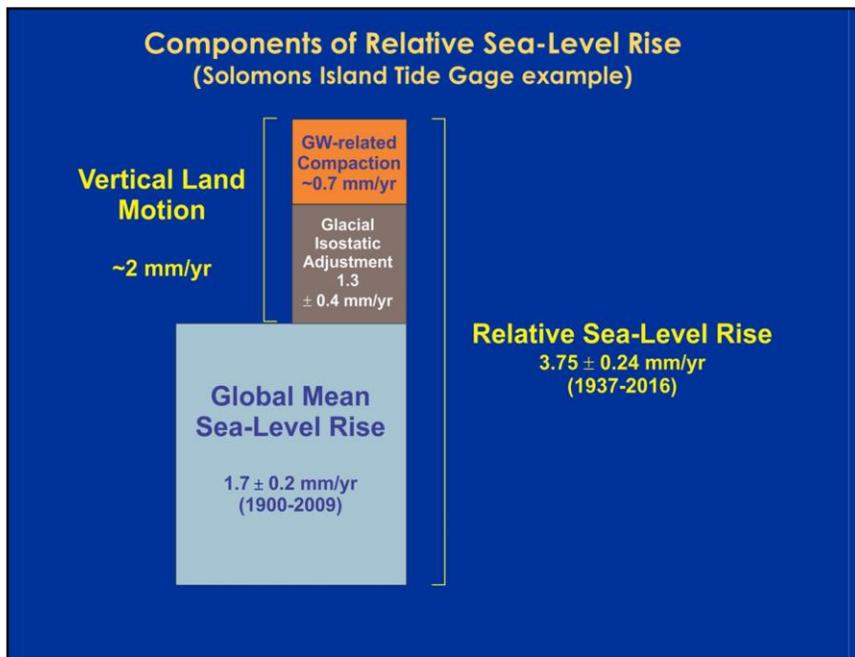
Long-term trends at tide gages in the mid-Atlantic region show linear trends greater than the global mean sea-level (GMSL) rise rate.

Zervas, C., 2009: Sea Level Variations of the United States 1854–2006. NOAA Technical Report NOS CO-OPS 053, 75p,

Kopp, R. E. (2013), Does the mid-Atlantic United States sea-level acceleration hot spot reflect ocean dynamic variability?, *Geophys. Res. Lett.*, 40, 3981–3985, doi:10.1002/grl.50781.

Sallenger, A. H., Jr., K. S. Doran, and P. A. Howd (2012), Hotspot of accelerated sea-level rise on the Atlantic Coast of North America,

Nat. Clim. Change, 2, 884–888, doi:10.1038/nclimate1597.

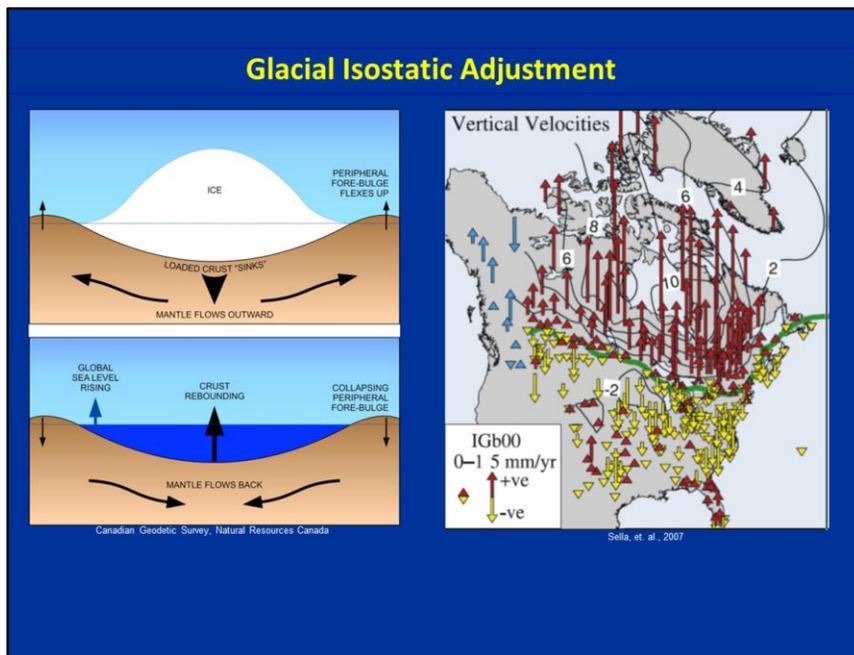


Estimated components of relative sea-level rise using the tide gage at Solomon's Island as an example.

Relative Sea-Level Rise at Solomon's Island gage (1937-2016): 3.75 ± 0.24 mm/yr (NOAA Sea-level trends <https://tidesandcurrents.noaa.gov/sltrends/sltrends.html>)

Global Mean Sea-Level Rise: 1.7 ± 0.2 mm/yr (Church, J. A., and N. J. White, 2011, Sea-level rise from the late 19th to the early 21st century, *Surv. Geophys.*, 32, 585–602)

Glacial Isostatic Adjustment: 1.3 ± 0.4 mm/yr (Miller, K. G., R. E. Kopp, B. P. Horton, J. V. Browning, and A. C. Kemp (2013), A geological perspective on sea-level rise and its impacts along the U.S. mid-Atlantic coast, *Earth's Future*)



The loading effect of the Laurentide ice sheet during the last glaciation (~20,000 years before present) caused downwarping of the earth's mantle below and a subsequent bulge southward of the ice sheet extent. As the ice sheet retreated the mantle beneath rebounded and the fore-bulge subsided. This slow process is still underway.

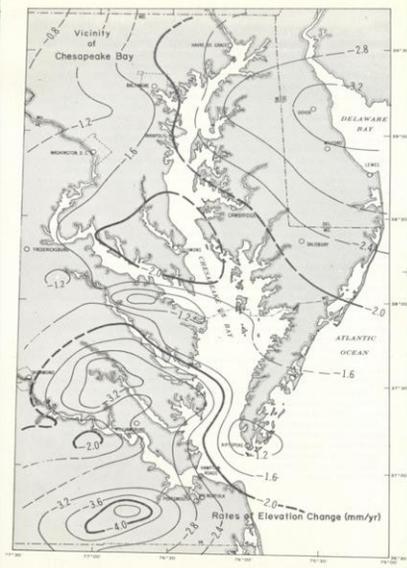
Map on right showing vertical velocities with respect to IGb00 reference plane

Sella, G. F., S. Stein, T. H. Dixon, M. Craymer, T. S. James, S. Mazzotti, and R. K. Dokka (2007), Observation of glacial isostatic adjustment in "stable" North America with GPS, Geophys. Res. Lett., 34, L02306

Vertical Land Motion in the Chesapeake Bay region

Holdahl and Morrison Report (1973)—National Geodetic Survey

Vertical Land Motion
mm/yr

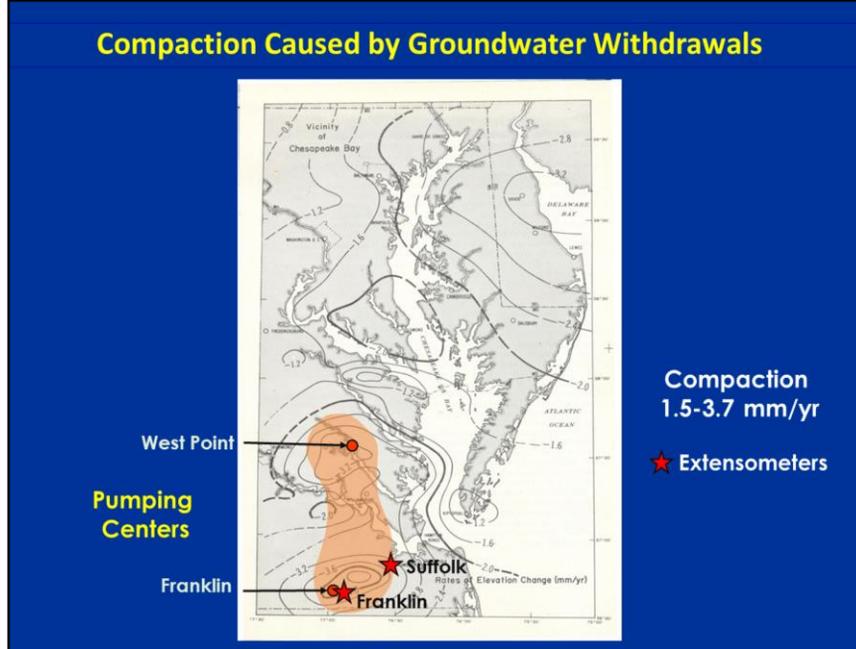


In the early 1970s the National Geodetic Survey conducted an extensive high accuracy re-leveling of vertical heights on a large set of benchmarks. The map shown here is the contoured rates of vertical land motion (VLM) calculated from those re-levels--the first indication of land subsidence across the Chesapeake Bay region.

VLM rates for period ~1940-1971

Holdahl, S.R., and Morrison, N.L., 1974, Regional investigations of vertical crustal movements in the U.S., using precise relevelings and mareograph data: *Tectonophysics*, v. 23, no. 4, p. 373–390.

Compaction Caused by Groundwater Withdrawals



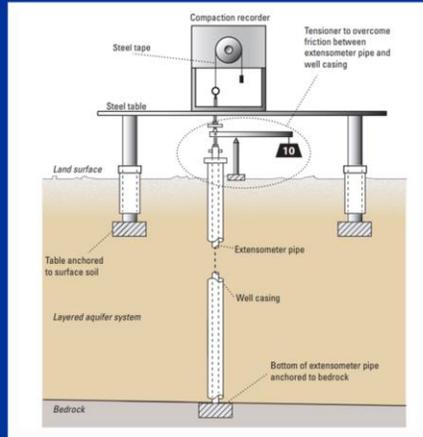
The areas of greatest vertical land motion coincided exactly with areas of high groundwater withdrawals centered around West Point and Franklin, Virginia. In light of this connection, the U.S. Geological Survey constructed two extensometer wells to directly measure land compaction.

Shaded area represents the cone of depression around major pumping centers.

Compaction ranges from 1.5 mm/yr (1979-1995) – 3.7 mm/yr (1982-1995)

Pope, J.P., and Burbey, T.J., 2004, Multiple-aquifer characterization from single borehole extensometer records: *Ground Water*, v. 42, no. 1, p. 45–58.

Monitoring by Extensometer



Eggleston and Pope, 2013

Courtesy David Nelms

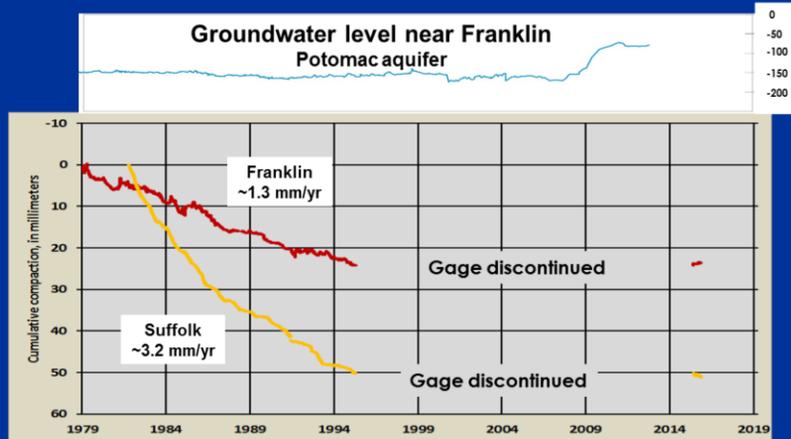


Extensometers are the “gold standard” for precise measurements of land compaction. Millimeter to sub-millimeter changes between the reference datum (bedrock rock) and the land surface can be detected and recorded.

Eggleston, Jack and Pope, Jason, 2013, Land subsidence and relative sea-level rise in the southern Chesapeake Bay region: U.S. Geological Survey Circular 1392, 30 p.

Pumping Induced Aquifer Compaction

Extensometer Records

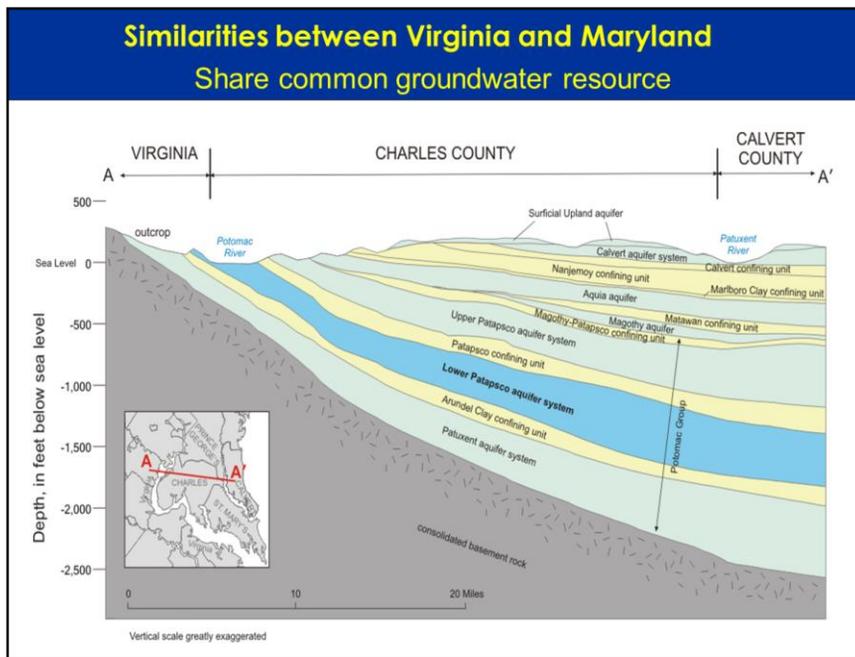


Courtesy David Nelms, USGS

Pope and Burbey, 2004, *Ground Water*, 42(1) p. 45–58

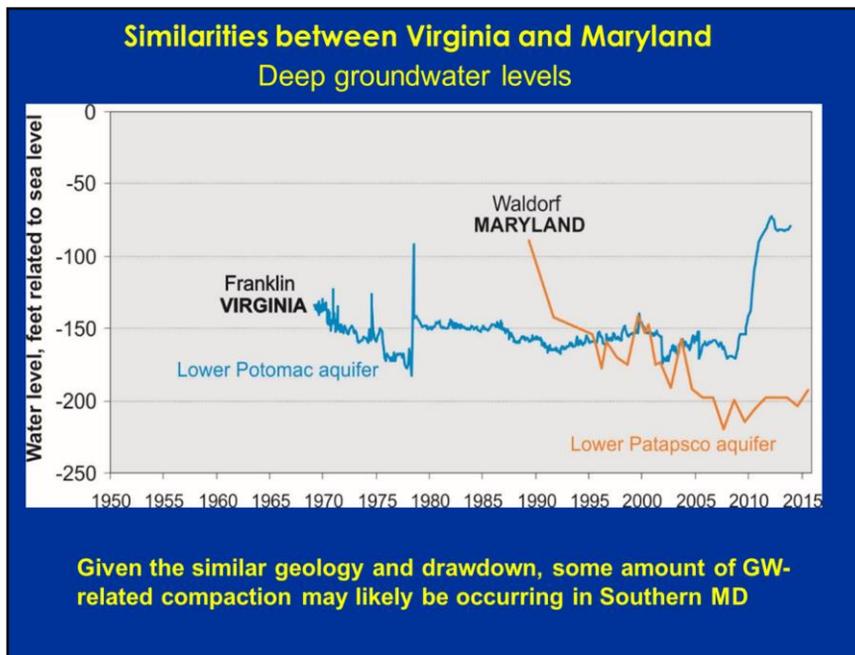
Rates of land subsidence at the two Virginia extensometers.

Pope, J.P., and Burbey, T.J., 2004, Multiple-aquifer characterization from single borehole extensometer records: *Ground Water*, v. 42, no. 1, p. 45–58.



VA and MD share a common groundwater resource. Both states pump extensively from the same aquifer systems.

Pope, J.P., Andreasen, D.C., McFarland, E.R., and Watt, M.K., 2016, Digital elevations and extents of regional hydrogeologic units in the Northern Atlantic Coastal Plain aquifer system from Long Island, New York, to North Carolina: U.S. Geological Survey Data Series 996, 28 p., <http://dx.doi.org/10.3133/ds996>.



While Virginia has a longer history of greater groundwater withdrawals than Maryland (in particular Southern MD), groundwater-level decline in Maryland is comparable to that experienced in VA.

+100 million gallons per day total withdrawals in VA coastal plain (~1/2 of that from the Franklin and Suffolk well fields)

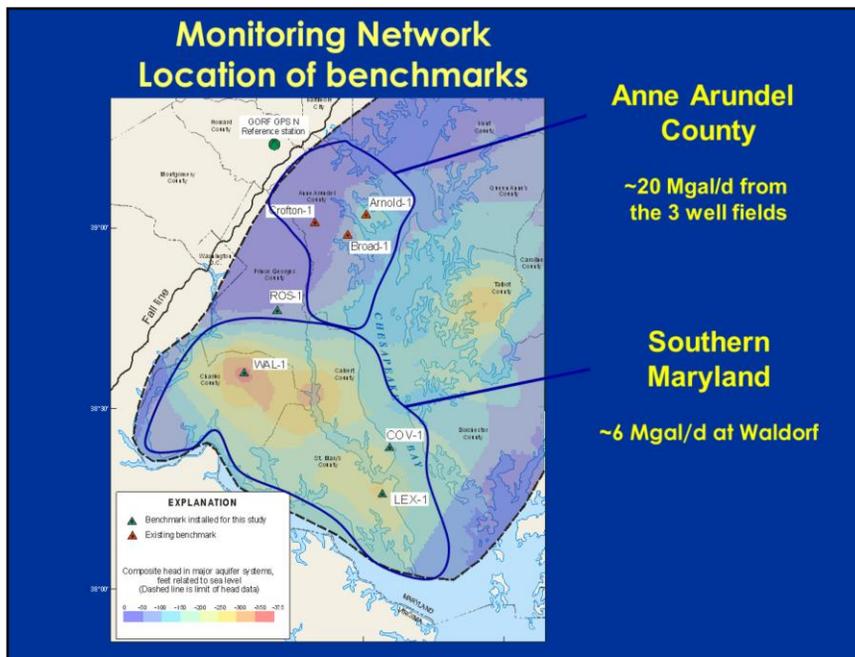
Pope and Burbey in U.S. Geological Survey Subsidence Interest Group Conference, Proceedings of the Technical Meeting, Galveston, Texas, November 27-29, 2001

Methods used to measure land subsidence

| Method | Positives | Negatives |
|--------------------------|-------------------------------|--|
| Borehole extensometer | Isolates compaction | High cost, point coverage |
| Tidal station | Already monitored, continuous | Indirect measurement of compaction |
| Geodetic surveying (GPS) | Low cost, spatial coverage | Accuracy, indirect measurement of compaction |
| Remote sensing (InSAR) | Excellent spatial coverage | High costs, resolution, indirect measurement of compaction |

**Best
Option**

Various methods are available to measure land subsidence. Given the overall low cost and spatial coverage, yearly GPS measurements were selected. GPS is somewhat limited in measuring vertical land motion at the millimeter scale, but given a sufficient period of record (years), trends should become apparent if land subsidence is occurring.



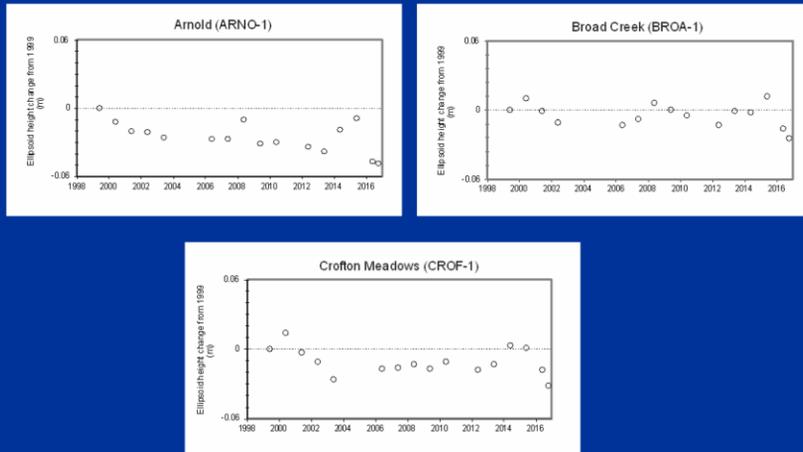
Seven 3d benchmarks (steel rods driven to refusal) have been installed in areas of high groundwater withdrawals (with the exception of ROS-1 located in southern Prince George’s County and completed for comparison purposes in an area of low groundwater use).

The marks in Anne Arundel County have been monitored by yearly GPS measurements for ~20 years. Those sites were selected because of the high rate of withdrawals (and projected withdrawals), but because the aquifers are more transmissive in those areas, water-level decline has been moderate. Continued use of the aquifers in Southern Maryland, however, has led to greater amounts of water-level decline prompting the additional monitoring sites. GPS monitoring at those sites began in 2016.

Andreasen, D.C., 2016, Establishment of a land subsidence-monitoring network to assess the potential effects of groundwater withdrawals in Southern Maryland: Maryland Geological Survey Open-File Report 16-02-01, 38 p.

Anne Arundel County monitoring results

- GW-related subsidence not clear given accuracy of GPS



The rate of change in ellipsoid height over a 17-year period of record at the Anne Arundel County marks ranges from approximately 0.62 to 1.3 millimeter/year, however there is significant scatter in the data.

Monitoring at the Southern Maryland marks just began last year, therefore several years will have to pass before assessing rates of elevation change.

Summary

- Conditions (geologic and hydrologic) similar to VA suggest GW-related subsidence is possible, especially in Southern Maryland
- Possible GW-related subsidence observed in Anne Arundel County, but significant scatter in GPS data
- Continue monitoring and possibly expand to include other well fields (Eastern Shore)
- If subsidence can be documented using GPS, then next step is extensometer? Costly \$\$\$