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Will Global Warming Overflow the Chesapeake Bay?

By Roger H. Bezdek, Ph.D.*

Introduction

Sea-level rise due to alleged global warming is a contentious issue with profound public policy implications. Numerous studies contend many regions of the United States are at risk. Many of those studies identify the Chesapeake Bay region as particularly susceptible to sea-level rise.[1]

> The research conducted for this *Policy Brief* indicates water intrusion problems in the Chesapeake Bay region are due not to sea-level rise, but primarily to land subsidence due to groundwater depletion and glacial isostatic adjustment.

One such report, released in 2014 and titled *Risky Business: The Economic Risks of Climate Change in the United States*, asserts, "On our current path, by mid-century, mean sea level at Norfolk, Virginia—home to the nation's largest naval base—will likely rise between 1.1 feet and 1.7 feet, and will rise 2.5 feet to 4.4 feet by the end of the century. However, there is a 1-in-100 chance that Norfolk could see sea level rise of more than 7.2 feet by the end of the century."[2] (See Figure 1.)

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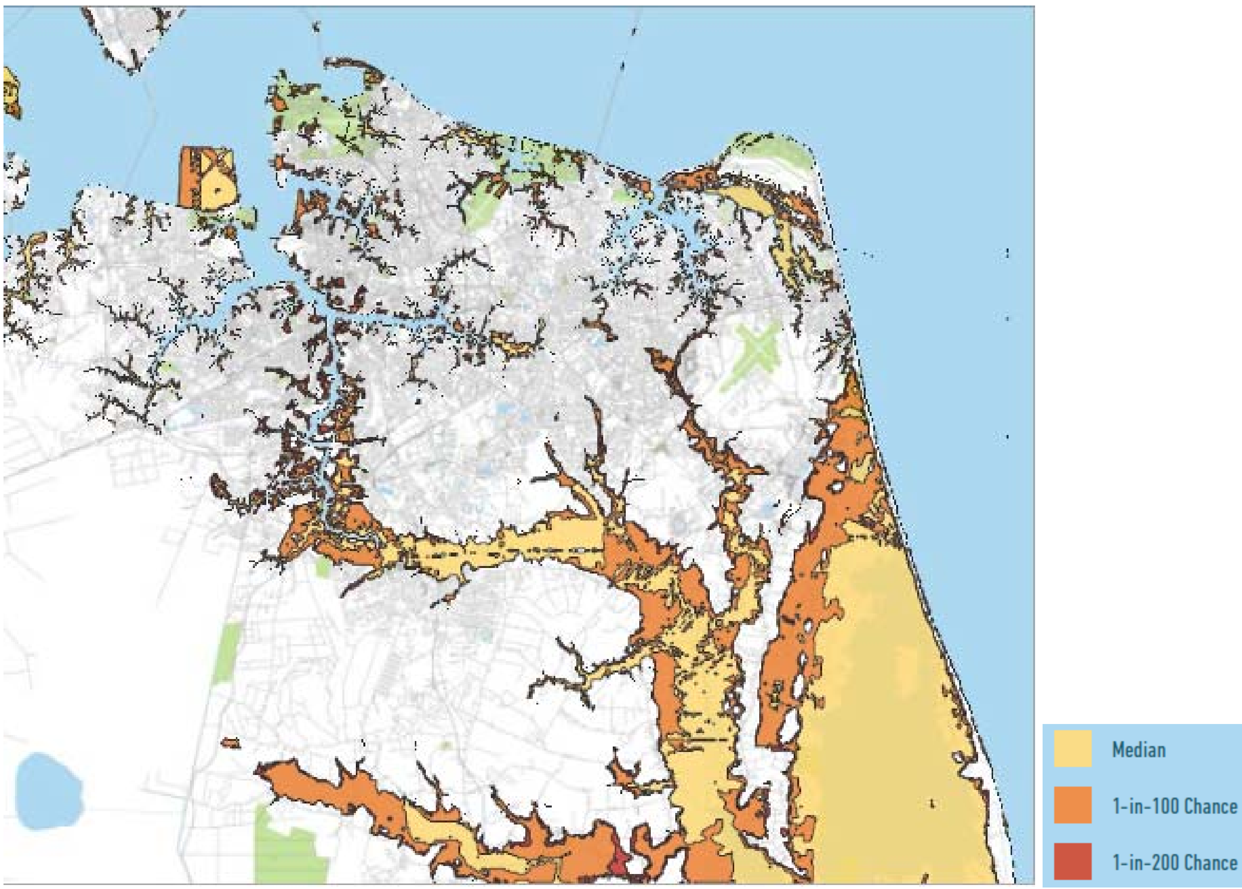
[1] George Van Houtven, *et al.*, "Costs of Doing Nothing: Economic Consequences of Not Adapting to Sea Level Rise in the Hampton Roads Region," report prepared for the Virginia Coastal Policy Center College of William & Mary Law School, RTI Project Number 0215176.000.001, November 2016; *Risky Business: The Economic Risks of Climate Change in the United States*, prepared for the Risky Business Project by the Rhodium Group, June 2014, updated September 2014.

[2] *Risky Business*, *ibid.*, p. 24.

A crucial question is whether this water intrusion is the result of climate-induced sea-level rise from anthropogenic global warming or is being caused by other factors. The research conducted for this *Policy Brief* indicates the water intrusion problems in the region are due not to sea-level rise, but primarily to land subsidence due to groundwater depletion and, to a lesser extent, subsidence from glacial isostatic adjustment. We conclude water intrusion may thus continue even if global sea levels do not rise or even decline. This finding suggests policymakers in the Chesapeake Bay area—in Maryland and Virginia in particular—should look to changes in local land and water use rather than concern themselves with global warming.

Figure 1
Mean Sea Level Rise in Norfolk by 2100



Source: *Risky Business: The Economic Risks of Climate Change in the United States*, prepared for the Risky Business Project by the Rhodium Group, June 2014, updated September 2014.

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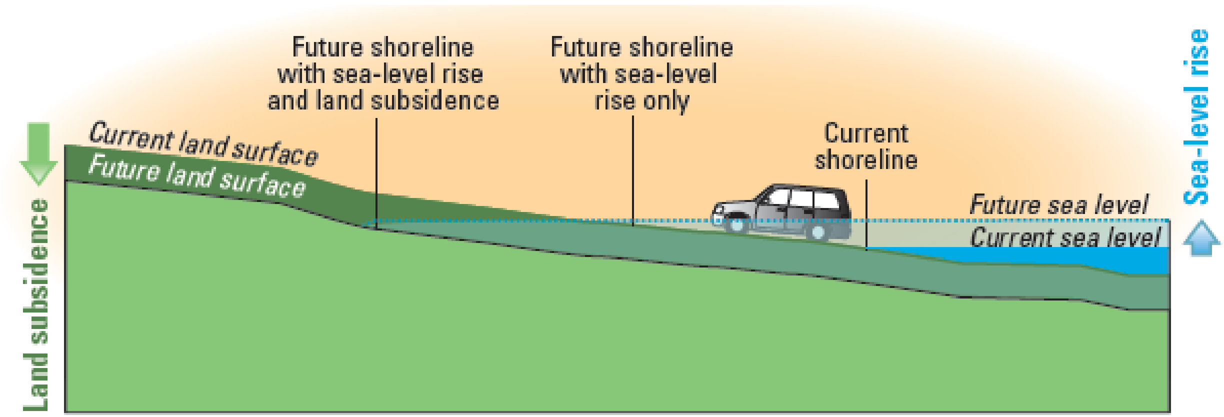
1. Land Subsidence and Relative Sea-Level Rise

Land subsidence is the sinking or lowering of the land surface. Most land subsidence in the United States is caused by human activities.[3] Land subsidence can increase flooding, alter wetland and coastal ecosystems, and damage infrastructure and historical sites. Land subsidence contributes to water intrusion and shoreline retreat. (See Figure 2.)

Figure 2
Shoreline Retreat Caused by a Combination of Sea-Level Rise and Land Subsidence



Source: Jack Eggleston and Jason Pope, "Land Subsidence and Relative Sea-Level Rise in the Southern Chesapeake Bay Region," *Circular 1392*, U.S. Geological Survey 2013, p. 4.

Two well-studied cases of land subsidence in the United States are in the Houston-Galveston, Texas, area and the Santa Clara Valley, California. Land sank by as much as three meters over 50 years because of intensive groundwater withdrawals in the two areas, as well as petroleum extraction in Texas, resulting in increased coastal flooding.[4] Regional authorities were established in the two areas to manage water use and land subsidence. The regional authorities set up monitoring networks and enlisted scientists to study the problem. Ultimately, the communities adopted new water-management practices to prevent land subsidence, including relocating groundwater withdrawals away from the coast, substituting surface water for groundwater supplies, and increasing aquifer recharge. In the Santa Clara Valley, subsidence has

[3] D.L. Galloway, D.R. Jones, and S.E. Ingebritsen, editors, "Land Subsidence in the United States," *Circular 1182*, U.S. Geological Survey, 1999.

[4] J.F. Poland, editor, *Guidebook to Studies of Land Subsidence Due to Ground-Water Withdrawal*, United Nations Educational, Scientific, and Cultural Organization, 1984; D.L. Galloway, *et al.*, *ibid.;* G.W. Bawden, *et al.*, *Investigation of Land Subsidence in the Houston-Galveston Region of Texas by Using the Global Positioning System and Interferometric Synthetic Aperture Radar, 1993–2000*, *Scientific Investigations Report* 2012–5211, U.S. Geological Survey, 2012.

mostly been stopped and, in the Houston-Galveston area, subsidence has been slowed, particularly along vulnerable shorelines.[5]

> Because land subsidence contributes to relative sea-level rise in the Chesapeake Bay region, it is important to understand why, where, and how fast it is occurring, now and in the future.

Rates and locations of land subsidence change over time, so accurate measurements and predictive tools are needed to improve understanding of land subsidence. Although rates of land subsidence are not as high on the Atlantic Coast as they have been in the Houston-Galveston area or the Santa Clara Valley, land subsidence is important because of the low-lying topography and susceptibility to sea-level rise in the southern Chesapeake Bay region.

Tidal-station measurements of sea levels do not distinguish between water that is rising and land that is sinking: The combined elevation changes are termed "relative sea-level rise." Because land subsidence contributes to relative sea-level rise in the Chesapeake Bay region, it is important to understand why, where, and how fast it is occurring, now and in the future.

As shown in Figure 2, as relative sea levels rise, shorelines retreat and the magnitude and frequency of near-shore coastal flooding increase. Although land subsidence can be slow, its effects accumulate over time. This has been an expensive problem in the Houston-Galveston area and the Santa Clara Valley[6] and contributes to current flooding problems in the Chesapeake Bay region.

Analysts found between 59,000 and 176,000 residents living near the shores of the Chesapeake Bay could be either permanently inundated or regularly flooded by 2100.[7] Potential damage to personal property was estimated to be $9 billion to $26 billion, and 120,000 acres of ecologically valuable land could be inundated or regularly flooded. Historic and cultural resources are also vulnerable to increased flooding from relative sea-level rise in the southern Chesapeake Bay, particularly at shoreline sites near tidal water, such as the seventeenth century historic Jamestown site.[8]

Land subsidence also can increase flooding in areas away from the coast. Low-lying areas, such as the Blackwater River Basin in Virginia, can be subject to increased flooding as the land sinks. Locations along the Blackwater River in the city of Franklin and the counties of Isle of Wight and Southampton have experienced large floods in recent years.[9] Land subsidence may be altering the topographic gradient that drives the flow of the river and contributing to the flooding.

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[5] D.L. Galloway, *et al.*, *supra* note 3. Hurricane Harvey struck the Houston-Galveston area after this was written but before peer review was completed. The extraordinary rainfall and consequent flooding in the area do not contradict or require any changes to this analysis.

[6] D.L. Galloway, *et al.*, *supra* note 3.

[7] This estimate was based on 2010 census data, using the spring high-tide as a reference elevation and assuming a 1-meter relative sea-level rise.

[8] See B.J. McFarlane, "Climate Change in Hampton Roads – Phase III – Sea Level Rise in Hampton Roads, Virginia," Report PEP12–06, Hampton Roads Planning District Commission, July 2012.

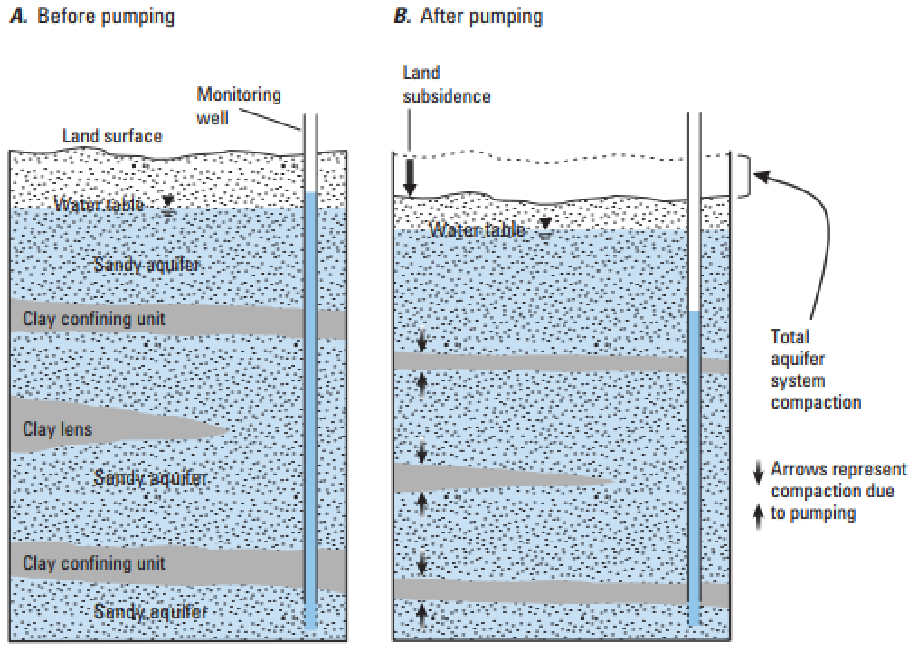
[9] Federal Emergency Management Agency, *Flood Insurance Study of Franklin, Virginia, Community*, September 2002.

2. Causes of Land Subsidence in the Chesapeake Bay Region

It is important to understand the causes of land subsidence so it can be more effectively managed. Most land subsidence in the United States is caused by human activities,[10] with groundwater withdrawals responsible for about 80 percent. Causes of subsidence most relevant to the Chesapeake Bay region include aquifer-system compaction caused by groundwater withdrawals and glacial isostatic adjustment.

When groundwater is pumped from an aquifer system, water pressure in the system decreases. The pressure change is reflected by water levels in wells, with water levels falling as aquifer-system pressure decreases. (See Figure 3.)

Figure 3
How Groundwater Pumping Changes
Water Pressure in Aquifer Systems



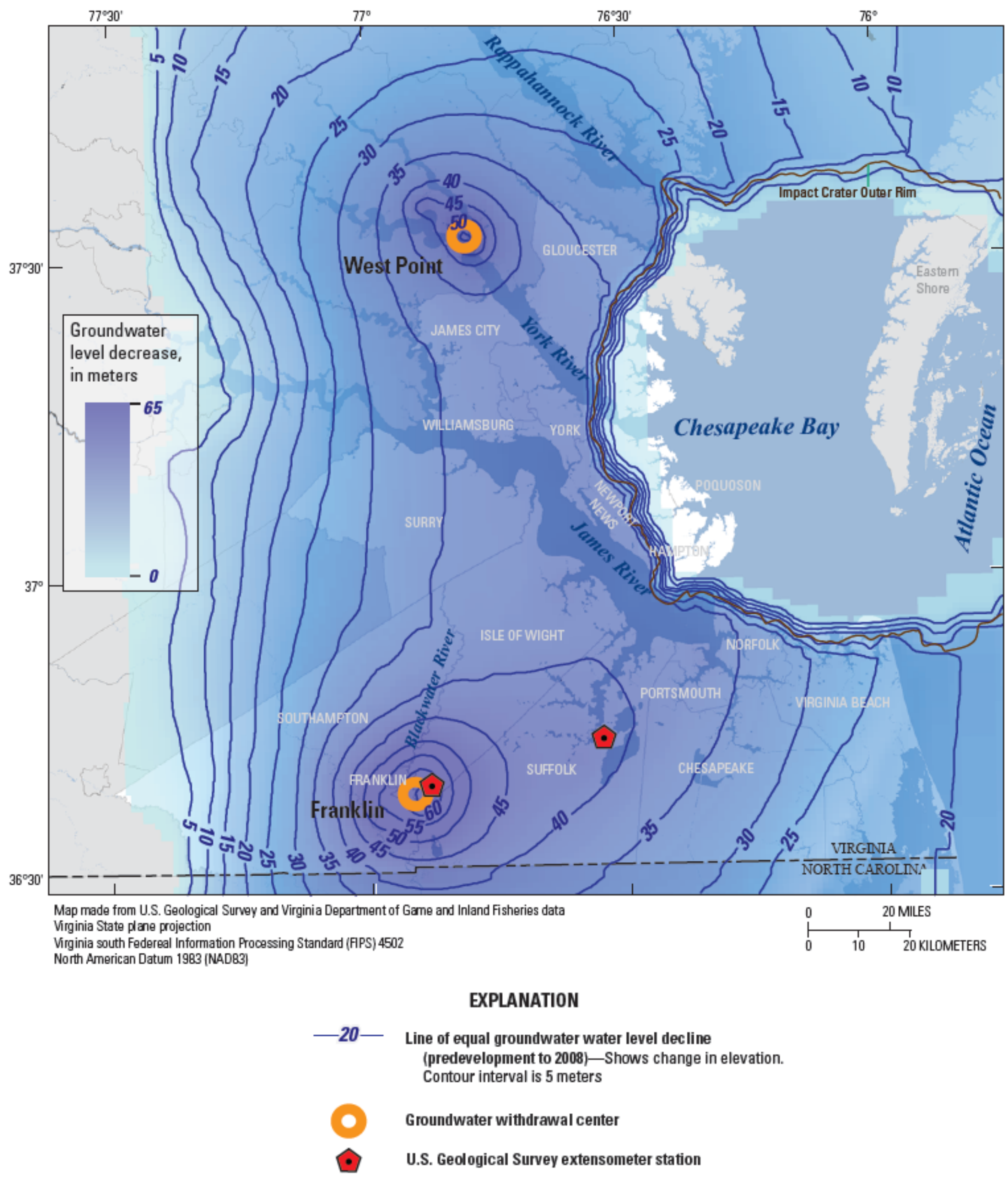
Aquifer-system compaction caused by groundwater withdrawals *A*, before and *B*, after pumping. Modified from Galloway and others (1999).

Source: Jack Eggleston and Jason Pope, "Land Subsidence and Relative Sea-Level Rise in the Southern Chesapeake Bay Region," *Circular 1392*, U.S. Geological Survey 2013, p. 13.

[10] D.L. Galloway, *et al.*, *supra* note 3.

This is happening over most of the Chesapeake Bay region, with the greatest drops in water-level seen near the pumping centers of Franklin and West Point, Virginia. (See Figure 4.)

Figure 4
Chesapeake Bay Groundwater Water-Level Decreases, 1900 to 2008



Source: Jack Eggleston and Jason Pope, "Land Subsidence and Relative Sea-Level Rise in the Southern Chesapeake Bay Region," *Circular 1392*, U.S. Geological Survey 2013, p. 12.

As water levels fall, the aquifer system compacts, causing the land surface above to subside. Water levels have fallen over the entire Virginia Coastal Plain in the Potomac aquifer, which is the deepest and thickest aquifer in the southern Chesapeake Bay region and supplies about 75 percent of groundwater withdrawn from the Virginia Coastal Plain aquifer system.[11]

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The amount of aquifer-system compaction is determined by three factors: water-level decline, sediment compressibility, and sediment thickness.

If any of these three factors increases in magnitude, then the amount of aquifer-system compaction and land subsidence increases. Because all three of these factors vary spatially across the southern Chesapeake Bay region, rates of land subsidence caused by aquifer-system compaction also vary spatially across the region.

The Virginia Coastal Plain aquifer system consists of many stacked layers of sand and clay. Although groundwater is withdrawn primarily from the aquifers (sandy layers), most compaction occurs in confining units and clay lenses, the relatively impermeable layers sandwiched between and within the aquifers.[12] The compression of clay layers is mostly non-recoverable; meaning that, if groundwater levels later recover and increase, the aquifer system nevertheless does not expand to its previous volume and the land surface does not rise to its previous elevations.[13] It has been estimated that 95 percent of the water removed from storage in the Virginia Coastal Plain aquifer system between 1891 and 1980 was derived from the confining layers.[14]

The timing of aquifer-system compaction is also important. Compaction can continue for many years or decades after groundwater levels decline. When groundwater is pumped from an aquifer, pressure decreases in the aquifer. The pressure decrease then slowly propagates into clay layers adjacent to or within the aquifer, and as long as pressure continues to decrease in the clay layers, compaction continues.

The layered sediments of the Virginia Coastal Plain aquifer system range in grain size from very fine (silts and clays) to coarse (sand and shell fragments).[15] Confining layers occupy about 16 percent of the total aquifer-system thickness, an average of 100 meters out of the total average

[11] Charles E. Heywood and Jason P. Pope, "Simulation of Groundwater Flow in the Coastal Plain Aquifer System of Virginia," *Scientific Investigations Report* 2009–5039, U.S. Geological Survey, 2009.

[12] Jason P. Pope and Thomas J. Burbey, "Multiple-Aquifer Characterization From Single Borehole Extensometer Records," *Groundwater* 42, no. 1 (2004): 45–58.

[13] Jason P. Pope, "Characterization and Modeling of Land Subsidence Due to Groundwater Withdrawals From the Confined Aquifers of the Virginia Coastal Plain," Virginia Polytechnic Institute, M.S. thesis, 2002.

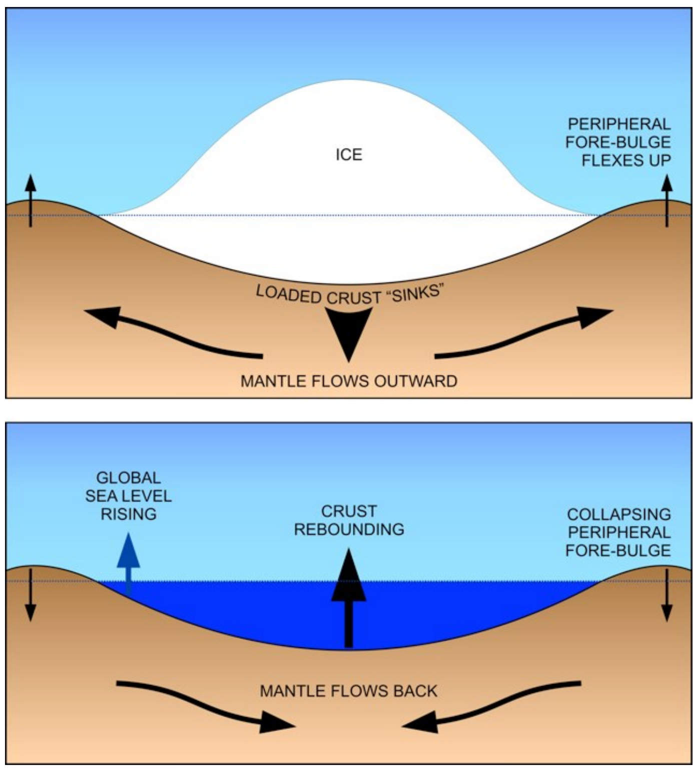
[14] L.F. Konikow and C.E. Neuzil, "A Method to Estimate Groundwater Depletion From Confining Layers," *Water Resources Research* 43, no. 7 (2007).

[15] E. Randolph McFarland and T. Scott Bruce, *The Virginia Coastal Plain Hydrogeologic Framework, Professional Paper* 1731, U.S. Geological Survey, 2006.

thickness of 619 meters.[16] Clay layers overlying and within the Potomac aquifer are compressing as aquifer pressure decreases migrate vertically and laterally from pumping wells.[17]

Crystalline bedrock underlies the layered sediments of the Virginia Coastal Plain aquifer system, but the bedrock is not solid and unyielding: It flexes and moves in response to stress. Bedrock in the mid-Atlantic region is moving slowly downward in response to melting of the Laurentide ice sheet that covered Canada and the northern United States during the last ice age.[18] When the ice sheet still existed, the weight of the ice pushed the underlying Earth's crust downward and, in response, areas away from the ice sheet were forced upward (called glacial forebulge). (See Figure 5.) The southern Chesapeake Bay region is in the glacial forebulge area and was forced upward by the Laurentide ice sheet.

Figure 5
Glacial Isostatic Adjustment



Source: GPS Research Group, "Glacial Isostatic Adjustment," Figure 1, http://xenon.colorado.edu/spotlight/index.php?product=spotlight&station=CHUR.

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[16] *Ibid.* and Charles E. Heywood and Jason P. Pope, *supra* note 11.

[17] These confining layers have high specific storage (compressibility) estimated to be 0.00015 per meter; Jason P. Pope and Thomas J. Burbey, *supra* note 12.

[18] Giovanni F. Sella, *et al.*, "Observation of Glacial Isostatic Adjustment in 'Stable' North America with GPS," *Geophysical Research Letters* 34, no. 2 (2007); John D. Boon, John M. Brubaker, and David M. Forrest, "Chesapeake Bay Land Subsidence and Sea Level Change – an Evaluation of Past and Present Trends and Future Outlook," *Special Report* 425 in Applied Marine Science and Ocean Engineering, Virginia Institute of Marine Science, 2010.

The ice sheet started melting about 18,000 years ago and took many thousands of years to disappear entirely. As the ice melted and its weight was removed, glacial forebulge areas, which previously had been forced upward, began sinking and continue to sink. This movement of Earth's crust in response to ice loading or melting is called glacial isostatic adjustment. Data from GPS measurements and carbon dating of marsh sediments indicate regional land subsidence in response to glacial isostatic adjustment in the Chesapeake Bay region may have a current rate of about 1 mm/yr.[19]

> Movement of Earth's crust in response to ice loading or melting, called glacial isostatic adjustment, may be contributing to land subsidence in the Chesapeake Bay region.

There are other causes of land subsidence, including bedrock dissolution, drainage and degradation of organic soils, settling of fill and disturbed soils,[20] and volcanic disturbances and tectonic motion related to continental crust movements. There is currently little or no evidence that these other causes are important to regional subsidence processes in the southern Chesapeake Bay region.

Settling of impact crater sediments associated with the Chesapeake Bay meteor crater is an unlikely cause of current land subsidence in the region because the meteor struck about 35 million years ago.[21] The passage of time since the meteor impact has been so great that, even if it was conservatively assumed that subsidence rates had stayed constant rather than decreasing during the past 1 million years, a rate of 1 mm/yr would equal 1 kilometer of subsidence, which is not compatible with current understanding of regional geology.[22]

3. Land Subsidence and Sea-Level Rise in the Chesapeake Bay Region

Land subsidence has been known and observed in the southern Chesapeake Bay region for many decades and is a factor that must be considered by urban planners and natural resource managers.

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[19] Simon E. Engelhart and Benjamin P. Horton, "Holocene Sea Level Database for the Atlantic Coast of the United States," *Quaternary Science Reviews* 54 (2012): 12–25; S.E. Engelhart, B.P. Horton, B.C. Douglas, W.R. Peltier, and T.E. Törnqvist, "Spatial Variability of Late Holocene and 20th Century Sea-Level Rise Along the Atlantic Coast of the United States," *Geology* 37, no. 12 (2009): 1115–8. This downward velocity rate is uncertain and probably not uniform across the region.

[20] This may be happening in local areas where construction has disturbed soils, marshes have been filled in, or islands have been constructed, such as the islands constructed for the Chesapeake Bay Bridge Tunnel. However, settling of fill and disturbed soils cannot explain the subsidence observed across the southern Chesapeake Bay region.

[21] D.S. Powars and T.S. Bruce, "The Effects of the Chesapeake Bay Impact Crater on the Geological Framework and Correlation of Hydrogeologic Units of the Lower York-James Peninsula," *Professional Paper* 1612, U.S. Geological Survey, 1999.

[22] Measured subsidence rates also indicate the crater has the indirect effect of reducing modern-day subsidence caused by aquifer-system compaction, because the low-permeability sediments associated with the impact crater reduce groundwater level decreases within the rim of the crater.

Land subsidence in the region was first documented more than four decades ago by Holdahl and Morrison, who reported results of geodetic surveys completed between 1940 and 1971 and found land surfaces across the region were sinking at an average rate of 2.8 mm/yr, with rates ranging from 1.1 mm/yr to 4.8 mm/yr.[23] The two areas where subsidence rates were the most rapid roughly coincide with groundwater pumping centers at Franklin and West Point. Measurements of land subsidence are currently made at Continuously Operating Reference Stations in the region. The National Geodetic Survey has computed velocities for three of these stations between 2006 and 2011 and found an average subsidence rate of 3.1 mm/yr.[24]

> Land subsidence has been known and observed in the southern Chesapeake Bay region for many decades and is a factor that must be considered by urban planners and natural resource managers.

Aquifer-system compaction was measured with extensometers at two locations in the region, at Franklin from 1979 to 1995 and at Suffolk from 1982 to 1995.[25] The extensometers showed 24.2 mm of total compaction at Franklin from 1979 through 1995 (1.5 mm/yr) and 50.2 mm of total compaction at Suffolk from 1982 through 1995 (3.7 mm/yr). Rates of compaction were correlated to groundwater-level decreases and to the aggregate thickness of compressible sediments at each location. The total thickness of compressible fine-grained sediments is 130.8 meters at Suffolk and 62.7 meters at Franklin. Water levels in the Potomac aquifer during the period of compaction measurement decreased more at Suffolk than at Franklin, about 5 meters versus about 2 meters. Aquifer-system compaction has not been measured at any other locations in the Chesapeake Bay region, but it likely affects most of the region because large water-level decreases in the aquifer system are widespread.

Relative sea-level rise measured at four National Oceanic and Atmospheric Administration (NOAA) tidal stations averaged 3.9 mm/yr from about 1950 through 2006. At the Sewells Point tidal station in Norfolk, Virginia, rising sea levels have been recorded since 1927: Sea level at Sewells Point rose at an average rate of 4.4 mm/yr from 1927 to 2006, with a 95 percent confidence interval of ±0.27 mm/yr.[26] In comparison, global average sea levels have been rising at about 1.8 mm/yr. Although rates of absolute sea-level rise (rise due only to increases in ocean volume) can vary substantially from one location to another and change over time,[27] the global average rate of 1.8 mm/yr from 1961 to 2003 is a widely accepted global benchmark rate.[28] The

[23] Sandford R. Holdahl and Nancy L. Morrison, "Regional Investigations of Vertical Crustal Movements in the U.S., Using Precise Relevelings and Mareograph Data," *Tectonophysics* 23, no 4 (1974): 373–90.

[24] Richard A. Snay and Tomás Soler, "Continuously Operating Reference Station (CORS) – History, Applications, and Future Enhancements," *Journal of Surveying Engineering* 134, no. 4 (November 2008): 95–104; National Geodetic Survey, "IGS08 Geodetic CORS Positional Antennae Reference Point (ARP) [GRS80 Ellipsoid] Computed Velocities," National Oceanic and Atmospheric Administration, March 2013.

[25] Jason P. Pope and Thomas J. Burbey, *supra* note 12.

[26] Chris Zervas, "Sea Level Variations of the United States, 1854–2006," *Technical Report* NOS CO–OPS 053, National Oceanic and Atmospheric Administration, 2009.

[27] Asbury H. Sallenger, Kara S. Doran, and Peter A. Howd, "Hotspot of Accelerated Sea-Level Rise on the Atlantic Coast of North America," *Nature Climate Change* 2, no. 12 (2012): 884–8.

difference between the average sea-level rise computed from the four NOAA tidal stations in the study area (3.9 mm/yr) and the benchmark global rate (1.8 mm/yr) is 2.1 mm/yr, which is an estimate of the average rate of land subsidence at the four NOAA stations.

> Tide-gauge records and paleo-sea-level records indicate rates of sea-level rise in Chesapeake Bay exceed the global average. That is because the land is subsiding.

However, as noted, local regional sea-level rise can differ significantly from the global mean sea-level rise.[29] Chesapeake Bay tide-gauge records and paleo-sea-level records from tidal marshes and the bay's main stem indicate rates of sea-level rise in Chesapeake Bay range from about 3.2 mm to 4.7 mm/yr, depending on the location and period of record for each tide gauge. These rates exceed the global average because the land is subsiding.

Further, the departure of sea-level trends in Chesapeake Bay from the global mean for the last century may not persist. Thus, rates measured at tide gauges do not necessarily reflect pre-twentieth century regional patterns, nor can they be necessarily expected to persist into the future.[30] Nevertheless, the estimates used here are currently the best available and are supported by the research literature.

Thus, the difference between the average subsidence rate of about 3.1 mm/yr and the average estimated sea-level rise computed in the Chesapeake Bay area of about 3.9 mm/yr is 0.8 mm/year. These data indicate land subsidence has been responsible for most of the relative sea-level rise measured in the Chesapeake Bay region over the past half-century.

4. Links between Groundwater Withdrawals and Land Subsidence

Aquifer-system compaction is responsible for most land subsidence in the Chesapeake Bay region, based on average measured land subsidence rates of about 2.8 mm/yr and measured average compaction rates of 2.6 mm/yr.

The aquifer-system compaction is caused by high groundwater withdrawal rates that have lowered water levels. As shown in Figure 6, groundwater withdrawal rates in the region increased sharply in the twentieth century as modern pumping technology was widely adopted.[31] The many decades of increasing groundwater withdrawals have caused groundwater levels to fall across the Chesapeake Bay region. Water levels are expected to continue falling for many years,

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[28] N.L. Bindoff, *et al.*, "Observations – Oceanic Climate Change And Sea Level," in *Climate Change: The Physical Science Basis*," contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (New York, NY: Cambridge University Press, 2007), pp. 385–432.

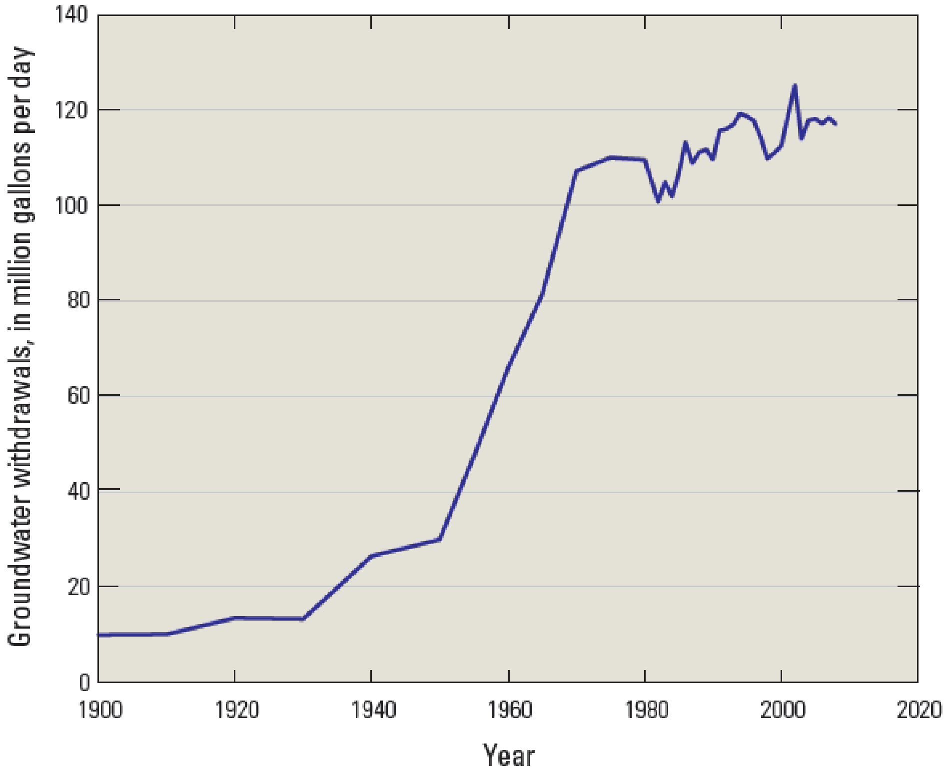
[29] J.A. Church, *et al.*, "Sea Level Change," in *Climate Change 2013: The Physical Science Basis,* contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (New York, NY and Cambridge, UK: Cambridge University Press, 2013).

[30] See the discussion in Thomas M. Cronin, "Sea-Level Rise and Chesapeake Bay," U.S. Geological Survey, May 2013.

[31] Charles E. Heywood and Jason P. Pope, *supra* note 11.

even if pumping rates do not increase further, because of delay caused by compressibility of the aquifer system.[32]

Figure 6
Groundwater Withdrawal Rates From Virginia Coastal Plain Aquifers, 1900 to 2008



Source: Jack Eggleston and Jason Pope, "Land Subsidence and Relative Sea-Level Rise in the Southern Chesapeake Bay Region," *Circular 1392*, U.S. Geological Survey 2013, p. 19.

[32] L.F. Konikow and C.E. Neuzil, *supra* note 14; R.E. Mace, "Peer Review of Virginia's Groundwater Management Program," Virginia Department of Environmental Quality final report, December 2011.

Recommendations

An important component of relative sea-level rise, land subsidence, could be prevented or reduced in the future if groundwater pumping strategies were changed. Future land subsidence caused by aquifer-system compaction can be reduced or stopped by changing water-use practices. Because aquifer-system compaction is the primary cause of land subsidence in the Chesapeake Bay region, reducing compaction can reduce land subsidence and associated flood risks.

> An important component of relative sea-level rise, land subsidence, could be prevented or reduced in the future if groundwater pumping strategies were changed.

Eggleston and Pope came to a similar conclusion and found more data and analyses are needed to provide a foundation of knowledge that can guide resource management decisions in the Chesapeake Bay region. They noted, "Scientific understanding of land subsidence is critical for making informed decisions about public investments and management of land and water resources in the southern Chesapeake Bay region. Many valuable resources, including developed urban centers, coastal marsh and wetland ecosystems, historic sites, and military facilities, are at risk of increased flooding due to land subsidence."[33]

In the Houston-Galveston area and the Santa Clara Valley, resource managers have successfully decreased land subsidence by moving groundwater pumping away from the coast, reducing groundwater withdrawal rates, and increasing aquifer recharge.[34] Similar findings have been reported for the San Joaquin Valley, California,[35] coastal Louisiana,[36] the Yellow River delta, China,[37] and the central Ganges-Brahmaputra Delta, Bangladesh.[38]

The small contribution to land subsidence from glacial isostatic adjustment in the Chesapeake Bay region—perhaps about 1 mm/yr[39]—cannot be prevented. This natural glacial isostatic adjustment of Earth's crust will diminish with time, but at a glacial or geologic pace.

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[33] See Jack Eggleston and Jason Pope, "Land Subsidence and Relative Sea-Level Rise in the Southern Chesapeake Bay Region," *Circular 1392*, U.S. Geological Survey, 2013.

[34] D.L. Galloway, *et al.*, *supra* note 3.

[35] Devin Galloway and Francis S. Riley, "San Joaquin Valley: California Largest Human Alteration of the Earth's Surface," pp. 23–34 in D.L. Galloway, *et al.*, *supra* note 3.

[36] Roy K. Dokka, "Modern-day Tectonic Subsidence in Coastal Louisiana," *Geology* 34, no. 4 (April 2006): 281–4.

[37] Stephanie Higgins, *et al.*, "Land Subsidence at Aquaculture Facilities in the Yellow River Delta, China," *Geophysical Research Letters* 40 (2013): 3898–902.

[38] Till J.J. Hanebuth, *et al.*, "Rapid Coastal Subsidence in the Central Ganges-Brahmaputra Delta (Bangladesh) Since the 17th Century Deduced From Submerged Saltproducing Kilns," *Geology* 41, no. 9 (September 2013), p. 987–90.

[39] S.E. Engelhart, B.P. Horton, B.C. Douglas, W.R. Peltier, and T.E. Törnqvist, *supra* note 19.

Conclusion

There is little doubt that water intrusion is a serious problem in much of the Chesapeake Bay region. However, the critical question is whether this water intrusion is the result of climate-induced sea-level rise or is being caused by other factors.

> The difference between land subsidence and sea-level rise is critical, and the solutions required to address the problem are entirely different.

Our findings indicate the water intrusion problems in the region are due not to sea-level rise, but, rather, primarily to land subsidence due to groundwater depletion and, to a lesser extent, subsidence from glacial isostatic adjustment.

The difference is critical, and the solutions required to address the problem are entirely different. If the cause of the problem is primarily land subsidence—as it is in Norfolk and the Chesapeake Bay region—then water intrusion will continue irrespective of sea level changes. For the Chesapeake Bay region, the required remedy is the reversal of groundwater withdrawal rates, which has been used successfully elsewhere in the United States to solve water intrusion problems—including in the Houston-Galveston, Texas, area and the Santa Clara Valley, California. Future land subsidence caused by aquifer-system compaction in the Chesapeake Bay region can be reduced or stopped by changing water-use practices. Our findings are significant because the water intrusion problems in the Chesapeake Bay—or elsewhere—cannot be successfully resolved unless their causes are correctly identified and appropriate remedies devised.

# # #

About the Author

Roger Bezdek, Ph.D. is an internationally recognized energy analyst and president of MISI—a Washington, DC-based economic, energy, and environmental research firm. He has more than 30 years of experience in the energy, utility, environmental, and regulatory areas in private industry, academia, and the federal government. He has previously served as senior advisor in the Office of the Secretary of the Treasury, as research director at the Department of Energy, as U.S. energy and environmental delegate to the European Community and to NATO, and as a participant in the U.S. State Department AMPART program.

Bezdek holds a Ph.D. in economics from the University of Illinois at Urbana-Champaign. He is the author of six books and more than 300 publications in scientific and technical journals. He is also the Washington editor of *World Oil* magazine.

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The Nongovernmental International Panel on Climate Change (NIPCC) is an international panel of nongovernment scientists and scholars who have come together to present a comprehensive, authoritative, and realistic assessment of the science and economics of global warming. Because it is not a government agency, and because its members are not predisposed to believe climate change is caused by human greenhouse gas emissions, NIPCC is able to offer an independent "second opinion" of the evidence reviewed—or not reviewed—by the Intergovernmental Panel on Climate Change (IPCC) on the issue of global warming.

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