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Prediction and Impact of Sea Level Rise on Properties and Infrastructure of Washington, DC

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The city of Washington, District of Columbia (DC) will face flooding, and eventual geographic changes, in both the short- and long-term future because of sea level rise (SLR) brought on by climate change, including global warming. To fully assess the potential damage, a linear model was developed to predict SLR in Washington, DC, and its results compared to other nonlinear model results. Using geographic information systems (GIS) and graphical visualization, analytical models were created for the city and its underlying infrastructure. Values of SLR used in the assessments were 0.1 m for the year 2043 and 0.4 m for the year 2150 to model short-term SLR; 1.0 m, 2.5 m, and 5.0 m were used for long-term SLR. All necessary data layers were obtained from free data banks from the U.S. Geological Survey and Washington, DC government websites. Using GIS software, inventories of the possibly affected infrastructure were made at different SLR. Results of the analysis show that low SLR would lead to a minimal loss of city area. Damages to the local properties, however, are estimated at an assessment value of at least US$2 billion based on only the direct losses of properties listed in real estate databases, without accounting for infrastructure damages that include military installations, residential areas, governmental property, and cultural institutions. The projected value of lost property is in excess of US$24.6 billion at 5.0 m SLR.

KEY WORDS: Inundation; sea level rise; Washington, DC

1. INTRODUCTION

Global warming is the result of increasing atmospheric concentrations of greenhouse gasses, mainly because of human activity. One of the most costly consequences of global warming is sea level rise (SLR), which is the result of thermal volumetric expansion of the oceans and the melting of global ice sheets.[1] Northeastern coastal areas and coastal cities of the United States, such as Washington, District of Columbia (DC), and New Jersey, are at high risk of inundation because of SLR. The short-term effects of SLR are the flooding of low-lying areas and the infiltration of salty water into fresh water sources. The long-term effects include readjustment of coast lines because of land loss, and increase saltwater intrusion and erosion.[2] A study found that with the complete collapse of the West Antarctic ice sheet, Washington, DC could face up to 6.4 m of flooding.[3]

In a recently published article, the projected SLR in 2100 from the melting of glaciers would be 0.124 ± 0.037 m. Although mountain glaciers hold less than 1% of all water held by glaciers, they were one of the largest contributors to global SLR in the 20th century. By the end of the 21st century, it is predicted that around 50% of all mountain glaciers and ice caps will melt. The major glacial contributors to SLR in the 21st century will be the Canadian Arctic, Alaska, the Russian Arctic, Antarctica, and the Svalbard areas.[4]

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A 2011 article states that even if CO_2 (the major greenhouse gas) is no longer released into the environment, the effects of climate changes would continue as the West Antarctic ice sheet would still melt. Global SLR could be 3–4 m by the year 3000 AD. Climate change because of CO_2 emissions is “irreversible.” Antarctic temperature rise and North African rainfall are certain to get worse, even if all CO_2 emissions are stopped.[5]

SLR poses a major threat to people, property, and infrastructure. Risk studies are, therefore, essential to study specific areas that are crucial but vulnerable. Understanding the risks and costs associated with SLR allows for the incorporation of countermeasures to manage the risks of SLR. There are three possible ways of dealing with SLR: (1) protection of areas or cities by using flood walls and levees, (2) accommodating to SLR yet maintaining infrastructure, and (3) planned retreat from areas that are to be severely flooded. All of these options have risks and costs, as well as many social-economic implications and impacts that need to be considered for each affected area.[2] Size, importance, historical heritage, population density, infrastructure impact, and infrastructure planning of an area must be considered by lawmakers and city planners before deciding how to deal with SLR.

The founding of Washington, DC was part of the Virginia Compromise.[6] George Washington selected this site because it was close to his plantation, and to the two inland ports of Georgetown and Alexandria. The geography of Washington, DC has changed dramatically since its founding. For example, the low-lying area between the Anacostia River and I-295 was originally open water.[7] The National Mall and Foggy Bottom were marsh land and part of the rivers. Eventually, these areas were filled in as the city developed.[8] Currently, the lowest points in Washington, DC are the Anacostia shoreline, the Potomac, and the Tidal Basin, which are at sea level.

During the past century, Washington, DC has experienced rising temperatures, increasing precipitation, increasing frequency of extreme weather, and rising sea levels. Since 1970, Washington, DC has been warming at a rate of 0.5 °F per decade, whereas the winter temperatures have risen at a rate of 1.3 °C per decade.[9] Since 1976, the precipitation rate continues to increase at a rate of 0.1 inch per decade.[10] In the year 2010, the Washington, DC area experienced record-breaking snowfall, in addition to multiple days of record-breaking heat. All of these patterns are consistent with climate change caused by global warming.

To protect the natural coast of Washington, DC from SLR, the city is considering the installation of protective buffers along the Anacostia River, as well as the removal of bulkheads.[7] In late 2010, the Federal Emergency Management Agency began building a system of barriers and levees to protect the National Mall from flooding. The barrier system is designed to stop floodwaters from entering the crest-like dip in Washington, DC that starts near the Washington Monument and ends near Fort McNair. The system is designed to protect the city for the 100-year flood, but eventually more improvements will have to be made.[11]

Currently, there are no precise analyses of the Mid-Atlantic region investigating the possible effects of SLR on population and infrastructure.[12] Analyses of SLR are limited because of lack of specificity in the elevation data.[12] It is difficult to find elevation data of increments of less than 1.0 m.[13] In 2008, the U.S. Department of Transportation (DOT) found that with an increase in SLR of 0.59, 15 km of roads would be flooded, and 3 km of railroad would also be inundated in the Washington, DC area.[12]

This article investigates impacts of SLR on Washington, DC by developing a hypothetical model of SLR, based on current sea level trends, and prediction model of future SLR. Analyses of levels less than 1.0 m are included. An inventory was created and damages were assessed. Based on its results, ways in which damages because of SLR can be reduced are discussed. A number of important assets would be impacted by SLR according to this investigation. Military facilities include the Bolling Air Force Base, the Anacostia Naval Air Base, Fort McNair, the Washington Navy Yard, and the U.S. Naval research labs. In the public sector, monuments/museums on or around the National Mall, marinas/docks, parks, and public services could be flooded, seriously impacting tourism. Governmental buildings and agencies affected by SLR would include the Federal Bureau of Investigation, the Internal Revenue Service, the Justice Department, the Federal Trade Commission, and the Department of Education.

2. METHODOLOGY

This study focuses on creating a model of SLR for the purpose of quantifying the potential damage

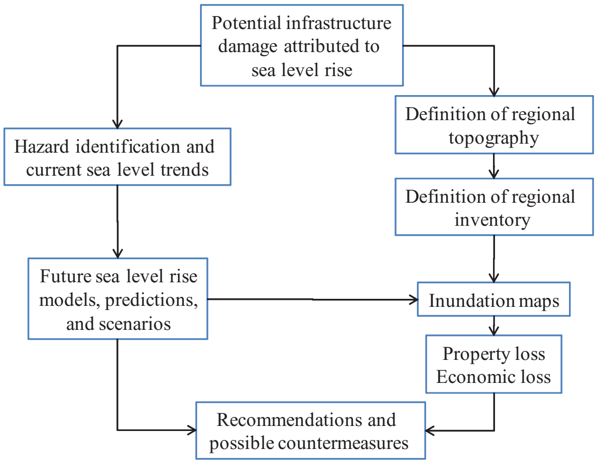

Fig. 1. Methodology used to assess the affected infrastructure in Washington, DC because of SLR.

to the infrastructure of Washington, DC. A block diagram of the methodology is provided in Fig. 1. The methodology starts with developing a trend of SLR. A number of different models were reviewed and are described in the article, including the Intergovernmental Panel on Climate Change (IPCC) 2007[14] prediction models, the 2009 Vermeer and Rahmstorf model,[15] and the 2009 Grinsted, Moore, and 2009 Jevrejeva model.[1] Data of SLR in the Washington, DC area were obtained from National Oceanic and Atmospheric Administration (NOAA). Based on these data, a rough timeline and a linear model of SLR were created.

A geospatial and analytical model of Washington, DC was created and analyzed in conjunction to the linear SLR model for Washington, DC. The topography of the city was defined. The location of infrastructure was determined with respect to topography. Using the aforementioned linear model of SLR, inundation maps were made. Different infrastructure data layers were overlaid with these maps. Analysis of the potential property and economic loss were based on these data layers. Recommendations of countermeasures to reduce the amount of damages were made based on the results.

2.1. Geographic Information Systems (GIS)

All data layers were obtained from free data banks on the Internet and are listed in a subsequent section of the article. The elevation data incorporate the city of Washington, DC, and suburban areas in both Maryland and Virginia. The projected elevation data were defined in the GCS_North_America_1983 datum, whereas all other data sets were defined in the Maryland State plane coordinates NAD 83 meters datum (compatible with the elevation data). The data were then projected into the NAD_Zone_18_UTM datum. All final layers were feature files (not raster files).

For each SLR, a clip was cut out from the elevation data between 0 m and the desired height. For example, five clips were made: 0.1 m, 0.4 m, 1.0 m, 2.5 m, and 5.0 m, as shown in Fig. 2. Each image shows the clipped river shape used for the analysis and the streets data layer of Washington, DC. Each clipped shape was overlapped with different data layers. Each clip was then reclassified with two values. The area of interest (from 0 to any elevation, e.g., a desired elevation of 0.1 m, 0.4 m, 1.0 m, 2.5 m, or 5.0 m) was given the value of one and all other elevations were given no data value (null). For example, for the 0.1 m SLR, the clip was cut from 0 m elevation to 0.1 m elevation. The area of interest, which started from the center of the river to the new river banks at 0.1 m, was given a reclassified value of one. All other area was given a value of null (0). This allowed the flooded river to be one large flat shape, and all other surroundings to disappear. The clips were then finally converted from a raster to a feature so they could be used with the other layers. The solid black shape shows the extent of SLR in each possible situation. The Potomac River and any other streams that spill into it increase in size with an increase in SLR.

These SLR clips were then overlapped with different infrastructure layers. This was done by individually clipping the data layer with the SLR shape, creating a new data layer. Using the attribute data table provided by the new clipped data layer and statistical tool provide by the ArcGIS 9 software, the results were obtained.

2.2 Sea Level Rise: A Linear Model

Before conducting the inventory and damage analysis of Washington, DC, estimates of SLR as a function of time were made. The data were obtained from the official website of the NOAA. The website provides SLR trends for Washington, DC and many other cities in the United States. For comparison purposes, the SLR trends for other cities were also obtained and compiled, as shown in Fig. 3. The raw data of average monthly mean sea level measurements since 1928 were used to develop the SLR trend

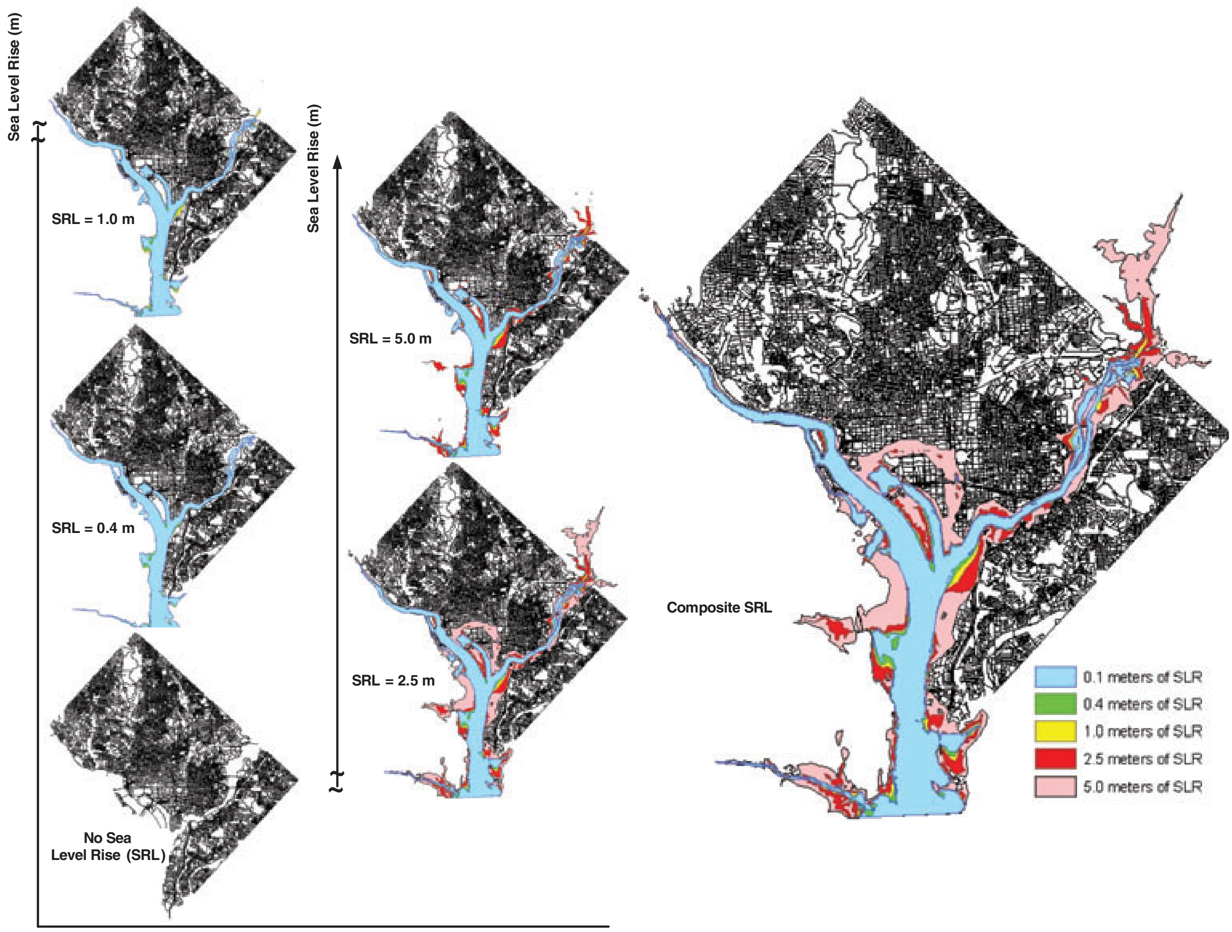

Fig. 2. Projected SLR clips in the city of Washington, DC for 0.1 m, 0.4 m, 1 m, 2.5 m, and 5.0 m SLR.

Table I. Sea Level Prediction Between 2020 and 2010 for Washington, DC, from the Linear Model

Year	SLR (m)	Year	SLR (m)
2020	0.03	2090	0.24
2030	0.06	2100	0.27
2040	0.09	2110	0.3
2050	0.12	2120	0.33
2060	0.15	2130	0.36
2070	0.18	2140	0.39
2080	0.21	2150	0.42

line for Washington, DC, as shown in Fig. 4. These data were collected at the Washington, DC measuring station #8594900. Table I shows the projected SLR relative to 2010 that was developed. Thereafter, other prediction models were examined such as the IPCC projections and the Vermeer and Rahmstorf model[15] to obtain other estimates of future SLR. After reviewing the SLR models, the inventory of the damages was estimated by using GIS software.

3. DATA AND DATA SOURCES

In 2007, the United Nation's IPCC, the leader in the field of global climate change, predicted that by the year 2100 AD there would be an overall global SLR of 0.6 m.[16,17] However, recent studies of the Antarctica ice sheet have increased the prediction to over 1 m.[2] From the late 19th century, SLR has been estimated to be 1.7 ± 0.3 mm/year. However, in the 1990s and 2000s this rate increased to 3.3 ± 0.4 mm/year.[2] The Antarctic coast is losing about 26 km^3 of ice per year, but about 150 km^3 of ice per year is melting from the West Antarctic.[18] Over the next millennium, SLR could range from 20 to 30 m.[18]

The Center for Operational Oceanographic Products and Services (COOPS), a part of NOAA

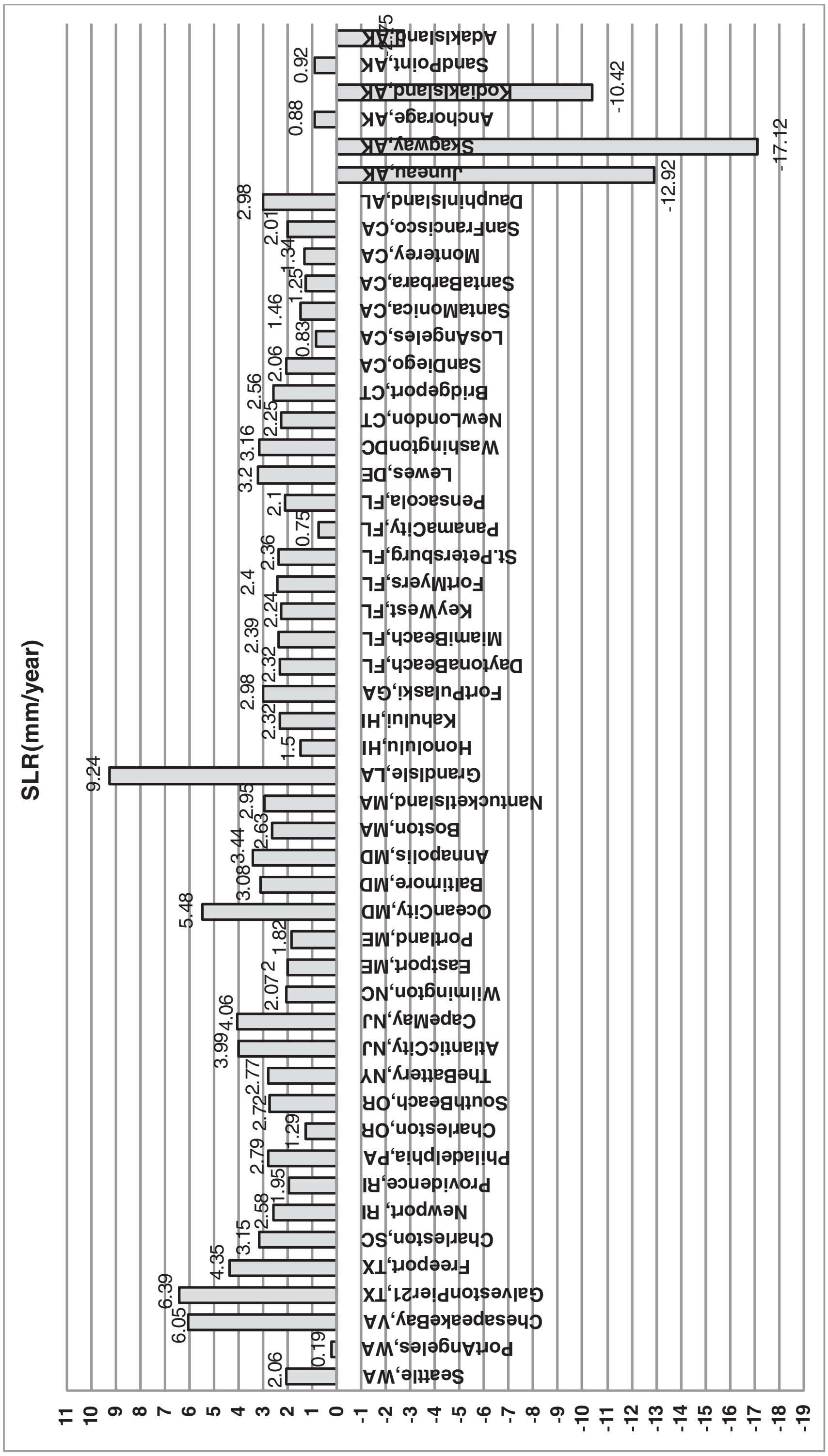

Fig. 3. SRL tends in different coastal cities in the United States.

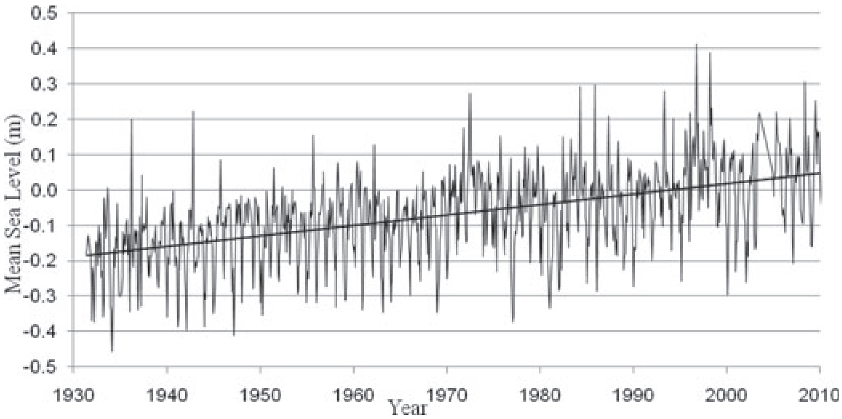

Fig. 4. Linear SLR for Washington, DC from NOAA station #8594900 from 1930 till 2010.

that provides oceanographic services and produces, has been measuring local sea levels for over 150 years, with tide stations operating on all U.S. coasts, including Alaska and Hawaii. A complete list of all the stations can be seen in Fig. 3. Local SLR is the change in the height of the sea as measured along the coast, relative to a specific point on land. Relative sea level trends reflect changes in local sea level over time and are typically used for many coastal applications, such as coastal mapping, marine boundary delineation, coastal zone management, coastal engineering, and sustainable habitat restoration.[9,10]

3.1. Current Sea Level Rise Tends

The measurements of the COOPS reflect SLR, and the sinking or, in some cases, the rising of the ground. For example, Alaska's coast has negative SLR. This means that instead of an increase in SLR, the ground is rising out of the sea. The capital of Alaska, Juneau, is rising at a rate of 12.92 mm/year, whereas Skagway, along the Alaska coast, is rising at 17.12 mm/year (the highest amount in the whole nation). This is because of the fact that Alaska's coast is on the Ring of Fire and subject to tectonic motion. Other states that are on the West Coast and along the Ring of Fire have positive SLR, although at a slower rate compared to the East Coast and Gulf areas. The land is rising, but at a lower rate than SLR. For example, Seattle's SLR is only 2.06 mm/year, San Francisco's 2.01 mm/year, Los Angeles' 0.83 mm/year, and Honolulu's 1.5 mm/year. On the other hand, Long Isle, Alabama, is sinking by 9.24 mm/year.

On the U.S. East Coast, SLR is greater; the ground is much softer and therefore sinking faster. For example, the coast of Alabama is mostly silt. In addition, on the coastline of the Gulf States there are many oil reserves, weakening the ground. As mentioned before, Long Isle, Alabama, is sinking by 9.24 mm/year, whereas Galveston, Texas, is sinking by 6.39 mm/year.

Along the Eastern Seaboard of the United States, all coastal cities are experiencing positive SLR. Although the levels are larger than those of the West Coast, compared to the Gulf region the values are smaller. For example, in Manhattan Island, New York, the SLR is 2.77 mm/year, in Atlantic City, New Jersey, it is 3.99 mm/year, and in Boston it is 2.63 mm/year. The SLR rate for Washington, DC is akin to these values and is 3.16 mm/year.

3.2. Sea Level Predictions

Because of uncertainty related to future SLR, current models take different scenarios into account. Predictions of SLR include linear extrapolation of the current trend, the IPCC models[14] and scenarios, the Rahmstorf and Vermeer model,[15] and the Grinsted model.[1]

3.2.1. Linear Extrapolation

Washington, DC is experiencing a positive change in SLR because of land subsidence. The factors that contribute to this include compression of surface sediment layers, compression of deeper layers because of ground water extraction, collapse of mantle forebulge with retreat of continental glacier, regional subsidence of a tectonic plate, and depression of the continental margins because of the weight of sediment and seawater.[19] Washington, DC experiences an average rate of land subsidence of 0.14 m per century.[19] In general, land subsidence in the Chesapeake Bay area is mostly a result of postglacial rebound or the readjustment of land elevations since the retreat of the glaciers at the end of the last ice age.[19]

The monthly mean sea level data for Washington, DC were obtained from NOAA station #8594900 to perform linear regression using least squares as shown in Fig. 4. The relative SLR is increasing at a rate of 3 mm/year. The resulting linear trends can be defined by the equation below:

$$Sea\ Level = 0.003x - 5.9461 \text{ mm}, \quad (1)$$

where x is in years (year 0 is 1995; $r^2 = 0.282$; $r = 0.531$; p value, two-tailed, <0.001). A prediction by this model is a mean estimate with an exceedance probability of 0.5, e.g., 0.4 m SLR in the year 2150.

Several uncertainty sources need to be addressed to improve such a prediction model, which include: (1) differentiating between SLR and subsidence of the ground in DC, i.e., values obtained from the model represent only the net difference, not SLR values alone, (2) the trend of SLR as governed by the IPCC differential equation that produces a nonlinear solution with two coefficients that can be calibrated based on adopting a set of assumptions per the IPCC storylines defining future human activity, (3) the contributions of accelerated melting of the West Antarctica ice sheet, and (4) the contribution of global SLR impact on the local SLR for Washington, DC. To enhance prediction, global SLR needs to be converted to local predictions and calibrated to local SLR measurements.

Although reviewed, the analysis does not take into account any prediction models and is solely based on current SLR trends. The linear model offers a quick overview of SLR and can be used for illustrative purposes.

SRL is predicted to rise at a faster rate because of the expected increase in the concentration of greenhouse gases; however, if the linear trend of Fig. 4 is extrapolated, then Washington, DC may expect to have a SLR of 0.12 m by 2050, 0.27 m by 2100, and 0.42 m by the year 2150, as listed in Table I.

3.2.2. IPCC Scenarios

The 2007 IPCC report on climate change used six different projections of future sea level and temperature rise until the year 2100, as listed in Table II. These four scenarios are narratives that try to predict the future of the environment in the 21st century with regard to greenhouse gases and aerosol precursor emissions (SRES scenarios 2011).[17] Each family of scenarios incorporates different social, economic, and scientific developments. The scenarios project the future defined by conflicting trends such as economic versus environmental, and globalization versus regionalization. After the scenarios were defined, they were computed by using integrated assessment models. Forty different scenarios were created, none of which have any occurrence probability (SRES scenarios 2011).[17]

Table II. IPCC Scenarios and Their Respective SLR and Temperature Rise by 2100

Case	SLR (m)	Temperature Rise (°C)
B1	0.18–0.38	1.11–2.89
A1T	0.20–0.45	1.39–3.78
B2	0.20–0.43	1.39–3.78
A1B	0.21–0.48	1.72–4.39
A2	0.23–0.51	2.00–5.39
A1FI	0.26–0.59	2.39–6.39

- A1: Storyline describes a future with rapid economic growth and a global population peak in 2050s. Because of rapid economic development, more efficient technologies are continuously being developed. In addition, different global regions' economies and cultures are integrated. This model can be broken down further into three subgroups, depending on scientific development, especially in terms of alternatives resources. The first subgroup, A1F1, focuses on development of fossil fuels. The second subgroup, A1T, focuses on development of nonfossil fuels. Finally, the third group, A1B, is defined as an "equilibrium" state with developments in both fossils and nonfossil fuels.[14]
- A2: Storyline describes a diverse and defragmented world. Although birth rates begin to slow down, there is continuous population growth. The economy is regionalized and diverse. There is also a strong sense of nationalism, as local cultures and customs are preserved. Therefore, scientific development is just as diverse and generally slower. Any issues and problems are solved at the local and regional scales.[14]
- B1: Storyline describes an integrated world with a population peak sometime in the 2050s. Financial systems have been quickly recognized towards a service and information

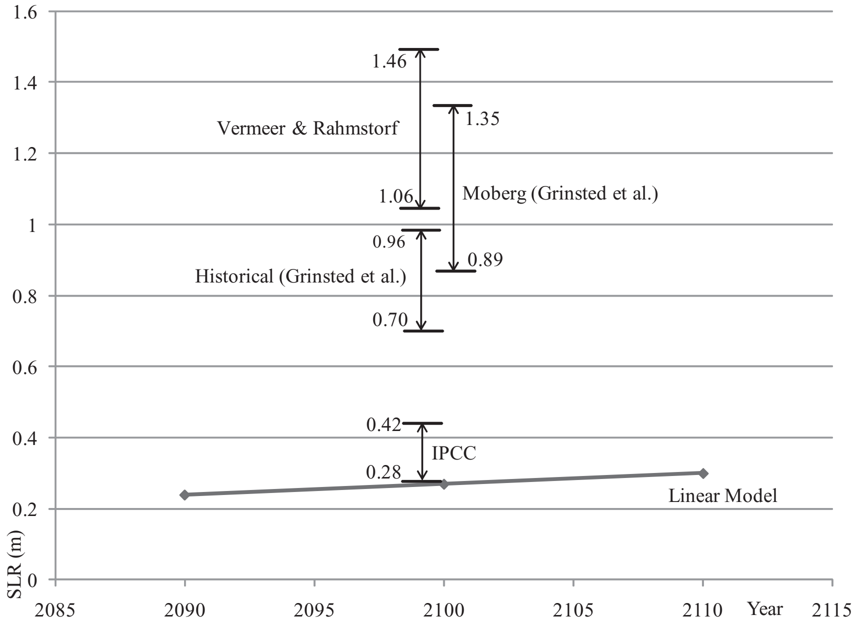

Fig. 5. The predicted SLR in 2100 of all the models examined: linear model of Washington, DC, IPCC,[14] Vermeer and Rahmstorf,[15] and Moberg and historical as reported by Grinsted *et al.*[1]

oriented economy. This in turn reduces the need for resources and allows for more alternative energy sources. Social, economic, and environmental problems are solved by international cooperation.[14]

- B2: Storyline describes a more regional focus on economic, social, and environmental sustainability. It considers a slow increase in population, intermediate levels of economic development, and slow but diverse scientific developments. Like in the B1 situation, this scenario focuses on environmental protection and social equity, but unlike the B1, this group of scenarios is based on regional solutions and developments.[14]

The results of this model are shown in Fig. 5.

3.2.3. Vermeer and Rahmstorf Model[15]

Another prediction of future SLR is the Vermeer and Rahmstorf model[15] (Table III), which includes the melting of ice masses. A relationship linking global sea level variation, on time scales of decades to centuries, to global mean temperature is used. This model adds a second term, which gives the model a rapid response time. The initial rate of SLR in response to large and rapid warming is approximated by:

$$\frac{dH}{dt} = a\,(T - T_0) + b\frac{dT}{dt}, \qquad (2)$$

Table III. IPCC Scenarios and Their Respective SLR and Temperature Rise as Predicted by the Vermeer Model[15]

Case	SLR Above 1990 (m)	Temperature Rise (°C) Above 1980–2000
B1	0.81–1.31	1.4–2.9
A1T	0.97–1.58	1.9–3.8
B2	0.89–1.45	2.0–3.8
A1B	0.97–1.56	2.3–4.3
A2	0.98–1.55	2.9–5.3
A1FI	1.13–1.79	3.4–6.1

where T is the global mean temperature, T_0 is the temperature at which sea level is in equilibrium with climate, a is the coefficient relating sea level to temperature (defined by the IPCC scenarios), and b is the constant defined the IPCC scenarios.

The model was run under three tests to make sure it was valid and could be used to approximate future SLR. The parameters a, b, and T_0 were fitted to conform to temperatures and sea levels from 1880 to 2000 in the first test. Given the fitted parameters, sea levels were calculated for the 21st century. The model can predict SLR after 2050, provided that temperatures do not increase exponentially. The first test only looked at the thermal expansion of oceans; the second term in the equation is the product of heat intake by the oceans.

The second test checked the model's validity by comparing it to observed temperatures and sea

Table IV. Parameter Values Used in the Different Experiments in the Grinsted, Moore, and Jevrejeva Model[1]

Experiment	τ (years)	a (m/C°)	b (m)	S_0 (m)	T (°C; when S = 0)
Moberg	208 ± 67	1.29 ± 0.36	0.77 ± 0.25	0.002 ± 0.55	0.0063 ± 0.0011
Jones and Mann	317 ± 117	2.56 ± 0.9	1.36 ± 0.52	0.035 ± 0.55	0.0082 ± 0.0011
Historical	1193 ± 501	3.1 ± 1.64	3.68 ± 1.64	0.249 ± 0.04	0.0030 ± 0.0018

levels from the climate model used in the Fourth Assessment Report (AR4) by the IPCC of the last millennium. Using a and b, the model was used to "predict" sea levels from the years 1000 to 2000. SLR was lower when "predicted" with the model, compared to the observed data. Therefore, a small adjustment had to be made to T_0 to accurately predict long-term SLR. This mismatch could be corrected in either the first part of the millennium or in the second part, but not both. This is because of the imbedded assumption that there is an infinite readjustment period. Overall, this did not significantly impact the results as the model was used to predict SLR for the years 2000 to 2100.[15]

In the final test, the model's predictions were compared to observed temperatures (from NASA) and sea levels (from Church and White, as used by the IPCC) from 1880 to 2000; however, the model was not limited to only thermal expansion. The results in this test were very similar to the observed data. The parameters a and T_0 are the average values, and trend over the 120-year time period. Parameter b is negative because ocean expansion is positive, and, in addition, a decade-long lag response to the ocean-ice system is observed in b. The model was corrected to incorporate sea levels because of reservoirs' storage of water and groundwater mining. All the fitted parameters were within 1 *SD*.[15]

After passing the three tests, the authors predicted 21st-century sea level by using the predicted temperatures from the AR4. The model's output was within 1 *SD*. Maximum values were based on the highest possible carbon cycle setting, whereas minimum values were based on the lowest possible carbon cycle setting.[15] Compared to the IPCC report, as shown in Table II, this model estimates a much higher SLR, as listed in Table III, which may be a more realistic prediction of SLR. The results of this model are shown in Fig. 5.

3.2.4. Grinsted, Moore, and Jevrejeva Model[1]

Sea levels and temperature data are limited to the last 150 years. The Grinsted, Moore, and Jevrejeva model[1] uses alternative data from ice cores and tree rings. The advanced, yet semi-empirical, model looks at sea levels as a function of temperature through a simple differential equation and uses four parameters:[1]

$$S_{\text{eq}} = aT + b \tag{3}$$

$$\frac{\partial S}{\partial t} = \frac{S_{\text{eq}} - S}{\tau}, \tag{4}$$

where T is the global mean temperature, S is the global mean sea level change, S_{eq} is the equilibrium sea level for a given temperature, a is the coefficient relating sea level to temperature (defined by the IPCC scenarios), b is the constant (defined the IPCC scenarios), τ is the a characteristic response time, and t is time.[1]

The model makes the simple assumption that S will approach S_{eq} within a unique response time as shown above. However, the equation can only be used over a short time period. Integration of the above equation with boundary condition gives S_0 as a function of S in terms of t and T.[15]

The authors of the model used global surface temperatures for T from the HadCRUT3v (which spans from 1850 to 2007). The equations were calibrated using data from a "virtual station" that reconstructed observed global sea levels (from 1850 to 2001). Because the response time behavior is unclear, the authors extended the data from HadCRUT3v by adding on the Northern Hemisphere Reconstruction (which spans 2,000 years). To minimize uncertainties in the data, the authors used two Northern Hemisphere Reconstructions to allow for a larger range of data, and the inclusion of more than one data set,[1] as shown in Table IV and V. The range of the results is from the 5th to the 95th percentile as shown in Table V. The IPCC values are almost three times lower compared to the findings of the authors.[1] The results were checked against the satellite altimetry of global sea level from 1993 to 2006. The authors concluded that both of these two models give a more accurate prediction than the IPCC's. The Jones and Mann experiment predicted a higher SLR than actual levels during 1993 to 2006, and could not be used.[1] The results of this model are shown in Fig. 5.

Table V. The Final Result of the Grinsted Findings for Different IPCC Scenarios for 2090–2099[(1)]

Experiment	A1B	A1FI	A1T	A2	B1	B2
Moberg	0.91–1.32	1.10–1.60	0.89–1.30	0.93–1.36	0.72–1.07	0.82–1.2
Jones and Mann	1.21–1.79	1.45–2.15	1.18–1.76	1.24–1.83	0.96–1.44	1.09–1.62
Historical	0.32–1.34	0.34–1.59	0.32–1.32	0.32–1.37	0.3–1.1	0.31–1.22
IPCC	0.21–0.48	0.26–0.59	0.2–0.45	0.23–0.51	0.18–0.38	0.20–0.43

Table VI. Data Layers Used in the Analysis, the Source Website of the Data Layer, Data Type, and the Date Obtained

Data Layer	Type of Data	Date Obtained
NED Shaded Relief (1 arc second)[a]	Raster	June 2010
Property Owner Polygon[b]	Polygon	July 2010
Buildings[b]	Polygon	June 2010
Streets Centerline[b]	Polyline	June 2010
Census Tracts–2000–DC[b]	Polygon	June 2010
Railroads[b]	Polyline	June 2010
Landmark Buildings and Structures[b]	Polygon	July 2010
Points of Interest (Address Alias Names)[b]	Points	July 2010
Embassies[b]	Points	July 2010
GSA Federal Locations[b]	Points	July 2010
DC Government Locations[b]	Points	July 2010
Fire Stations[b]	Points	July 2010
Police Stations[b]	Points	July 2010
Hospitals[b]	Points	July 2010
Metro Stations–Complete System[b]	Points	July 2010
Metro Lines–Complete System[b]	Lines	July 2010
University Areas[b]	Polygon	July 2010
Schools Grounds[b]	Polygon	July 2010
Property Owner Points[b]	Points	July 2010

[a]Obtained from USGS Seamless website (www.seamless.usgs.gov).
[b]Obtained from the Washington, DC All-in-One-Atlas website (www.dcatlas.dcgis.dc.gov/dcgis_allservices/viewer.htm).

3.3. Geographic Information Systems

Data layers used in this analysis were obtained from two different online data banks as listed under Table VI: USGS seamless servers for the National Elevation Dataset (NED), and the DC All-in-One-Atlas. All of the data layers were built by different governmental organizations and agencies, both federal and local, in the Washington, DC area. Data layers provided by federal agencies include: the NED Shaded Relief by the U.S. Geological Survey, the Census Track for 2000 by the U.S. Census Bureau, the GSA Federal Locations data layer by the U.S. General Service Agency, and the Universities Areas data layer by the Homeland Security Agency and the Emergency Management Agency.

The remaining data layers were made by different departments within the Washington, DC municipal government. The Buildings, Railroads, Embassies, and Points of Interest data layers were all made by the Office of the Chief Technology Officer. Property Owner Points was by the Tax Payer Service Center for Washington, DC. The School Grounds data layer was developed by the DC Public Schools Department. The Metro Stations and Metro Lines data layer were made by the Washington Metropolitan Area Transit Authority. The Hospital data layer was made by Washington, DC's Department of Health. The Police Data layer was made by the Metropolitan Police Department. The Fire Stations data layer was created by the Fire and EMS Department. The DC Government location was made by the Department of Real Estate Services. The Landmark Buildings and Structures data layer was made by the Office of Planning. The Street Centerline data layer was built by the District Department of Transportation. Finally, the Property Owner Polygon was made by the Department of Consumer and Regulatory Affairs and the Office of the Chief Finical Officer. Because this report required the use of many data layers and because each different agency uses its own definitions and standards, there are a number of discrepancies in the results of this analysis.

4. ANALYTICAL RESULTS

As sea levels rise, so will the number of affected properties. The seven specific property types provided by the Washington, DC data layers are listed in Table VII. The number of affected unspecified properties is seven at 0.1 m SLR, eight at 0.4 m SRL, and nine at 1.0 m SLR. The number then jumps to 23 at 2.5 m SLR, and doubles to 64 at 5.0 m SLR. At 0.1 m SLR, 29 commercial properties would be

Table VII. Property Type Count at Different Sea Level Rise

Property Types	0.1 m SLR	0.4 m SLR	1.0 m SLR	2.5 m SLR	5.0 m SLR
Unspecified	7	8	9	23	64
Commercial	29	53	72	103	316
Flats conversions	0	0	0	0	33
Hotels/motels	0	1	1	1	5
Residential multi-family	0	1	1	3	67
Residential single-family	0	2	2	6	262
Garage unimproved land	67	78	95	166	478

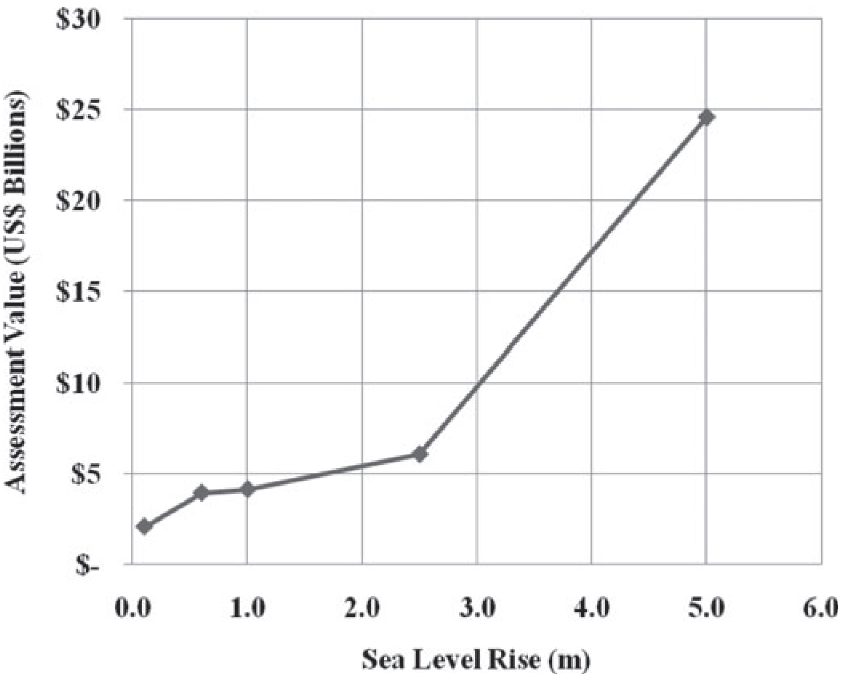

Fig. 6. Assessment value of properties in DC versus SLR.

inundated, at 0.4 m SLR 53 properties, at 1.0 m SLR 72 properties, and at 2.5 m SLR 103 properties. Finally, at 5.0 m SLR the number triples to 316 commercial properties affected. At 0.1 m, 0.4 m, 1.0 m, and 2.5 m SLR there would be no flat conversions affected. However, at 5.0 m SLR, 33 properties would be flooded. At 0.1 m SLR no hotels or motels would be affected. At 0.4 m, 1.0 m, and 2.5 m SLR only one hotel would be affected. Finally, at 5.0 m SLR four additional hotels/motels would be affected. There would be no residential multi-family property loss at 0.1 m SLR. At 0.4 and 1.0 m SLR, only one property would be affected. At 2.5 m SLR only three properties would be affected. At 5.0 m SLR the number jumps up to 67 properties. There would be no residential single-family property loss at 0.1 m SLR, two at 0.4 and 1.0 m SLR, and six at 2.5 m SLR. At the 5.0 m SLR the number jumps up to 262 properties.

Garages/unimproved land is the category of properties that would have the largest amount of properties flooded due to increased SLR. A total of 67 properties would be lost at 0.1 m SLR, 78 at 0.4 m SLR, 95 at 1.0 m SLR, 166 at 2.5 m SLR, and 478 at 5.0 m SLR, as listed in Table VII.

The overall number of properties flooded would slowly increase from 103 to 180 from 0.1 m of SLR to 1 m of SLR. At 2.5 m of SLR the number would increase to 302. Finally, at 5 m of SLR, 1,225 properties would be inundated, as presented in Table VIII. The surface area of flooded property would also increase slowly from 1.4 km^2 at 0.1 SLR to 2.6 km^2 at 2.5 SLR. Then it would dramatically increase to 11.6 km^2 at 5.0 SLR. The assessment value of the flooded areas increases in an exponential-like rate: 2.1 billion USD at 0.1 m, 2.3 billion at 0.4 m SLR, 4.2 billion at 1.0 m SLR, 6.1 billion at 2.5 m SRL, and 24.6 billion dollars at 5.0 m SLR, as shown in Table VIII and Fig. 6.

At 0.1 m SLR 66 buildings would be lost at total surface area of 0.02 km^2, at 0.4 m SLR 115 buildings with 0.045 km^2 surface area lost, and at 1.0 m 179

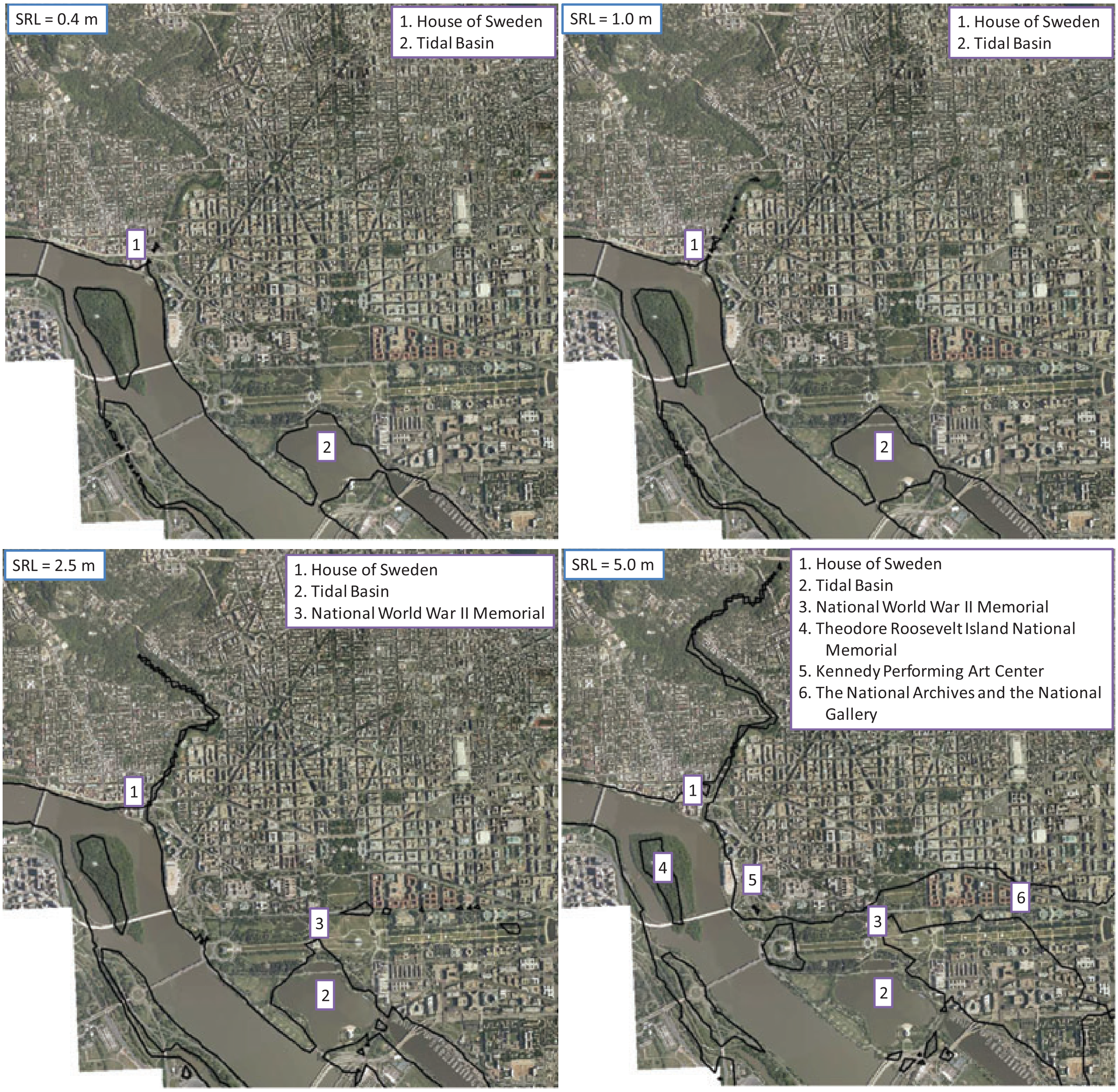

Fig. 7. Satellite images of inundation profiles of selected areas of DC.

buildings with 0.073 km^2 surface area lost. At 2.5 m SLR the number would jump to 606 buildings, with 0.27 km^2 surface area, and finally at 5.0 m SLR, 2,919 buildings with 1.32 km^2 surface area lost, as shown in Table IX. Surface area only incorporates the building plan and the surrounding area, such as street or sidewalk.

At 0.1 m SLR, 10.5 km of street would be inundated, 17.8 km at 0.4 m SLR, and 25.4 km at 1.0 m SLR. At 2.5 m SLR the number would double to 55.1 km, and at 5.0 m SLR 174 km streets would be flooded. The analysis does not incorporate any roads outside of Washington, DC's city limits, such as the Capital Beltway, although bridges were included in the road length. The length of railroad line flooded would be 3.7 km at 0.1 m of SLR, 4.2 km at 0.4 m SLR, and 4.7 km at 1.0 m SLR. The length of flooded railroad would double at 2.5 m SLR to 8.2 km and

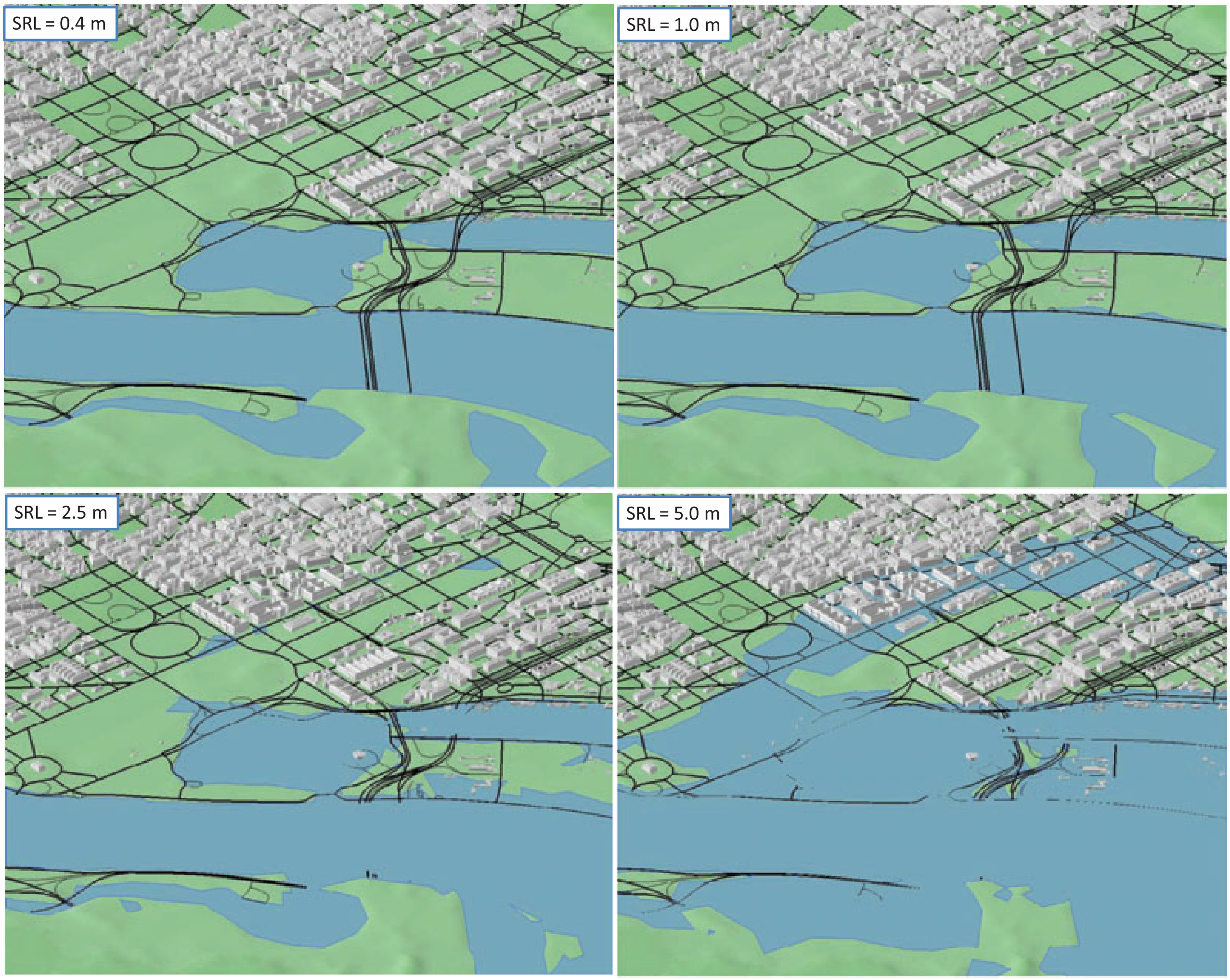

Fig. 8. GIS generated inundation profiles of selected areas of DC.

Table VIII. Properties in Flooded Zones, Including Surface Area and Assessment Value

SLR (m)	Number Properties in Flooded Zone	Total Area in Flooded Area (km^2)	Assessment Value (billions of USD in 2005)
0.1	103	1.4	2.1
0.4	143	1.8	2.3
1.0	180	2.6	4.2
2.5	302	4.8	6.1
5.0	1225	11.6	24.6

finally to 21 km at 5.0 m of SLR. These values are close to the findings of the U.S. DOT 2008 report.(12)

Finally, the number of people in the flooded area is 68,000 at 0.1 and 0.4 m SLR, 74,000 at 1.0 m SLR, 78,000 at 2.5 m SLR, and, finally, 103,000 people affected at 5.0 m SLR, as listed in Table IX.

At 0.1 and 0.4 m SLR there is no loss of secondary institutions. The National Defense University at Fort McNair would be the only university affected at 1.0 m SLR. The total amount of surface area of the university flooded would be 0.022 km^2. At 2.5 m and 5.0 SLR there would be no addition losses. At 0.1 m, 0.4 m, 1.0 m, and 2.5 m SLR there would be no loss of any schools. However, at 5.0 m SLR, one school and 0.244 km^2 of the school grounds would be inundated, as shown in Table X.

Currently, there are four metro lines of the Washington, DC metro system that run under the Potomac River. At 0.1 m, 0.4 m, 1.0 m, and 2.5 m SLR all four metro lines would be affected; however, at 5.0 m SLR a fifth metro line would be affected.

Table IX. Basic Infrastructure Statistics

SLR (m)	0.1	0.4	1.0	2.5	5.0
Number of buildings in flooded zone	66	115	179	606	2919
Total building' surface in flooded zone (km^2)	0.021	0.045	0.073	0.27	1.32
Total length of streets in flooded zone (km)	10.5	17.8	25.4	55.1	174
Total number of people in flooded zone (thousands)	67.49	67.49	74.45	78.35	107.26
Total length of railroads in flooded zone (km)	3.7	4.2	4.7	8.2	21.2

Table X. Number and Surface Area of Educational Institutions in Flooded Zone

SLR (m)	0.1	0.4	1.0	2.5	5.0
Number of universities in flooded zone	0	0	1	1	1
Area of universities in flooded zone (km^2)	0	0	0.022	0.022	0.022
Number of schools in flooded zone	0	0	0	0	1
Area of schools in flooded zone (km^2)	0	0	0	0	0.244

The length of metro tracks affected would be 3.4 km at 0.1 m SLR, 3.8 km at 0.4 m SLR, 3.9 km of SLR, 7.1 km at 2.5 m SLR, and 17.6 km at 5.0 m SLR. These values already incorporate the current length of the metro lines that are under the river. For 0.1 m, 0.4 m, 1.0 m, and 2.5 m of SLR there are no metro stations in the flooded zone. However, at 5.0 m SLR, five metro stations would be flooded, as shown in Table XI.

The number of public safety institutions that could be flooded is relatively minimal, as shown in Table XII. Fortunately, there would be no hospitals in the flooded area. However, one police station and two fire stations would be in the flooded zone at 5.0 m SLR, as listed in Table XII. One of the fire stations affected is used for the maintenance and storage of three fireboats.

At 0.1 m, 0.4 m, 1.0 m, and 2.5 m SLR there would be no federal, DC governmental, or foreign embassy buildings in the flooded zone. However, at 5.0 m of SLR, 23 federal, 29 DC governmental, and

Table XI. Number and Length of the Washington Metro System in the Flooded Zone

SLR (m)	0.1	0.4	1.0	2.5	5.0
Number of metro lines in flooded zone	4	4	4	4	5
Length of metro lines (km)	3.4	3.8	3.9	7.1	17.6
Number of metro stations in flooded zone	0	0	0	0	5

Table XII. Number of Public Safety Institutions in the Flooded Zone

SLR (m)	0.1	0.4	1.0	2.5	5.0
Number of fire stations in flooded zone	1	1	1	1	2
Number of police stations in flooded zone	0	0	0	0	1
Number of hospitals in flooded zone	0	0	0	0	0

Table XIII. Number of Government Institutions in the Flooded Zone

SLR (m)	0.1	0.4	1.0	2.5	5.0
Number of federal government buildings in the flooded zone	0	0	0	0	23
Number of DC government buildings in the flooded zone	0	0	0	0	29
Number of embassies in the flooded zone	0	0	0	0	1

one foreign embassy buildings would be inundated, as shown in Table XIII.

Bolling Air Force Base would be greatly affected by even a minimal SLR: from 23 buildings flooded at 0.1 m SLR to 129 buildings at 2.5 m SLR. Eight hundred seventy-two buildings would be inundated at 5.0 m of SLR. Other important military facilities such as the Anacostia Naval Air Base, Fort McNair, the Washington Navy Yard, and the U.S. Naval research labs would be inundated at 2.5 m of SLR. They are situated on higher land and all are smaller properties compared to Bolling Air Force Base. Anacostia would lose three buildings at 2.5 m SLR, and six at 5.0 m SLR. The U.S. Navy research labs would lose six buildings at 2.5 m SLR, and 21 at 5.0 m SLR. At Fort McNair, one building would be flooded at 2.5 m SLR. However, at 5.0 m of SLR, the number dramatically jumps to 74. Finally, the Navy Yard would see

Table XIV. Inventory of Points of Interest in Washington, DC at Different Sea Levels

Places of Interest	0.1 m of SLR	0.4 m of SLR	1.0 m of SLR	2.5 m of SLR	5.0 m of SLR
Bridges	15	15	16	16	19
Bolling Air Force Base faculties	23	39	39	129	872
Markets	2	2	2	2	2
Monuments/museums	2	5	5	13	73
Marinas	3	3	5	13	18
Park/recs.	1	3	6	25	98
Public services	0	1	2	6	15
Other	0	1	1	1	1
Anacostia Naval Air Station facilities	0	0	0	3	6
U.S. Naval research labs	0	0	0	6	21
Navy Yard facilities	0	0	0	18	63
Government buildings	0	0	0	1	46
Fort McNair facilities	0	0	0	1	74
Places of worship	0	0	0	0	3
Educational institutions	0	0	0	0	6

18 facilities flooded at 2.5 m SLR, and 63 facilities at 5.0 m SLR, as listed in Table XIV.

As SLR increases, the number of monument/museums, marinas/docks, parks, and public services affected also increases. Regardless of SLR only two markets would be flooded. At 0.1 m and 0.4 m of SLR three marinas would be inundated, five at 1 m SLR, 13 at 2.5 m SLR, and 18 at 5 m SLR. At 0.1 m SLR one park would be flooded, at 0.4 m SLR three parks, at 1.0 m SLR six parks, at 2.5 m SLR 25 parks, and at 5.0 m SLR 98 parks. Most of the parks are located close to each other or are on the Mall. The same is true with monuments and museums. At 0.1 m SLR two monuments/museums would be lost, five at 0.4 m SLR, 13 at 1.0 m SLR, 13 at 2.5 m SLR, and 73 at 5 m SLR, as shown in Table XIV. At 5 m SLR the National Gallery, holder of many valuable works, would be one of the museums inundated.

As seen with the military bases in Washington, DC, there would be no loss of governmental building until 2.5 m of SLR. At 2.5 m SLR, only one building would be flooded, however at 5 m SLR 46 building would be lost, as shown in Table XIV. Some agencies that would be located in the flooded area include (but not limited to) the Federal Bureau of Investigation, Internal Revenue Service, the Justice Department, the Federal Trade Commission, and the Department of Education.

Bridges that link Washington, DC to the surrounding area would also be lost. At 0.1 m and 0.4 m SLR, 15 bridges would be lost. One extra bridge would be added at 1.0 m and 2.5 m SLR. Finally, 19 bridges would be lost at 5.0 m SLR. One public service facility would be inundated at 0.4 m SLR, two at 1.0 m SLR, six at 2.5 m SLR, and finally 15 at 5.0 m SLR. Three places of worship would be lost at 5 m SLR, and six educational institutions at 5.0 m SLR, one of which would be in Fort McNair, as shown in Table XIV.

Table XV shows satellite images of Washington, DC overlaid with 2.5 m SLR data layer. Four points of interest—the Bolling Air Force Base and the Anacostia area, Downtown DC, the National Arboretum, and the Georgetown area, most affected by the flooding—are included. Losses at 0.4 m and 2.5 m of SLR are listed. The results are also spatially displayed in Figs. 7 and 8.

5. CONCLUSIONS

A seal level rise is an inevitable future for Washington, DC that would impact the city even with a relatively small rise. Current predictions range from a modest SLR of 0.2 m to a more dramatic rise of 2.15 m in the next 100 years. The linear model described in this article underpredicts the SLR compared to other models and places it at 0.42 m by 2150.

Even using a modest SLR of 0.1 m, the analysis of the data layers shows a relatively negative impact on the city. A total of 103 properties will be flooded at 0.1 SLR, costing the city of Washington, DC 2.1 billion USD. These estimates, however, continue to increase to 142 properties and 2.3 billion at 0.4 SLR, and 180 properties and 4.2 billion at 1.0 m SLR. Above these levels, the numbers become staggering: at 2.5 m of SLR 302 properties are affected, costing 6.1 billion USD, and finally at 5.0 m SLR the numbers increase to a dramatic 1,225 properties and at

Table XV. Vulnerability-Based Ordinal Ranking of Different Places of Interest for Illustration Purposes

Vulnerability Ordinal Level	Impacted Inventory at 0.4 m SLR	Impacted Inventory at 2.5 m SLR	Area Map at 2.5 m SLR
1. Bolling Air Force Base and Anacostia Area (both bases are U.S. Navy Posts)	39 facilities	129 facilities 6 U.S. Naval research labs 3 Anacostia Naval Air Stations	
2. Downtown Washington, DC is home to a number of federal agencies and the National Mall, home of the Smithsonian Institute, world largest museum and cultural complex; in addition the Naval Yard is a administrative center for the Navy	5 museums 3 bridges 1 park	13 museums 1 Fort McNair facility 1 government building 18 Naval Yard facilities 10 marinas 22 parks	
3. National Arboretum	3 bridges 1 park	4 bridges 1 park	
4. Georgetown	2 markets 3 marinas 1 park	2 markets 3 marinas 1 park	

least 24.6 billion USD. These monetary estimates are based on only properties in the city's real database, and additional damage valuations to infrastructure, federal facilities, industrial facilities, etc. should be included. Although current models do not predict a rise as high as 5.0 m in the next 100 years, the flooding of Potomac could temporary reach those levels and adversely impact the city.

SLR will also have an impact on the residents of Washington, DC. At 0.1 m of SLR, 68,000 people will be impacted. This number remains the same at 0.4 m SLR, but jumps to 74,000 at 1.0 m SLR, 78,000 at 2.5 m SLR, and 103,000 at 5.0 m SLR. Although these numbers are high at even at 0.1 m SLR, they are relatively small as a percent of the city population because of the fact that the immediate areas adjacent to the shorelines are not mainly residential in land use. As a consequence, a limited number of schools and public services would be flooded. Indeed, no hospitals would be flooded at any of the SLR levels examined. Allowing the city to flood would have a relatively small impact on these services, although a large number of the city population would need to relocate.

The "doing nothing" option is viable if one considers the number of important federal and military buildings that would be affected. Most notably, at even a small SLR of 0.1 m, 23 buildings would be lost on the Bolling Air Force Base. At 2.5 m SLR, the number jumps to 129 buildings. At 5.0 m SLR, the number of federal buildings inundated is 23. Some important buildings that would be flooded include the National Gallery with many valuable works, other museums, the Federal Bureau of Investigation, the Internal Revenue Service, the Justice Department, the Federal Trade Commission, and the Department of Education. Although SLR may not reach these high levels in 100 years, these levels might be reached during storms.

Finally, there will be a significant impact on transportation infrastructure. Most notable are the metro lines that already go under the Potomac. The lines directly under the river are insulated to protect the tracks from water seepage. The lines that are not under the river do not have similar protections, and would require insulating from water seepage though the ground.

At 0.1 m SLR, the impact seems deceptively small. The city, however, would have to act. The city has the option to accommodate to the increasing levels by insulating buildings, the metro, and allowing some areas to flood. As Washington, DC is an important political and cultural center of the United States, this option will inevitably cause damage, and leave the city vulnerable to further rises in SLR. Protecting the city by building flood barriers might be a more practical solution. At the current predictions, the barriers do not have to be especially high to protect the city. As sea levels increase, they would have to be increased in height and reinforced. City planners should also consider SLR in defining or changing land use.

As previously mentioned, the data layers were made by different agencies in the Washington, DC government and the U.S. federal government. Each organization had different definitions and therefore there are discrepancies in the results. For example, the analysis of school grounds affected by 5.0 m SLR showed that only two educational institutions would be impacted; however, the analysis for the Points of Interest data layer shows that six educational areas would be impacted. Future studies would have to validate the analysis by performing field checks and an carefully examination of the GIS coordinates of a facility in terms of a curb point or center of facility point, or something else; perhaps a universal convention should be adopted for the city purposes. In addition, this report only looked at a few key components of a city's infrastructure. Because of security restrictions, key systems could not be considered in this report, such as the energy grid, the sewer, and water systems in Washington, DC. Future studies need to include these very important structures. In addition, the model of SLR was based on a linear increase, whereas a number of articles predict a nonlinear increase, rendering the linear model nonconservative. Indeed, the models reviewed in this article predict that sea levels are rising faster and higher than previously thought. The linear model also does not take into account the ground settlement and consolidation with changes in water content and water payload. Built on a very "wet" environment, flooding could have a detrimental effect, affecting more areas than predicted by this model. A probabilistic model of future SLR needs to be developed to fully understand the future of Washington, DC, and develop a risk profile.[20]

Decisions must be made in the near future by lawmakers or city planners on how to reduce the impact of and adapt to SLR. A planned retreat is not an option when dealing with SLR in such an important area. City planners have to decide whether to build countermeasures to keep the city from flooding or to accommodate the SLR either by modifying land use regulations or by reducing current financial investments in the affected area. A “do- nothing” approach would directly lead to irrevocable losses. A short-term solution, like creating a small flood barrier, may give the city time to examine this challenge and produce cost-effective solutions. Cost-effective methods to deal with SLR should be developed, and long-term solutions that extend well into this millennium are necessary.

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