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Sea Level Rise and Flooding Risk in Virginia

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Cover photograph of Norfolk, VA flood waters courtesy of the United States Navy.

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Sea Level Rise and Flooding Risk in Virginia

Larry P. Atkinson, Tal Ezer, and Elizabeth Smith[1]

Abstract: Consistent rises in sea level have occurred throughout the world for thousands of years. Flooding, storm surges, and other consequences of the rise in sea level have had widespread effects on coastal communities across the globe. Nowhere is this more apparent than the Norfolk/Virginia Beach region along the U.S. Atlantic coastline, where the sea level is rising more rapidly than the global average. This article discusses the causes of and the differences between the rise in sea levels globally and the rise of the sea level in the mid-Atlantic region of the United States. The article also emphasizes the problems and consequences this sea level rise is creating for the mid-Atlantic region and outlines how communities along the coast are responding in order to adapt to the ever-changing sea levels.

I. Introduction

Communities in the coastal areas from Norfolk to New York City were settled over 400 years ago. Since that time sea level has risen well over one foot and in many locations over two feet.[2] Because of the rise in sea level, communities see more frequent flooding from the same type of storms. Some communities now experience minor flooding even during normal high tides. This article reviews the past history of sea level, the changes in sea level locally in the Norfolk/Virginia Beach region, and future predictions of sea level in the region. This article also discusses and shows graphically how minor flooding, sometimes called nuisance flooding, has increased. In addition, this article briefly reports on how communities are planning their adaptation.

A. Changes in Global Sea Level

Sea level has been rising and falling in a regular pattern for at least 400,000 years. As a glacial cycle starts, ice forms over land and sea level drops as water is transferred from the ocean to land. When a glacial cycle ends, the land ice melts, water returns to the ocean, and sea level rises. This cycle repeats

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[2] *See* U.S. Geological Survey, The Chesapeake Bay: Geologic Product of Rising Sea Level, Fact Sheet 102-98 (Oct. 1998), *available at* http://pubs.usgs.gov/fs/fs102-98/?.

itself about every 100,000 years. This regular cycle is caused by changes in the earth's orbit and tilt in relation to the sun.

Global sea level also changes as the temperature of the oceans' waters change. As the oceans warm, as they are now, they expand. The expansion caused by warming results in sea level rising because a very small increase in temperature can cause a large increase in the sea level because the ocean is on average several miles deep. The warming and consequent expansion of the ocean and the addition of melting land ice over Greenland and the Antarctic result in the sea level rise (SLR) currently being observed by scientists, communities, and property owners.

Since the last glaciation ended about 18,000 years ago, global sea level has risen about 400 feet as the oceans have warmed and ice has melted. It is important to note that over the last 6,000 years sea level rise has been relatively slow. Interestingly, the last 6,000 years of slow sea level rise corresponds with the time period in which many civilizations grew in the coastal areas of the Middle East.

Since the late 1800's tide gauge measurements, which are now combined with satellite altimetry (since about 1993), give a more detailed picture of global sea level rise (Figure 1). Even a casual look at the plot in Figure 1 suggests an increasing rate of global sea level rise. The variation that occurs every ten years or so is related to ocean processes such as el Niño and la Niña. Excellent reviews of the physics of sea level rise and adaptation can be found in the June 2011 special issue of the journal *Oceanography*.[3] In addition, a very recent assessment of global sea level rise with reference to the U.S. coastline was recently published by the National Oceanic and Atmospheric Administration.[4]

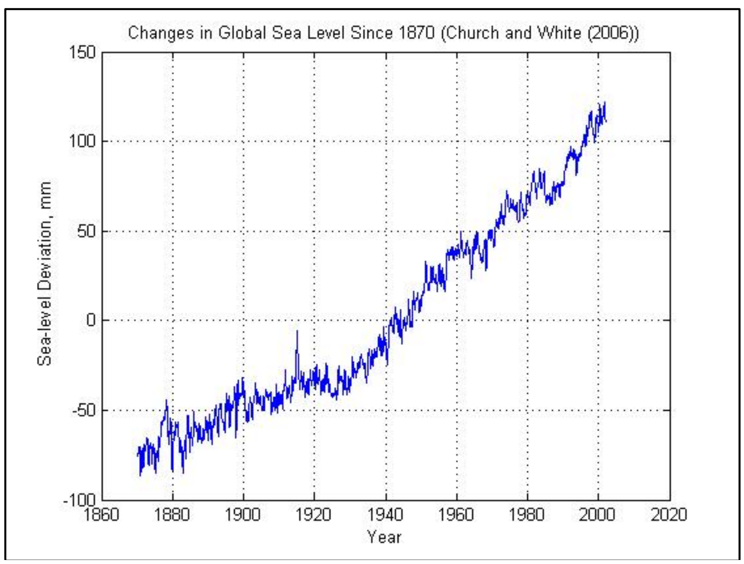

Fig. 1. Global sea level. Global average sea level from coastal tide gauges.[5]

B. Local or Relative Sea Level Rise

The global sea level changes that are often referred to in the press are frequently very different from the actual sea level rise at any coastal location. Local sea level changes are measured at tide

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[3] The articles from this special issue can be accessed at http://www.tos.org/oceanography/archive/24-2.html.

[4] A. PARRIS ET AL., GLOBAL SEA LEVEL RISE SCENARIOS FOR THE US NATIONAL CLIMATE ASSESSMENT, NOAA TECH. MEMO OAR CPO-1 (Dec. 2012), *available at* www.cpo.noaa.gov/reports/sealevel/NOAA_SLR_r3.pdf.

[5] Data derived from John A. Church and Neil J. White, *Sea-level rise from the late 19th to the early 21st Century*, 32 SURVEYS IN GEOPHYSICS 585 (2011), *available at* http://link.springer.com/article/10.1007/s10712-011-9119-1.

gauge stations maintained by the U. S. Government (Figure 2). These gauges are critical to determining the present rise rates and predicting the future rates of sea level rise. The Sewells Point gauge is on the Norfolk Naval Base and has been making measurements since 1928 (Figure 3). That is one of the longer records in the U.S. and is almost iconic for SLR in Virginia. Data from this gauge shows a rise rate of about 1.5 feet per 100 years or about 2 inches per decade over the past decades. This may not sound like much, but recall that Hampton Roads and many coastal areas along the Gulf, southeast, and northeast coasts are very flat with little elevation changes within a few tens of miles of the shore.

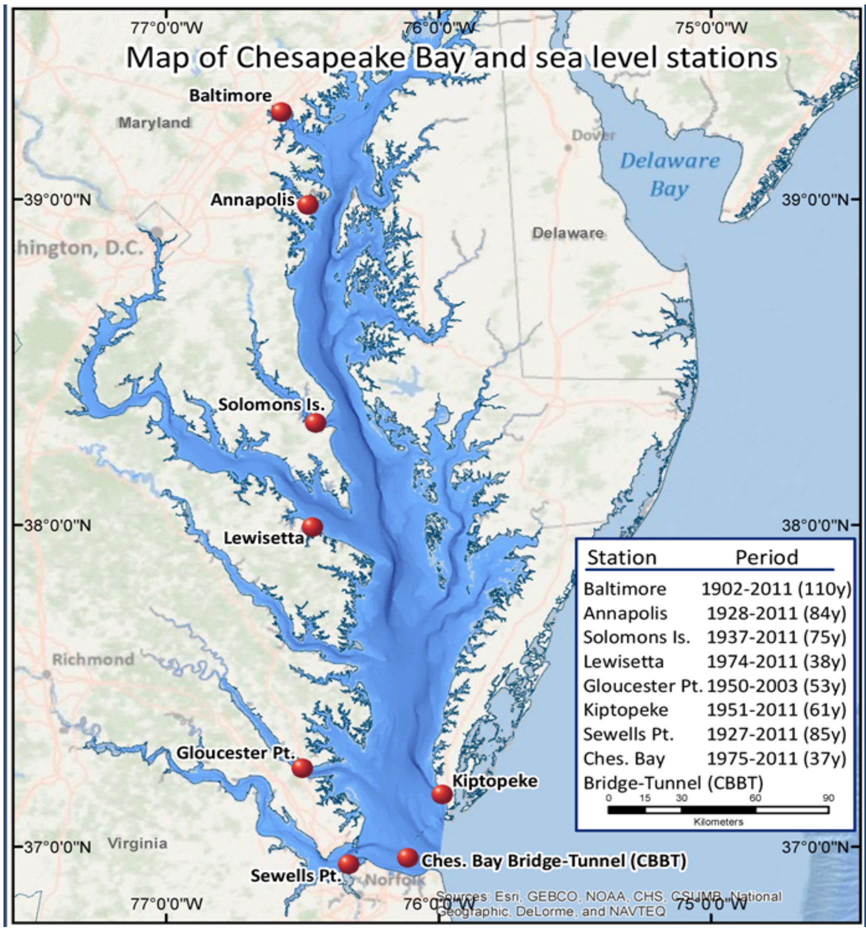

Fig. 2. Chesapeake Bay map showing tide gauge stations. Note location of Sewells Point gauge in Norfolk, VA. Prepared by G. McLeod (Old Dominion University).

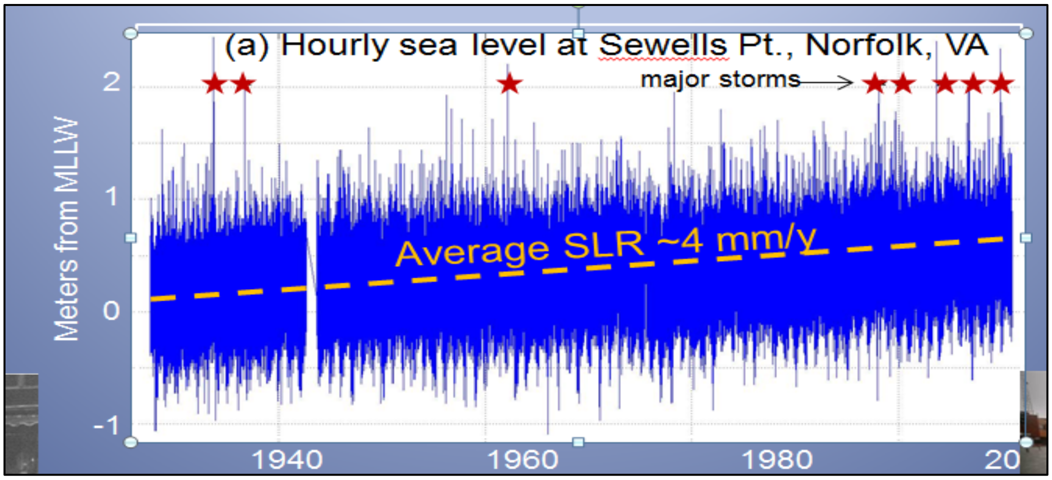

Fig. 3. Sea level trends in Norfolk. This figure shows the water level height at the Sewells Point NOAA tide station in Norfolk. The average sea level rise since 1928 has been about 1.45 feet. Major flooding events because of hurricanes or northeasters are indicated with stars.

The local SLR in the mid-Atlantic is higher than the global rise for several reasons. First, there is local subsidence. In the mid-Atlantic, the land is sinking because of compaction related to the nature of the underlying rock including the presence of the Chesapeake Bolide[6] and groundwater withdrawal. Additionally, over the years many structures have been built on fill that compacts, leading to local sea level rise. Second, there is glacial isostatic rebound or glacial forebulge subsidence. During the last glaciation the earth crust under the ice in the northeast U.S. and Canada was depressed and the crust below Virginia rose. Now, with the ice removed, the northeast U.S. and Canada is rising and the crust below Virginia is sinking.[7] Third, local sea level rise in the mid-Atlantic is higher because of ocean circulation dynamics. The North Atlantic Ocean is not level. For example, when the Gulf Stream current flows northward along the coast, it has an east-west tilt in elevation of about 3-5 feet across its flow, keeping the sea level along the U.S. East Coast lower than the rest of the Atlantic Ocean east of the stream (imagine a dome of water sitting in the North Atlantic Ocean, but as the dome expands, contracts or shifts onshore/offshore the boundary of the dome laps up on the U.S. coastline). What might be minor relative to the size of the North Atlantic Ocean is significant for the U.S. coastlines. As discussed later, climatic changes in the North Atlantic Ocean circulation and weakening of the Gulf Stream may cause an acceleration of sea level rise along the mid-Atlantic coast.

C. Global vs. Local Sea Level

As discussed, global sea level rise is different than local sea level rise. Consider the comparison of global SLR to local SLR in the Hampton Roads area. Figure 4 shows the height of global sea level from satellite measurements (red monthly average and linear trend line) compared to the height of local sea level from a tide gauge in Hampton Roads (blue monthly average and linear trend line). The recent report for the National Assessment states for global sea level rise: "We have very high confidence (>9 in 10 chance) that global mean sea level will rise at least 0.2 meters (8 inches) and no more than 2.0

[6] *See* C. Wylie Poag et al., *Meteoroid Mayhem in Ole Virginny: Source of the North American Tektite Strewn Field*, 22 GEOLOGY 691 (1994).

[7] *See* Timothy W. Scott et al., *Glacioisostatic Influences on Virginia's Late Pleistocene Coastal Plain Deposits*, 116 GEOMORPHOLOGY 175 (2010).

meters (6.6 feet) by 2100."[8] The local Hampton Roads data (blue line) varies almost 2 feet month-to-month because of seasonal temperatures, wind patterns, and ocean circulation. Note that the local sea level rise in Hampton Roads is more than twice as fast as the global sea level rise. Again, this is because of local subsidence and ocean circulation in the nearby ocean.

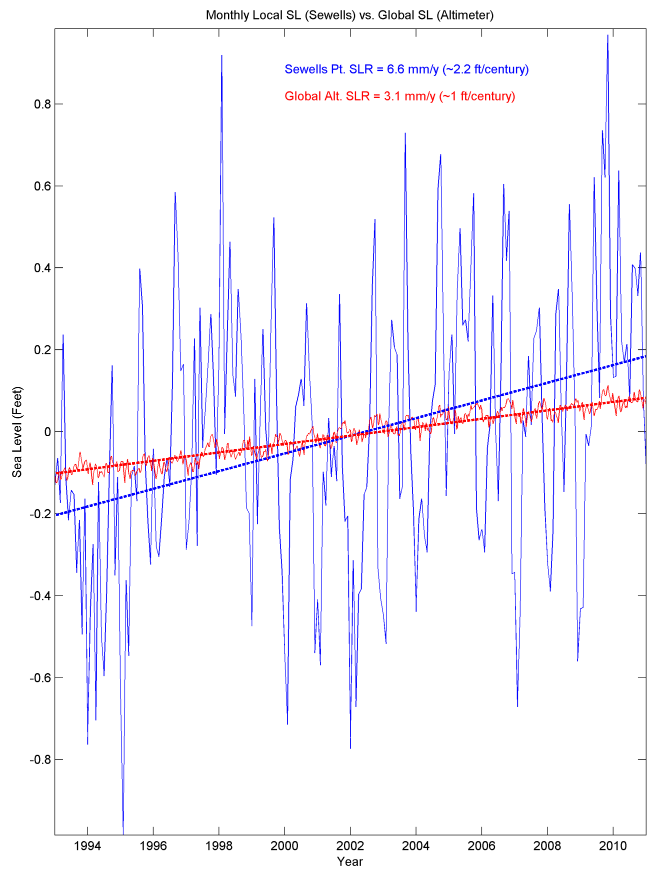

Fig. 4. Global and local sea level trends and local variability. This figure shows the global rise in sea level (red variable line), the global trend (red straight dashed line), local sea level (blue variable line), and local sea level trend (straight blue dashed line).

II. Sea Level Rise, Storm Surge, and Flooding

As there is often some confusion about what kind of flooding is being discussed, some definitions (all unofficial) are in order.

- Global sea level rise: this refers to the slow rise of the average sea level of all the oceans because of ocean warming and land ice melting over decades and centuries.

- Relative or local sea level rise: this refers to the level of the ocean relative to a landmark in a specific location. For example, in Hampton Roads sea level is rising at a rate of at least 2 inches every 10 years when measured from a dock on the Navy base. In Finland, the opposite is

[8] Parris, *supra* note 4, at 1.

happening. Because of glacial isostatic rebound, the land is rising and local sea level is dropping there. Relative or local sea level is what anyone working on coastal issues must be aware of.

- Storm surge: this refers to flooding caused by the winds and low barometric pressure associated with storms such as hurricanes or northeasters. These storms push water toward the shore, raising the water level on the coast. Over a period of hours or days water floods onshore into areas that are not normally flooded with salt water. For example, a passing storm may cause the ocean in Hampton Roads to be 3 feet above what would normally be expected from the tide. Thus the storm surge is 3 feet. Local sea level rise means that 10 years from now the same storm would result in a 3-foot and 2-inch rise (approximately).

- Flooding: this refers to flooding due to rain or rivers. When a heavy rain occurs at the same time as a storm surge there is no place for the rainwater to drain to and a locale can have both storm surge flooding and rain flooding.

- Tides: the regular ebb and flow of the tides (semi-diurnal tide every 12 hours 25 minutes and diurnal tide about every 24 hours) does not normally cause unexpected flooding. When a high tide coincides with a storm surge, the storm surge flooding will be worse.

- Tidal flooding: this often refers to storm surge flooding but really just means being flooded by saltwater during normal tides. The tides go in cycles such that about every two weeks (during full moon and new moon) there are higher tides (called "spring tides").

- Tsunami wave flooding: this refers to the flooding by a tsunami which is caused by undersea earthquakes that causes a very long wave to propagate toward the shore where it increases dramatically in height.

III. Recent Local Sea Level Rise Acceleration and the Future of Local SLR

Up until this point in the discussion, the sea level rise rate has been assumed to be constant. That is, for example, one foot every 100 years. Some very new studies, however, indicate that sea level is not just rising, but in the mid-Atlantic region is actually accelerating. That means that every year the rise is a little bit faster than the year before. For example, if sea level is rising 0.2 inches this year (about 5 mm/y), but in the following year sea level is rising by 0.21 inches (about 5.3 mm/y), SLR would be accelerating by 0.01 inches per year per year (or about 0.3 mm/y^2). Over time, SLR acceleration will result in a much higher future sea level than if sea level will continue rising at a constant rate.

Sea level in the future must be predicted so engineers can effectively design structures such as storm drains, docks, and other coastal structures. Predicting local sea level out 10 to 20 years can be done with reasonable accuracy by simple linear extrapolation from existing trends. However, many projects require knowing sea level out 20 to 150 years. Those predictions depend on different climate change scenarios.

Interestingly, in late 2012, three papers have been published (and more submitted) that examine the rate of sea level rise and show that it is accelerating. Following are key quotes from those papers:

- Sallenger et al. (2012) stated that "Our analyses support a recent acceleration of SLR on 1,000 km of the east coast of North America north of Cape Hatteras. This hotspot is consistent with SLR associated with a slowdown of AMOC [Atlantic Meridional Overturning Current.]"[9]

- Ezer and Corlett (2012) stated that "The analysis shows that most sea level records in the Chesapeake Bay have significant positive SLR acceleration, so the SLR rates today are about twice the SLR rates of 60 years ago."[10]

- Boon (2012) stated "Evidence of statistically significant acceleration in sea level rise relative to land is found in a recent analysis of monthly mean sea level (mmsl) at tide stations on the Atlantic coast of North America."[11]

The future rise of sea level depends partly on the momentum in the system right now and partly on future greenhouse gas emissions that cause warming of the ocean. Ezer and Corlett[12] show sea level rise at different locations in the Chesapeake Bay and calculate projections for different scenarios, for example, whether SLR acceleration is included or not. (Figure 5). The Sewells Point location can expect about 2.5 feet of rise by 2100. This is similar to the recommended guidance from the Virginia Commission on Climate Change.

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[9] Asbury H. Sallenger, Jr., Kara S. Doran, and Peter A. Howd, *Hotspot of Accelerated Sea-Level Rise on the Atlantic Coast of North America*, 2 NATURE CLIMATE CHANGE 884, 884 (2012).

[10] Tal Ezer and William Bryce Corlett, *Is Sea Level Rise Accelerating in the Chesapeake Bay? A Demonstration of a Novel New Approach for Analyzing Sea Level Data*, 39 GEOPHYSICAL RESEARCH LETTERS L19605 (2012), *available at* http://onlinelibrary.wiley.com/doi/10.1029/2012GL053435/full.

[11] John D. Boon, *Evidence of Sea Level Acceleration at U.S. and Canadian Tide Stations, Atlantic Coast, North America*, 28 J. COASTAL RESEARCH 1437, 1437 (2012), *available at* http://www.jcronline.org/doi/pdf/10.2112/JCOASTRES-D-12-00102.1.

[12] Tal Ezer and William Bryce Corlett, *Analysis of Relative Sea Level Variations and Trends in the Chesapeake Bay: Is there Evidence for Acceleration in Sea Level Rise?*, IEEE Xplore Paper # 2478367, MTS/IEEE Oceans '12 (2012), *available at* www.ccpo.odu.edu/~tezer/PAPERS/2012_MTS-IEEE_SLR.pdf.

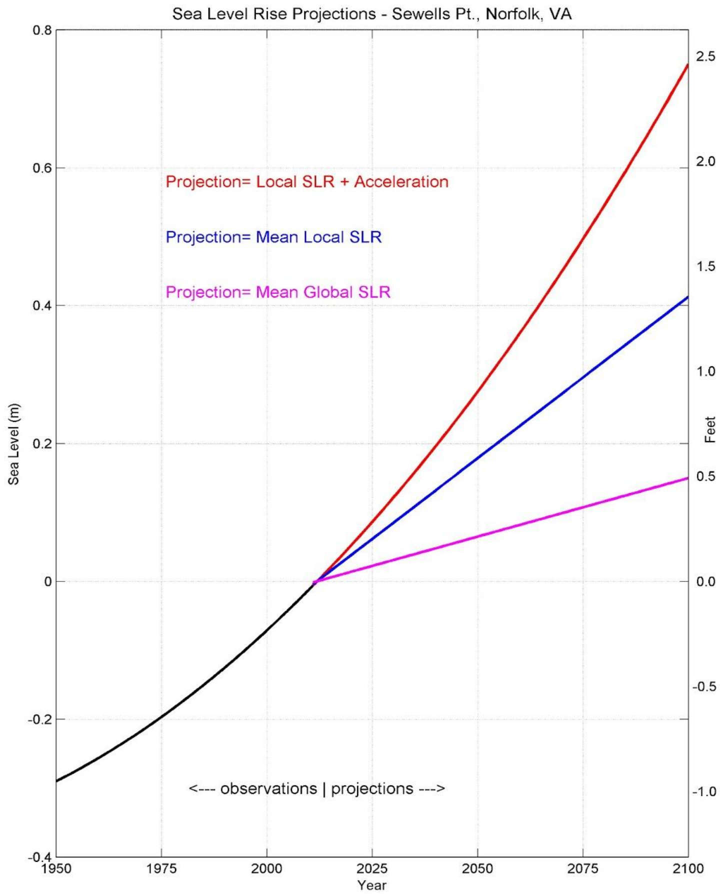

Fig. 5. Future sea level heights. This figure shows projected sea level heights based on the work of Ezer and Corlett. The purple lower curve is a projection using the current global sea level rise rate. The blue (middle) curve is the projection using the current rise rate at Sewells Point. The red (top) curve shows the projection based on the measured present acceleration at Sewells Point. The estimate of 2.5 feet of rise by 2100 is in the range of many other studies.

This local rise rate is nearly the highest rise rate seen anywhere in the U.S. The causes of the increased sea level rise rate, as previously noted, are warming and expanding ocean water, ground subsidence because of local geology and glacial rebound. A final and important factor is called dynamic sea level change caused by changes in the Gulf Stream. Recent studies suggest this "dynamic ocean circulation" factor, and in particular a climate-related weakening of the Gulf Stream, is causing the acceleration.[13] Future sea level rise is expected to be at least 2.3 and possibly as high as 5.2 feet by 2100.

The recent report for the U.S. National Assessment makes the following recommendation for the mid-Atlantic region:

> ... the observed rates of [relative sea level] rise and the evidence presented by Sallenger et al (2012) and more recently by Boon (2012) are sufficient to suggest that experts and decision

[13] Tal Ezer et al., *Gulf Stream's induced sea level rise and variability along the U.S. mid-Atlantic coast*, J. OF GEOPHYSICAL RESEARCH, 118(2): 685-697 (2013), *available at* http://onlinelibrary.wiley.com/doi/10.1002/jgrc.20091/full.

makers may consider accelerated rates along the northeastern stretch of coast into their risk-averse, worst-case scenarios.[14]

IV. Local Effects of SLR

What does this rise rate mean to low lying communities like Norfolk, Virginia at the mouth of the Chesapeake Bay and facing the Atlantic Ocean? How does SLR affect residents of Norfolk and surrounding cities? The effect is most easily visualized by looking at how many hours a specific part of the region is flooded each year. A historic district neighborhood in downtown Norfolk called "The Hague" regularly has flooded streets. The number of hours per year that this site is flooding was determined by comparing the tidal height when it floods to the corresponding height at a nearby tide gauge (Sewells Point). Figure 6 shows the exponentially increasing hours per year that this neighborhood is experiencing flooded streets. Floods that in the past were only caused by unusually strong storms are now often happening during a little above normal high tide.

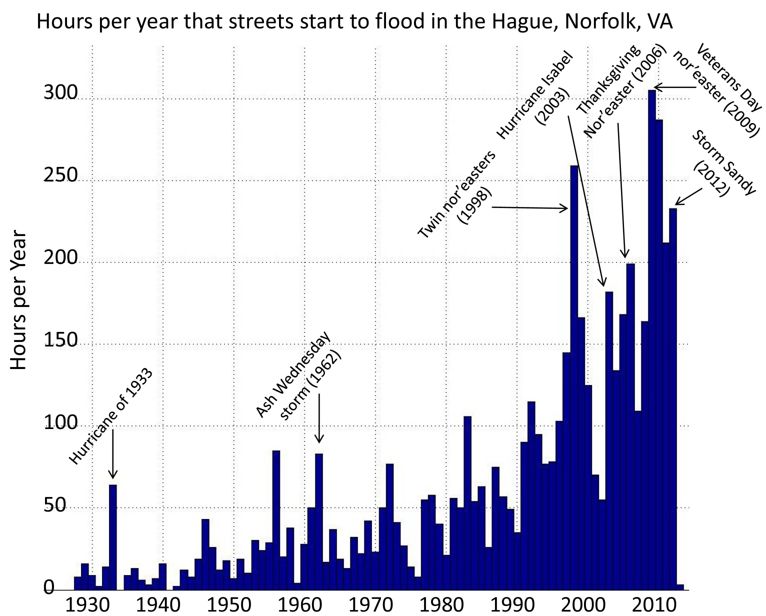

Fig. 6. Street flooding example. This figure shows the hours per year that there is street flooding in the Hague section of Norfolk. There is a clear trend of more street flooding with around 100 hours per year now.

A second way to look at this is estimating when a street will be flooded at every spring high tide. Hampton Boulevard at a location between Old Dominion University and the Norfolk Navy base has a spot that routinely is flooded by saltwater from the nearby Lafayette River (a tidal river). Flooding occurred at about 4.5 feet above MLLW (Mean Lower Low Water) at Sewells Point. Figure 7 shows the extrapolation of higher tides into the future. Note that the sloping projection of higher water will be above 4.5 feet in about 2040. That means that twice a day for an hour or so tens of thousands of commuters will drive through saltwater, if they can drive at all.

[14] Parris, *supra* note 4, at 10.

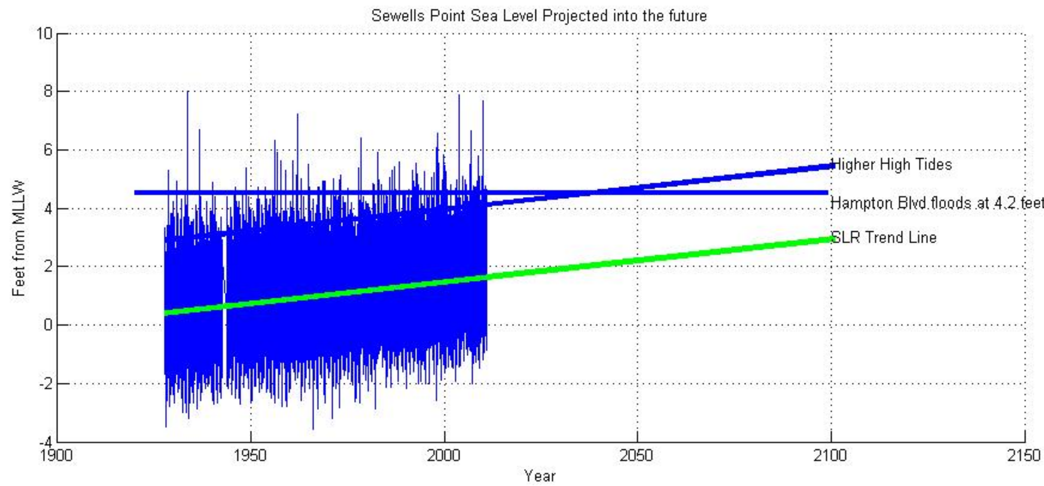

Fig. 7. Example of future street flooding. This figure shows the trend in sea level rise at Sewells Point. The street will be flooding every high tide by 2050.

V. Communities Adapting

There are many reports of potential damage from storm surge. Storm surge is the higher waters that occur when a storm such as a hurricane or northeaster pass northward along the Virginia coast. A 2011 report by Core Logic estimated 289,000 properties with a value of $45 billion are at risk to damage from storm surge in the Hampton Roads area.[15] This is very high compared to other densely populated cities in the U.S.

Coastal communities are developing adaptation plans, having moved well beyond the questions "Is it changing?" or "Why is it changing?" Vulnerable communities have made the transition to asking "Can society (*i.e.*, human beings) manage the changes, avoid the unmanageable, reduce vulnerability, and enhance resilience in order to sustain a way of life on the coast?" How residents of coastal communities respond and react will be critical. Rosina Birnbaum and co-authors recently published a comprehensive review of climate adaptation, not specific to sea level rise, "to understand what types of adaptation activities are underway across different sectors and scales throughout the country."[16] Birnbaum's paper is a resource and not meant as a critical review of adaptation efforts; however, it is a valuable compilation of illustrative adaptation activities happening across the United States.

Understanding human behavior, individual as well as collective/community behavior, will be the key to developing adaptation strategies that become "best practices." There is considerable uncertainty about the exact nature of the changes, in terms of ranges of SLR over decades. This uncertainty should not be a rationale for inaction or a barrier to adaptation[17] and understanding how humans behave in the face of uncertainty will facilitate communicating about adaptation and implementing adaptive strategies.

Sea level rise adaptation planning is underway, though on a steep learning curve, in Virginia. A solid, "bottom-up" approach is to build from communities' existing Hazard Mitigation Plans.

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[15] CORELOGIC, 2011 CORELOGIC STORM SURGE REPORT: RESIDENTIAL STORM-SURGE EXPOSURE ESTIMATES FOR 10 U.S. CITIES 26 (2011), *available at* http://www.corelogic.com/about-us/research.aspx.

[16] Rosina Birnbaum et al, *A Comprehensive Review of Climate Adaptation in the United States: More than Before, but Less than Needed*, MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE (Sept. 18, 2012), *available at* http://link.springer.com/article/10.1007%2Fs11027%E2%80%90012%E2%80%909423%E2%80%901.

[17] *See* NATIONAL RESEARCH COUNCIL, ADAPTING TO THE IMPACTS OF CLIMATE CHANGE (2010), *available at* http://www.nap.edu/catalog.php?record_id=12783.

Unfortunately, the issue has been highly politicized which has made a regional or state approach difficult. The Virginia Institute of Marine Science (VIMS) was funded by the General Assembly in May 2012 to synthesize and report on the effects of climate change and SLR on the state's coastlines.[18] The specific goals of the VIMS "Recurrent Flooding Study" are to:

- Review and develop a comprehensive list of strategies for dealing with recurrent flooding;
- Convene a stakeholder advisory panel; and
- Offer specific recommendations on options for sea level rise adaptation which merit investigation.

This report will support and recommend mapping of storm surge and flood frequency, at high resolution, as essential to identifying vulnerabilities in populations, infrastructure, and natural resources. GIS-based mapping can also identify where resources could have the biggest impact.

Adaptation plans will vary within Virginia because the local sea level rise rates vary considerably and the coast varies from industrialized to remote wetlands. Categories of adaptation include:

- Management, through laws like the Coastal Barrier Resources Act;
- Accommodation, by raising houses for example; and
- Protection, through hardened (tide gates, walls, barriers) or soft (living shorelines, wetlands restoration) structures.

In urban centers like Norfolk, new development increases the consequences of flooding. As lower risk areas are built out, higher and higher risk areas are developed. A result is the reduction in natural areas, which increases the extent of flooding and removes any potential natural (*i.e.*, soft) protection. Protection-type projects are under consideration in the city of Norfolk, with detailed design plans for a number of vulnerable locations in the city. However, the cost is high for these types of protections.[19] Figure 8 shows an example of a raised home in Norfolk.

Fig. 8. Flooding in the Lafayette River area.

[18] MOLLY MITCHELL ET AL., RECURRENT FLOODING STUDY FOR TIDEWATER VIRGINIA, VIRGINIA SENATE DOCUMENT NO. 3 (2013), *available at* http://ccrm.vims.edu/recurrent_flooding/Recurrent_Flooding_Study_web.pdf.

[19] *See generally*, engineering reports completed for the City of Norfolk's Environmental Storm Water Division of Public Work, *available at* http://www.norfolk.gov/publicworks/SW/SWEStudies.asp.

Norfolk has a comprehensive "Flooding Strategy" which emphasizes, among other things, planning, preparation, mitigation and communication and outreach to insure its citizenship is prepared.[20] Norfolk, however, is only one of sixteen localities that comprise the Hampton Roads Planning District Commission (HRPDC).[21] HRPDC is assisting in organizing the response planning of the entire Hampton Roads region.

As stated in a recent HRPDC report on sea level rise:

> Which adaptation strategies are most appropriate will depend on both the resources available to localities and the amount and character of existing developments. Sea level rise also poses challenges for the implementation of regulatory programs and laws, such as the Chesapeake Bay Preservation Act and its associated regulations, wetlands protection, floodplain management, and hazard mitigation efforts. These programs provide potential opportunities for localities to adapt to sea level rise within the existing regulatory framework.[22]

In rural, or low development areas, of Hampton Roads, houses are spread out which makes it challenging to provide protection over a large area. In these areas, citizen income is frequently linked to water access so retreating is problematic. In agricultural areas, saltwater intrusion can destroy crops. Finally, ecotourism makes hard engineering (walls, gates, breakwaters) unattractive.

Each city in the region has its own adaptation plans. This may range from changes in building codes to periodic upgrades to storm water pumping stations. The city of Norfolk has contacted several companies to assess the options the city has for adaptation. The report shows that a mix of tidal barriers that are both solid and inflatable would be suitable for some locations.

VI. Conclusion

Coastal communities, both urban and rural, have dealt with coastal flooding for centuries and will continue adapting for the coming centuries. Now sea level is rising more rapidly and the threat will only increase. The legal property issues will be significant and will affect the way communities adapt. In addition to the scientific studies of climate change and sea level rise, an important issue is communicating the scientific results and the nature of increased coastal flooding threat to the public and to decision makers.

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[20] *See* City of Norfolk, Flooding Strategy, http://www.norfolk.gov/flooding/flooding_strategy.asp (last visited Jan. 11, 2012).

[21] Hampton Roads Planning District Commission, http://www.hrpdcva.gov/ (last visited Jan. 11, 2012).

[22] BENJAMIN J. MCFARLANE, HAMPTON ROADS PLANNING DISTRICT COMMISSION, CLIMATE CHANGE IN HAMPTON ROADS: PHASE III: SEA LEVEL RISE IN HAMPTON ROADS, VIRGINIA 2 (2012).