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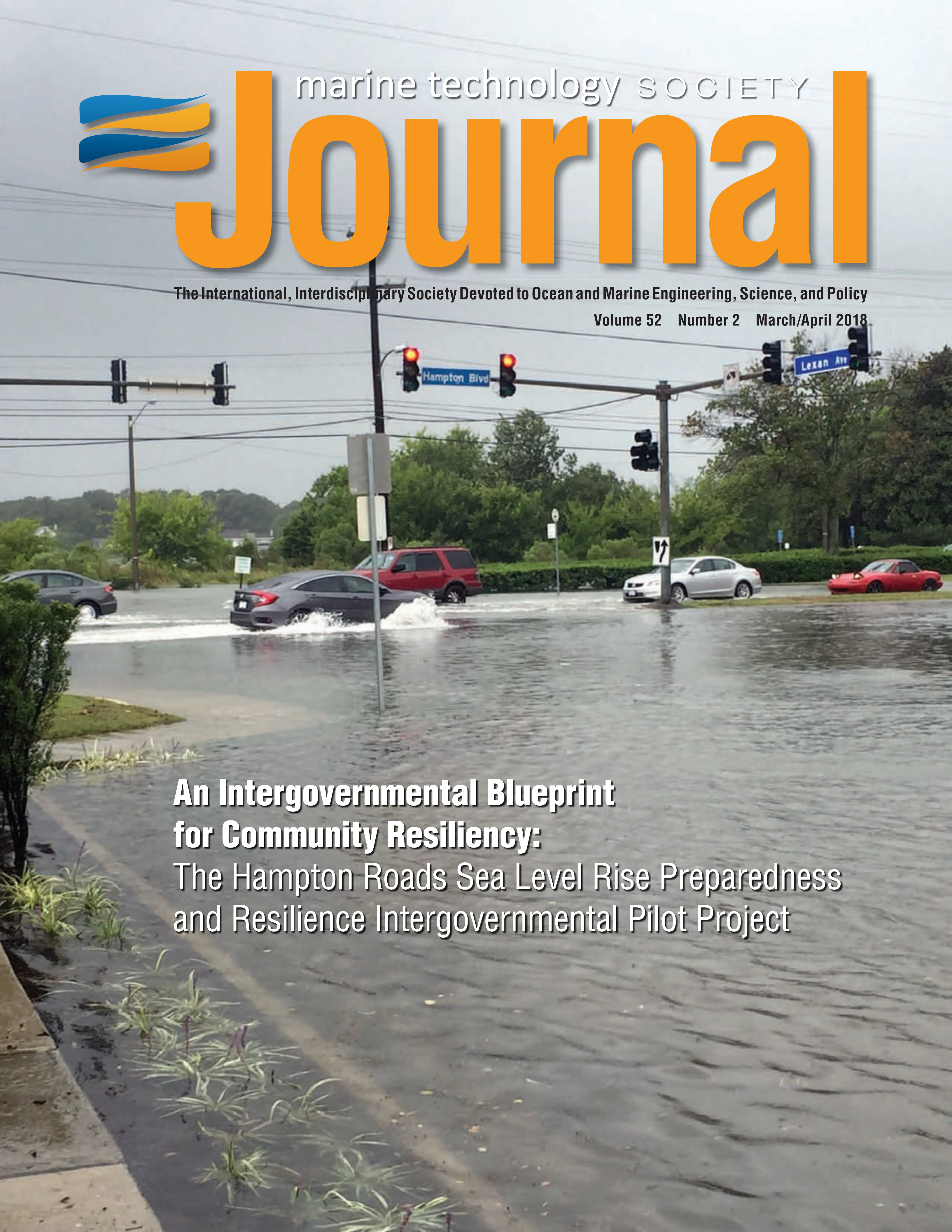

An Intergovernmental Blueprint for Community Resiliency:

The Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Pilot Project

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An Intergovernmental Blueprint for Community Resiliency: The Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Pilot Project

Guest Editors: Ray Toll and Gerhard F. Kuska

In This Issue

Front cover: Coastal flooding is of growing concern across Tidewater Virginia and in other coastal areas worldwide. Photo depicts flooding resulting from 2016 Hurricane Hermine in front of Norfolk's Larchmont Library at the intersection of Hampton Blvd. and Lexan Ave. on 9/3/2016 at 10:30 am EDT. Photo by J.D. Loftis/VIMS.
Back cover: Top: Inundation on Manchester Ave. on 9/3/2016 at 10:48 am EDT during 2016 Hurricane Hermine in Norfolk's Larchmont Neighborhood Photo by J.D. Loftis/VIMS. Middle: Figure 4 from Castrucci & Tahvildari paper, this issue. Bottom: Flooding in Norfolk's Larchmont Neighborhood along Richmond Pl. on 9/3/2016 at 10:52 am EDT during 2016 Hurricane Hermine. Photo by J.D. Loftis/VIMS.

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INTRODUCTION

An Intergovernmental Blueprint for Community Resiliency: The Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Pilot Project

Ray Toll
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Office of Research,
Old Dominion University
Immediate Past President,
Marine Technology Society

This special *Marine Technology Society (MTS) Journal* issue on resilience features authors presenting various perspectives on the challenges and solutions that we all must face. Many of these perspectives are a follow-up to the recommendations from a 2014–2016 pilot run by Old Dominion University (ODU) that used a whole-of-government/community approach to an integrated regional solution in Hampton Roads. An intergovernmental blueprint for community resiliency, *The Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Pilot Project* (convened by ODU and launched in June 2014 with MTS), was one of the three White House National Security Council pilots and one of the three Department of Defense pilots in response to the 2013 Presidential Executive Order, "Preparing the U.S. for the Impacts of Climate Change" (http://www.centerforsealevelrise.org/).

Two key national leaders, Secretary of State John Kerry and Assistant Secretary of the Navy for Installations, Energy and Environment Dennis McGinn, touted this effort as an effective process to both mitigate and adapt to rising sea levels and to address both national security and economic impact concerns. They went on to say that the ideas of an integrated regional approach could serve as an effective and efficient building block for a national water plan, providing a template for other regions of the country and overseas, particularly where our Navy has a presence.

Background

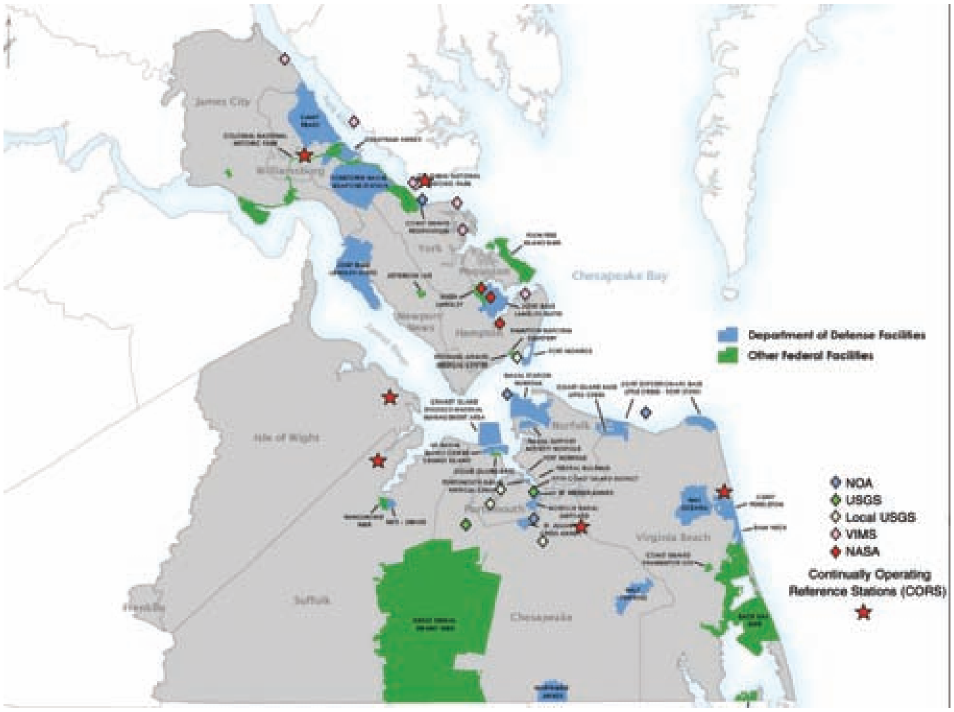
It was fitting that ODU would be the chosen site to convene this effort; situated in Norfolk, Virginia, the university is 20 min from the largest naval base in the world. ODU President John Broderick announced in 2009 that sea level rise (SLR) would be a research and academic priority for years to come. Boasting the largest natural coastline in the world, southeastern Virginia has an economy and culture tied largely to the strength of its ports and waters. The Hampton Roads region's geography has attracted multiple military installations, including the naval base, and also encompasses the third largest commercial harbor on the eastern seaboard, manufacturing facilities, commercial fisheries, residential development, and tourism.

ODU and MTS began partnering in 2012 with the OCEANS 2012 conference (http://hamptonroads12.oceansconference.org). This annual MTS/IEEE meeting highlighted coastal resiliency as a regional priority, as many technical papers were presented on the topic from the 3,000 conference delegates representing 35 countries. In June 2014, MTS cosponsored the pilot rollout on campus with a TechSurge workshop (http://mtshamptonroads.org/mtshr/?page_id=389).

From 2014 to 2016, Hampton Roads localities including Virginia Beach and Norfolk, four Cabinet Departments of Virginia Governor Terry McAuliffe, 11 federal agencies (including the Department of Defense), the Virginia Port Authority, a variety of private businesses, and three nonprofits worked together on a White House-announced intergovernmental pilot project (IPP) convened by ODU to figure out how to build coastal resilience in the face of increasing SLR (Figure 1).

FIGURE 1

Project interaction map.



Whole of Government and Community

The goal of this initiative was to establish an intergovernmental planning process to effectively coordinate SLR preparedness across multiple federal, state, and local government agencies as well as the private and nonprofit sectors, while taking into account perspectives and concerns of the region's citizens.

Led by a steering committee, volunteers focused on legal issues, infrastructure requirements, citizen engagement, public health, science, and economic impacts. Several aspects are worth mentioning:

- linking infrastructure interdependencies (on and off base) by sharing maps, plans, etc., with neighboring jurisdictions and municipalities;
- creating and maintaining an integrated regional network to observe impacts to the economy, storm water, public health, and infrastructure (these data could be used in real time but also archived to properly monitor longer-term changes at a greater level of spatial and temporal fidelity);
- incentivizing "whole-of-government" practices for each municipality through grants, requests for proposals, and other federal and non-federal acquisition practices;
- integrating planners' and emergency managers' plans and procedures to address real-time threats (such as Hurricanes Sandy and Matthew) and long-term trends like SLR; and
- improving scientific research methods through data integration and model improvement.

Upon completion of the pilot project, Hampton Roads will have laid the groundwork for a regional whole-of-government and whole-of-community organizational framework and procedures that effectively coordinate SLR preparedness and resilience planning. An important next step is a U.S. Department of Transportation initiative to quantify climate change impacts. Federal transportation officials chose Hampton Roads for this work and were proactive partners throughout the 2-year pilot effort (2014–2016).

The papers that follow present early results from research that addresses various aspects of the challenge from a whole-of-community perspective using a multidisciplinary approach. The College of William & Mary's Virginia Institute of Marine Science and Virginia Coastal Policy Center were key partners during the entire IPP.

INTRODUCTION

Resilient Communities and Regional Integrated Ocean Observing: A Partnership Greater Than the Sum of Its Parts

Gerhard F. Kuska
Executive Director, Mid-Atlantic Regional Association
Coastal Ocean Observing System (MARACOOS)
Vice Chair, IOOS Association

Coastal hazards are persistent and severe and present unique challenges to communities large and small. Flooding is one type of coastal hazard, with causes that stem from a variety of factors. In the Mid-Atlantic and the Virginia Tidewater region, in particular, our coastal residents and visitors, businesses, infrastructure, and our overall security are negatively impacted by flood-related events on a regular basis. Flooding affects our jobs, national security, economy, and public health and safety.

Preparing for and remaining resilient in the face of recurring flood events and other coastal hazards is the charge of every person and entity in our region. Communities and individuals rely on government leaders at the federal, state/commonwealth, regional, and local levels to disseminate and interpret vital messages. Accurate and effective messaging is fundamental for preparation and decision making, and requires access to reliable information.

Information comes in many forms and is delivered by many different groups, and the underlying data are often of varying and sometimes unknown quality. Compounding the challenges of multiple entities and varying approaches to data collection, data quality, and information management is the advent of new technologies and the tremendous growth in the amount of data being collected. This is where IOOS comes in.

The U.S. Integrated Ocean Observing System (IOOS, pronounced as “EYE-oos”) is a public-private partnership, established in law by Congress in 2009. The U.S. IOOS partnership, under the stewardship of the National Oceanic and Atmospheric Administration, is composed of 17 federal agencies and 11 nonfederal regional associations around the country that coordinate efforts to provide data and information products needed to address our country’s most important challenges, including coastal hazards and flooding.

The regional associations are extensions of government: working on the front lines with users, decision makers, and stakeholder communities; providing reliable and cost-effective data and predictions; leveraging data and resources from a wide variety of sources; enabling user-friendly access in a variety of standard formats and via portals; and ensuring data quality at the same quality standards or better than the federal government (including applying Quality Assurance/Quality Control of Real Time Oceanographic Data [QARTOD], which is featured in this special Journal edition), as established by the federal government. By the end of 2018, all 11 regional associations will be certified by the federal government for their data quality, extending federal tort liability coverage to the regional associations for the data they collect, leverage, and serve to the community of users. The bottom line: IOOS regional association data are the same as using federal data.

IOOS in the Mid-Atlantic region is MARACOOS (pronounced as “Mær-ə-ko͞oz”): the Mid-Atlantic Regional Association Coastal Ocean Observing System, a federally certified Regional Information Coordination Entity, covering the geographic area from Cape Cod to Cape Hatteras. MARACOOS brings together the best and the brightest partners from government, the private sector, academia, and the nonprofit sector to address the specific challenges in the Mid-Atlantic region, including the Virginia Tidewater region. Two great examples of IOOS academic partners in this part of the region are Old Dominion University and the Virginia Institute of Marine Science—both with featured authors in this special Journal edition.

Virginia’s Tidewater region is home to organizations and activities that are not only important for Virginia and the Mid-Atlantic but also for the nation as a whole. The opportunities are great, and the challenges in many areas are daunting. Because of its physical features and location, the Tidewater region is particularly affected by coastal hazards, such as storms and recurrent flooding. These impacts affect jobs, the economy, and public health and safety and require a concerted and coordinated effort to maintain and enhance the region’s prosperity.

The Mid-Atlantic IOOS partners at MARACOOS are uniquely positioned to support the Tidewater region in addressing its challenges in areas of flooding, maritime transportation and safety, public health, fisheries and shellfish, offshore wind energy, and tourism. One of the key roles of MARACOOS is as data integrator. MARACOOS and its partners bring together a comprehensive set of high-quality, reliable data that are made available to government, academia, and the private sector to create information products that decision makers can use to prepare and respond to the region’s challenges. The IOOS partnership is truly unique in that it does not compete with similar organizations or any of its partners. IOOS regional associations are venues to bring together and promote efforts, build on them, fill gaps where necessary, and create a whole that is greater than the sum of its parts.

As a data integrator, MARACOOS powers understanding and prediction of the Mid-Atlantic by bringing together varied data sources that otherwise would be lost or unavailable, ensuring their quality, and combining them with government, academic, and private sources to provide a comprehensive source of data and predictions in our region. A key tenet of IOOS is to measure once and apply multiple times, extending the value and impact of data collection and prediction efforts. MARACOOS is focused on supporting and building on local efforts in the Tidewater region, such as the Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Pilot Project.

The IOOS partnerships improve our ability as a nation of resilient communities to observe and predict the natural environment from weather-related impacts to flood forecasts and beyond.

By integrating data with purpose, MARACOOS is able to provide reliable, quality data that extend into many areas with benefits to our regional and national economies and overall well-being. IOOS is driven by the needs of our unique communities and promotes a stronger economy, good-paying jobs, and safe and healthy communities for residents and visitors. This is the promise of IOOS in the regions and the future of ocean, coastal, and Great Lakes data and predictions in our nation.

PAPER

Quality Control of Real-Time Water Level Data: The U.S. IOOS® QARTOD Project

AUTHOR
Mark Bushnell
U.S. Integrated Ocean
Observing System

ABSTRACT

Within the U.S. Integrated Ocean Observing System Program, the Quality Assurance/Quality Control of Real-Time Oceanographic Data (QARTOD) Project develops manuals that describe variable-specific quality control (QC) tests for operational use. The QARTOD's *Manual for Real-Time Quality Control of Water Level Data: A Guide to Quality Control and Quality Assurance for Water Level Observations* was created with broad support from entities engaged in operational observations of water levels. The process used to generate this manual and all other QARTOD manuals exemplifies the integration of "federal, state, and local government agencies as well as the private and nonprofit sectors" described by the Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Pilot Project.

Another project that supports Hampton Roads, Virginia, sea level rise and utilizes multiple partners is the deployment of continuous global positioning system (cGPS) receivers directly on water level sensors. These cGPS installations enable the determination of absolute sea level rise and local land subsidence. Successful transition of cGPS to an operational status requires the application of real-time data QC.

Keywords: water level, real-time quality control, QARTOD, continuous GPS, tide gauge leveling

Introduction

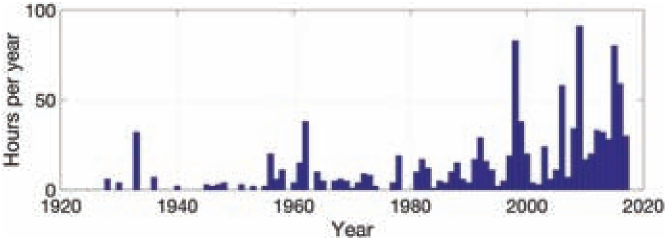
Relative sea level rise in Hampton Roads, Virginia, is well documented (Atkinson et al., 2013; Eggleston & Pope, 2013). The Sewells Point water level gauge operated by the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) is often used to quantify the regional long-term rise of more than 4 mm/year or about 1.5 feet per 100 years (https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8638610). Impacts upon the region are now readily noticeable. Figure 1 shows the increasing number of hours of nuisance flooding experienced each year. Nuisance flooding is defined empirically by NOAA for a specific location, and at Sewells Point it is water levels higher than 0.53 m above mean higher high water (MHHW).

As these impacts are realized, the need for quality control of water level data disseminated in real time increases. Human safety, safe and efficient maritime commerce, and the associated legal and financial concerns create a compelling justification for real-time quality control (QC) standards. Real-time QC has been found to speed the detection of problems and support troubleshooting and repair, thereby improving system uptime and making data delivery more robust.

The Quality Assurance/Quality Control of Real-Time Oceanographic Data (QARTOD) Project began as a grassroots effort in 2004. It was formally adopted by the U.S. Integrated Ocean Observing System (U.S. IOOS®) in 2012. The U.S. IOOS's mission is to "Lead the integration of ocean, coastal, and Great Lakes observing capabilities, in collaboration with Federal and non-Federal partners, to maximize access to data and generation of information products, inform decision making, and promote economic, environmental, and social benefits to our Nation and the world." As a part of this mission, the QARTOD Project works with many volunteers from diverse entities to create quality control manuals. Manuals are initially created with the assistance of the QARTOD technical coordinator, a technical writer, and a committee of about a dozen subject matter experts. Each manual is then reviewed by additional subject matter experts and the U.S. IOOS Regional Associations (RAs must plan to utilize QARTOD tests to obtain certification). After further editing, the draft manual is distributed as broadly as possible for a third review, which includes international partners. The draft manual is then returned to the original committee for their final review and then submitted for signature by the Project Manager, the

FIGURE 1

The number of hours per year of nuisance flooding at Sewells Point, defined as water levels higher than 0.53 m above MHHW. Plot courtesy of Dr. Larry Atkinson, Old Dominion University.



Board of Advisors Chair, and the Director of U.S. IOOS. Manuals are then posted on the QARTOD website at https://ioos.noaa.gov/project/qartod.

Throughout the process, an adjudication matrix is maintained. Every written comment received is acknowledged and logged and receives a response recorded in the adjudication matrix. In this way, contributions to manual development can be tracked, providing useful metrics and documentation should questions arise.

Eleven real-time QC manuals have been posted, and others are planned (U.S. IOOS, 2017a). Manuals are updated every 2–3 years, either receiving an incremental update (improvements to definitions, added explanatory tests, examples, additional figures, and updated web links) or a substantial update, which might require changes to the operational implementation of the tests. Substantial updates have not yet been needed, and they would occur only with the agreement of the affected community.

The manuals are designed to deliver sufficient information to those creating software needed for real-time QC. The tests are described in pseudocode, and examples of thresholds are provided. However, the determination of the actual thresholds to be employed is left to the local operator. Tests are either required, strongly recommended, or suggested. Test output results in data being flagged as either pass, suspect/of high interest, or fail, with the idea that human expertise should be used to examine the suspect or of high interest data (Table 1). Flags are also identified for data that have not been evaluated or are missing. Additional information regarding data flagging can be found in U.S. IOOS (2017b).

The water level QC manual (U.S. IOOS, 2016) was first created in 2014 and updated in 2016. Together, a total 230 comments were logged from 27 individuals representing 16 institutions who contributed to the manual. The manual has received a surprising amount of international interest. An Australian engineering company used the QARTOD water level and waves QC manuals for commercial dynamic under-keel clearance determinations (Hofmann & Healy, 2017). Two of the tests (rate of change and the attenuated signal water level tests) have been adopted by the British Oceanographic Data Centre for use in the Global Sea Level Observing System's *Quality Control of Sea Level Observations* manual. All QARTOD manuals have been posted in the Ocean Best Practices repository, and the statistics generated by this utility show the manual has been viewed 237 times in 10 different countries (http://www.oceanbestpractices.net/handle/11329/267/statistics).

The QARTOD water level QC manual describes the applications of real-time water level observations and identifies six different observational technologies used for the determination of water level to which the tests could be applied. It describes five required tests, three strongly recommended tests, and three suggested tests (Table 2).

TABLE 1

QARTOD flag scheme (Intergovernmental Oceanographic Commission of UNESCO, 2013).

Flag	Description
Pass = 1	Data have passed critical real-time QC tests and are deemed adequate for use as preliminary data.
Not evaluated = 2	Data have not been QC-tested, or the information on quality is not available.
Suspect or of high interest = 3	Data are considered to be either suspect or of high interest to data providers and users. They are flagged suspect to draw further attention to them by operators.
Fail = 4	Data are considered to have failed one or more critical real-time QC checks. If they are disseminated at all, it should be readily apparent that they are not of acceptable quality.
Missing data = 9	Data are missing; used as a placeholder.

TABLE 2

Tests in order of implementation and hierarchy.

Group 1 *Required*	Test 1	Timing/Gap Test
	Test 2	Syntax Test
	Test 3	Location Test
	Test 4	Gross Range Test
	Test 5	Climatology Test
Group 2 *Strongly recommended*	Test 6	Spike Test
	Test 7	Rate of Change Test
	Test 8	Flat Line Test
Group 3 *Suggested*	Test 9	Multivariate Test
	Test 10	Attenuated Signal Test
	Test 11	Neighbor or Forecast Test

The routine use of these tests at stations throughout Hampton Roads, Virginia, and elsewhere can help to ensure that critical disseminated water levels such as storm surge observations are reliable and accurate. Although larger operators such as NOS/CO-OPS maintain real-time QC processes, such QC efforts may be beyond the capabilities of entities with fewer resources. Bushnell (2017) suggested that, with the proper data communications links, all QARTOD water level tests could be conducted within the field-deployed components. However, manufacturers must believe there is a probability of a return on their investment before such systems are developed.

Continuous Global Positioning Systems

An emerging capability involves the use of continuous global positioning system (cGPS) observations to improve detection of water level station stability. Water level sensors must be installed on stable structures to minimize vertical motion. That stability must be proven, typically by leveling to nearby benchmarks and observing a network of vertically stable components. When motion is seen, such as the slow subsidence of a pier, corrections can be applied to the water level observations. However, regional subsidence will not be detected with such local leveling techniques, and the leveling is generally conducted at yearly or less frequent intervals. Regional subsidence is well documented in Hampton Roads (Eggleston & Pope, 2013) and has recently been shown to be quite variable (Bekaert et al., 2017).

As stated by Woodworth et al. (2017), “In an ideal but uncommon situation, the GNSS equipment is attached directly to the tide gauge or located nearby.” Such an arrangement permits the continuous detection of the absolute elevation of a sea level sensor relative to a Global Navigation Satellite Systems datum.

Starting in 2015, a cooperative effort to install cGPS receivers at four Hampton Roads water level gauges operated by CO-OPS was initiated. The Trimble NetR9 cGPS receivers and supporting equipment were provided by Old Dominion University (ODU). CO-OPS partnered with ODU, allowing the installation and assisting in the deployment. The receivers were configured using settings obtained from UNAVCO (University NAVSTAR Consortium, http://www.unavco.org), a nonprofit university-governed geoscience consortium funded by the National Aeronautics and Space Administration (NASA) and the National Science Foundation. The configuration enables tracking of only GPS satellites (not GLONASS, Galileo, Beidou, or other components of the global navigation satellite system); hence, these are referred to as cGPS installations. Data are automatically downloaded and archived from the four sites daily by NASA Langley Research Center, which has an interest in sea level rise and threats to the Langley Air Force

FIGURE 2

The cGPS antenna can be seen on the water level station at Wachapreague. Credit to M. Bushnell.

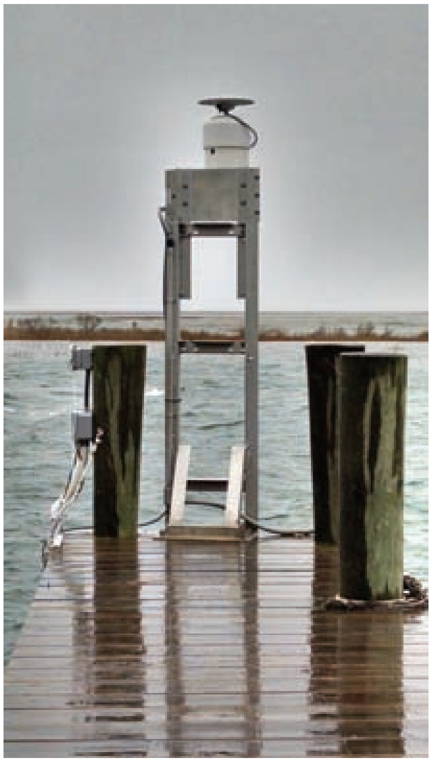
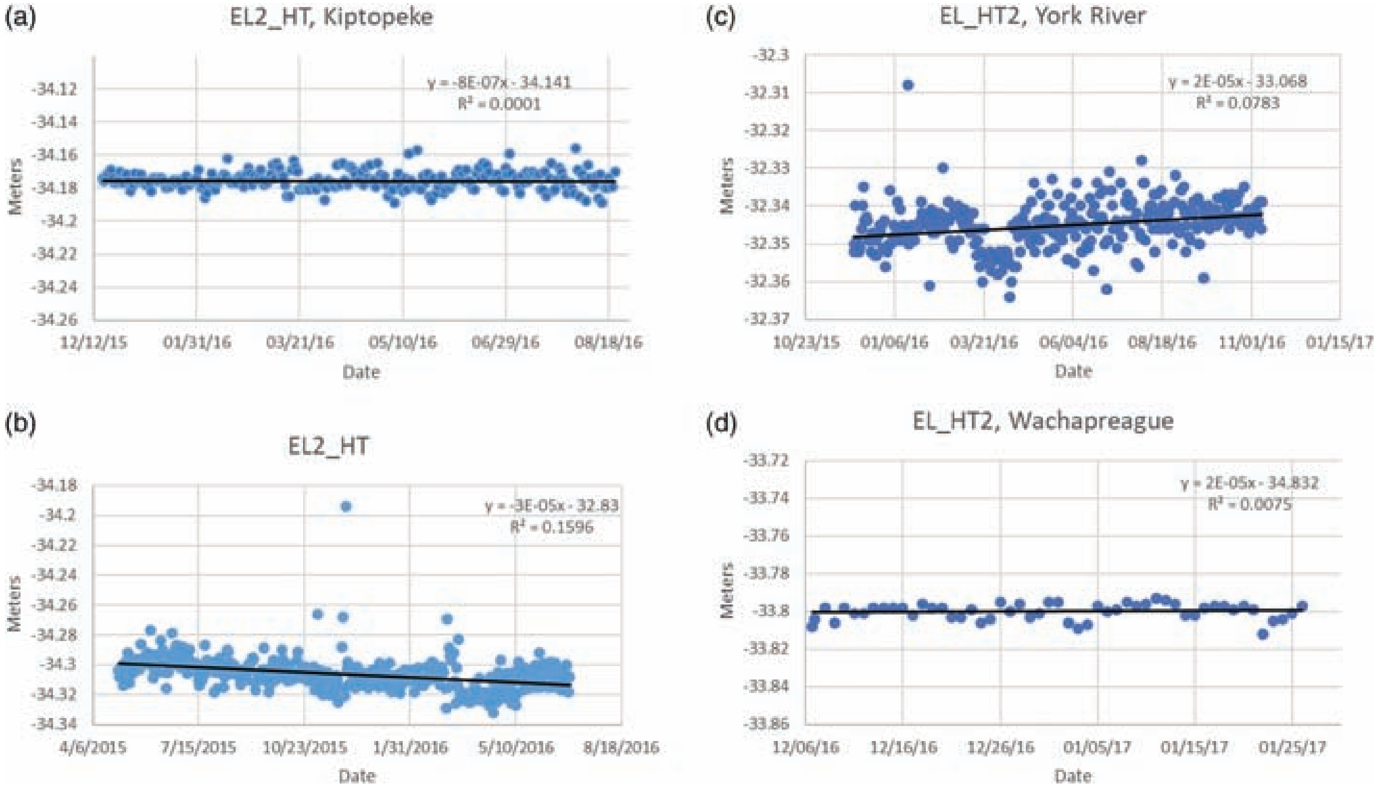


FIGURE 3

Preliminary results for Kiptopeke (a), Sewells Point (b), York River (c), and Wachapreague (d).



Base. Data have been processed using the National Geodetic Service Online Positioning User Service (OPUS) to achieve accurate vertical elevations. This effort represents a unique cooperation of multiple entities in Hampton Roads, Virginia.

The cGPS systems were installed at Sewells Point (04/30/15), Yorktown (12/02/15), Kiptopeke (12/16/15), and Wachapreague (12/06/16). Figure 2 shows the cGPS mounted atop the protective housing covering a microwave water level sensor. It takes a time series of about 5 years before such observations may be used to identify trends.

Some very preliminary results are shown in Figure 3. In the plot, EL2_HT is referenced to the IGS08 reference frame. The averages of the EL2_RMS (peak-to-peak error) are about 1.3 cm. Improvements to OPUS processing and time series analysis once the records are sufficiently long can be expected to reduce this value.

If cGPS observations are to be used operationally, real-time QC of the data such as documented in QARTOD manuals will be required.

Summary

Two little-known projects involving multiple cooperating entities are shown to support critical water level observations in the Hampton Roads, Virginia, region. The first, real-time QC tests documented in QARTOD manuals can be applied immediately by operators of water level stations. If manufacturer support can be found, those tests might be implemented within the field-deployed components. The second, using cGPS observations to detect vertical motion of any cause, is an emerging capability, and Hampton Roads is fortunate to have both the local support and national infrastructure to make the observations possible.

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PAPER

Well-being and Mental Health Impact of Household Flooding in Guyana, the Caribbean

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ABSTRACT

Guyana has annually experienced excessive rainfall and flooding since 2005. This study investigated the general well-being and mental health problems among occupants of households affected by the December 2008 flooding in Guyana. A cross-sectional study design was used to administer validated questionnaires, which included sections on demographics, environmental exposure, general health, and personal behavior. The response rate to the survey was 70% (130/185). The findings indicate an increased self-reported poor health for study participants who smelled moldy odors inside of their home (OR: 4.1, 95% CI: 2.0–12.0) and for individuals who had mold or mildew inside of their homes (OR: 3.0, 95% CI: 1.2–7.5). Individuals whose homes had flooded previously were also shown to be slightly more at risk for experiencing diminished interest in daily activities (OR: 1.3, 95% CI: 0.5–2.9) as well as diminished involvement in social activities (OR: 1.9, 95% CI: 0.7–4.8). Also, participants who had their houses previously flooded reported an increased difficulty in concentrating (OR: 2.4, 95% CI: 0.9–6.4). Flooding might be a possible risk factor for well-being and mental health problems among the occupants of affected households.

Keywords: flooding, health outcomes, Guyana, mental health

Introduction

Floods are the most common type of disaster globally, and they are responsible for about half of the deaths caused by all types of natural disasters (Alberman et al., 2012). A report from the World Health Organization (WHO) posits that flooding is expected to occur more frequently over the coming decades, at a higher intensity and for longer durations as a consequence of climate change and sea level rise (WHO, 2009). The steady rise of sea level puts coastal regions at high risk of flooding especially for storm surges and big waves. Flooding has significant social, economic, and environmental consequences on both individuals and communities (Alberman et al., 2012). The effects of flooding are felt unequally and are dependent on the location, vulnerabilities, and capacities of the communities they affect, and the ability of healthcare providers and public health practitioners to quickly assess community needs and allocate resources effectively and efficiently.

Flooding is associated with short- and long-term health outcomes. The short-term health impacts of flooding have been well documented by the scientific community and include injuries, water-borne diseases, respiratory diseases, vector-borne diseases, exposure to toxic substances, skin rashes, exacerbation of asthma, and malnutrition (Ohl & Tapsell, 2000). Researchers have established that the levels of indoor dampness in homes following a flood are higher in homes inundated with water compared to those that were not inundated, making the inundated homes more susceptible to higher levels of mold (Riggs et al., 2008; Azuma et al., 2013). In many developing countries, the damage and impact of floods persisted at least 6 months following the initial event (Oluwatayo, 2013; Kirsch et al., 2012). Rose and Akpinar-Elci (2015) found a statistically significant relationship between the presence of mold inside of a home and respiratory symptoms experienced among the occupants of the flooded homes in Guyana. Because floods disrupt the normal course of life for many people, it is possible that flooding may cause or exacerbate certain aspects of health including chronic conditions, psychological stress, depression, emotional trauma, and anxiety. Bei et al. (2013) found that flooding was associated with adverse psychological impacts especially among older adults.

Guyana's coastal regions experience two rainfall seasons each year, with the major peaks occurring in June and December (Bovolo et al., 2009). Prior to January 2005, the average amount of annual rainfall in Guyana was 7.3 inches over the previous 100 years (GINA, 2005). Since 2005, Guyana has annually experienced excessive rainfall over shorter periods. From January 2005 to February 2005, Guyana experienced torrential rains that amounted to over 60 inches (GINA, 2005). Since then, several areas of the country have been subject to frequent flooding. In December 2008, Guyana experienced extreme rainfall that affected many of the low-lying communities (Grosvenor, 2009). The coastal lowland areas of Guyana are below sea level and are therefore more prone to frequent flooding events of these residential communities. This predisposes them to not only damage to their property, crops, and livestock but also to illnesses associated with flooding and subsequent stagnant water (Lane et al., 2013).

In this study, we focused on the Atlantic coastal communities of Guyana that were affected by a major flood in 2008. The aim of this study was to examine the potential effects of flooding events on mental health and overall well-being among occupants of affected households.

Methods

Study Design

The study was conducted in 2009 in Cove and John, Guyana, which is often prone to flooding, given its proximity to the coast. Methodological study details of the project and selection criteria can be found in our previous publication (Rose & Akpinar-Elci, 2015). Approval was received from the institutional review board from St. George's University before data collection began.

Study Population and Data Collection

Criteria of inclusion of households in the research study include "(1) have experienced flooding in December 2008 and have been at least 30% of the community flooded during the December 2008 flooding, (2) have between a minimum of 100 and a maximum of 500 households, (3) have 75% or more of its homes as wooden homes, and (4) be a residential community" (Rose & Akpinar-Elci, 2015).

In total, 185 households were generated from the criteria and they were invited to participate in the study, and 130 households completed the study (Rose & Akpinar-Elci, 2015). Three trained interviewers were responsible for the data collection. In total, 349 questionnaires were collected from participants who were 16 years and older from 130 households.

An adapted version of the questionnaire designed by the U.S. National Institute for Occupational Safety and Health was used by the research team to assess health-related variables in the affected communities (Rose & Akpinar-Elci, 2015). The questionnaire was used to ascertain self-reported information about feelings of depression, general health, level of physical activity, social life, self-reported symptoms, physician diagnoses, demographic and environmental characteristics, the presence of chronic diseases, and family history (Rose & Akpinar-Elci, 2015).

Data Analysis

Using the SPSS statistical software package, Version 24, the data were analyzed to predict the prevalence of self-reported poor health, feelings of downheartedness or depression, and the level of interference with social and daily activities. Fisher exact test was used to determine if there is a nonrandom association between variables. Measuring depression by age, gender, race, income, and education level, we adjusted unconditional logistic regression models by comparing flooded and not-flooded household occupants. The odds ratio (OR) was also calculated to determine the strength of the association, including 95% confidence interval (CI). The unconditional logistic regression model was used to control for uncertainties related to the limitations of cross-sectional study, such as failure to establish causality among variables and the lack of comparability between households.

Descriptive analysis was conducted to examine the demographic, environmental exposure, personal behavior, and health-related characteristics of the study population. Table 1 summarizes the results of the descriptive statistics.

Results

The median age of the participants was 41 years (*SD* = ±18.1 years), 52.4% were female, 75.1% reported as East Indian origin, and 19.8% reported as African origin. Among the participants, 59.6% had less or equal to primary education, and 47.3% made less than $50,000 GYD (Guyana dollar) monthly (1 USD ≈ 200 GYD). The results also showed that there were 77.8% who reported owning their home and 76.8% who reported having their home flooded during the December 2008 flooding. Of the respondents,

TABLE 1

Self-reported house and household occupants' characteristics.

Characteristics	Participants	
	n	%
House characteristics		
Flooded in 2008	268	76.8
Previous flooding	312	89.4
House owner	272	77.8
Roof leaking	151	43.0
Visible mold inside the house	37	10.7
Smell of mold	36	10.6
Household occupants characteristics		
Poor health	46	13.3
Less interest in daily activities	161	46.1
Trouble to concentrate	147	42.1
Interference with social life	133	38.2
Feeling downhearted	183	52.4

52.4% indicated experiencing feeling downhearted and depressed since the flooding. A total of 46.1% reported having less interest in daily activities due to emotional problems such as depression and anxiety since the flooding (Table 1).

The analysis indicated a statistically significant association between having residual mold on the surface inside of the home and self-reported poor health ($p < .05$, Fisher exact test: 0.034). A statistically significant relationship was also found between the smell of moldy odor inside of the house and self-reported poor health ($p < .05$, Fisher exact test: 0.000). Fisher exact test is used in place of chi-square to determine if there is a nonrandom association between variables.

There was an increased risk of self-reported poor health for participants who experienced previous flooding (OR: 4.9, 95% CI: 0.6–39.4), for individuals who smell moldy odors inside of their home (OR: 4.1, 95% CI: 2.0–12.0), and for participants who reported having mold or mildew inside of their home (OR: 3.0, 95% CI: 1.2–7.5) (Table 2). There was a slight nonsignificant increase in feelings of depression or downheartedness for individuals who reported having their home previously flooded (OR: 1.4, 95% CI: 0.6–3.1), for people who had mold or mildew on surfaces inside of their home (OR: 1.3, 95% CI: 0.6–2.8), and for participants who reported smell of moldy odor inside of their home (OR: 1.5, 95% CI: 0.6–3.3). Slight, nonsignificant increase was also found in interest in daily activities for individuals who reported having their home previously flooded (OR: 1.3, 95% CI: 0.5–2.9) and for participants who reported smell of moldy odor inside of their home (OR: 1.2, 95% CI: 0.6–2.7). Participants who had their home previously flooded were at an increased risk of having trouble concentrating (OR: 2.4, 95% CI: 0.9–6.4). This was also found to be true for people who reported having their homes flooded during the December 2008 flooding (OR: 1.4, 95% CI: 0.7–2.6). In addition, individuals who had water coming in their home because of roof or window damage reported a slight nonsignificant increase in difficulty with concentrating (OR: 1.2, 95% CI: 0.7–2.0).

TABLE 2

Risk factors of self-reported health-related perspective among the study participants.

Risk Factors	OR (95% CI)[a]				
	Feeling Downhearted and Depressed	Poor Health	Interest in Daily Activities	Interference With Social Activities	Trouble Concentrating
Previous flooding	1.4 (0.6–3.1)	**4.9 (0.6–39.4)***	1.3 (0.5–2.9)	1.9 (0.7–4.8)	**2.4 (0.9–6.4)***
Mold inside home	1.3 (0.6–2.8)	**3.0 (1.2–7.5)***	0.9 (0.4–1.9)	1.2 (0.5–2.5)	1.1 (0.5–2.3)
Smell of mold	1.5 (0.6–3.3)	**4.1 (2.0–12.0)***	1.2 (0.6–2.7)	1.7 (0.8–3.7)	1.5 (0.6–3.2)

[a] Age, gender, income, race, and education adjusted.

**P*-value < 0.05

Discussion

This study investigated the overall well-being and emotional health of people who continued to live in homes in coastal Guyana that were flooded in December 2008. The findings of this study indicated that participants who had previous flooding reported poor health. Previous research also indicates that individuals who are affected by repeated flooding events exhibit adverse health outcomes over time (Trugeon, 2006; Wieslander et al., 2007).

Riggs et al. (2008) found that a higher level of mold was found in homes that experienced repeated floods. Furthermore, Reponen et al. (2010) established a consistently high association between the presence of microbial concentrations and homes with moldy odors. The microbial exposure was associated with asthma development and reduction of the individual quality of life. Our study identified the increased prevalence of self-reported poor health for people who reported having mold or mildew on the surface inside of the home and for participants who smelled moldy odor inside of the home. Mendell et al. (2011) found a consistent association between indoor mold and multiple respiratory health issues.

The results of our study indicate a slight risk of feeling downhearted and depressed for people who had their homes previously flooded, for people who had visible mold inside of the home, and for those who smell moldy odors inside of their home. Our results indicated that participants who reported previous flooding also reported decreased interest in daily activities, had trouble concentrating, and participated less in social events due to emotional problems. Research has established that flooding exacerbates psychological problems, such as stress, depression, and anxiety (Azuma et al., 2013; Alberman et al., 2012; Chae et al., 2005). In addition, emotional problems such as depression and anxiety might impact the people's social and physical activities negatively (Steger & Kashdan, 2009). Furthermore, Munro et al. (2017) have established that people who were displaced from their homes due to flooding were more likely to experience post-traumatic stress disorder, depression, and anxiety.

Although the need of mental health services for flooding victims has been well documented in the United States, other countries are still lagging. Although there is little data, the prevalence of mental health disorders in Guyana is 10% to 15% (WHO, 2008). However, only 1% of health care resources are devoted to mental health in Guyana. Flooding responses need to include mental health components to their disaster response and relief plans in order to better address a population that is already subjected to a high level of mental health disorders.

Flooding often disrupts social interactions that are beneficial to people's mental well-being. Mental health resources for short- and long-term flooding responses are critical and should therefore be included in disaster management plans. The impacts of flooding in developing countries are much higher compared to developed nations regarding the loss of life, infrastructure, health, and well-being. As changing climate threatens to exacerbate the rate of these events, the lack of proper local governance and inadequate economic support puts these communities who are already impacted by major flooding events at even higher risk. The impacts of floods in developing countries have become more devastating on the livelihood, security, health, and well-being of the affected population (Oluwatayo, 2013; Walker-Springett et al., 2017).

Some of the limitations of this study are related to cross-sectional study design and the use of self-reported and recalled information due to the lapse of time between the December 2008 flood and the start of data collection. Further studies using qualitative design might help to understand the psychosocial needs of people whose communities are affected by repeated flooding. The strength of this research is backed by a representative sample, which consisted of the entire community, high participation rate, and the use of the previously validated and tested data collection instrument.

Our results showed that individuals who had mold or mildew inside of their home were at an increased risk of poor health. These individuals were also at a slightly risk of depression, have less interest in activities, and have trouble concentrating. Addressing psychological and emotional problems such as depression and anxiety is essential for improving the well-being and quality of life for everyone, especially those who are recovering from a natural disaster. In light of the impact of floods on the mental health and the well-being of the exposed population, it is essential that the local and state leaders understand the long-term effects of floods on all aspects of health and integrate coping measures in all levels of flooding management response in order to safeguard and improve the quality of life among those affected.

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PAPER

Review on Seaport and Airport Adaptation to Climate Change: A Case on Sea Level Rise and Flooding

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ABSTRACT

Seaports and airports are the critical nodes of international supply chains and thus stand on the edge of social and economic disasters. They are often affected by extreme and rough weather. Comparing all climate threats, sea level rise (SLR) and storming and flooding currently present, according to the relevant literature, the most severe impact in ports and airports. This paper aims to provide a comprehensive review of seaport and airport adaptation to climate change with a focus on SLR and flooding. We have summarized all related research papers and divided them into different types and described the trend of studies. After that, the study involves a comparison to analyze the synergy between previous studies in seaports and airports and provides insights for further studies to emphasize the needs and opportunities for the collaborative work that can complement the adaptation planning of and ensure the resilience of seaports and airports.

Keywords: climate change, climate adaptation, transportation resilience, literature review, climate risk

Introduction

Over the past few years, the focus on climate change studies has switched from mitigation to both mitigation and adaptation. As global warming brings more extreme weather, accidents and failures become more frequent, and losses and fatalities are more severe. In the past two decades, several serious weather-related events have caused significant economic loss and deaths. In 2005, Hurricane Katrina in the United States was one of the deadliest hurricanes (CNN Library, 2017b). In 2011, the Tohoku Japan Tsunami destroyed several provinces (CNN Library, 2017a); it was responsible for more than 15,000 deaths, and about 230,000 people lost their homes. In 2011, Missouri experienced the deadliest U.S. tornadoes, which killed 161 people (Wheatley, 2013). In 2012, Louisiana, Mississippi, Alabama, and Arkansas faced a strong and rainy Hurricane Issac, which caused $2.0 billion in terms of insured loss and left more than 644,000 people without power (Castellano et al., 2012). In 2013, a 2-mile tornado near Oklahoma City caused more than 50 deaths and destroyed many homes (Howell et al., 2013). During the 2017 Atlantic hurricane season, there were more than nine hurricanes threatening North America and Caribbean areas. Until October, hurricanes, including the most powerful, Maria, brought more than $200 billion in losses and a death toll of 103 in the United States (Johnson, 2017). Transportation is highly affected by extreme weather, especially by flooding and storming. Seaports and airports are the critical nodes of international supply chains and thus stand on the edge of social and economic disasters. It is therefore important to review the previous studies and understand the research gaps for future research directions.

In previous years, there were some literature reviews in similar research areas. However, they did not focus on seaports and airports as they are affected by SLR and flooding. For examples, Jonkeren and Rietveld (2016) reviewed waterborne transport infrastructures with an economical focus, and Lee (2007) did a review with a focus on emission reduction for all transport modes. Given the similarity of seaports and airports, it is valuable and beneficial to conduct a comparative analysis on their climate adaptation measures for cross fertilization.

Methodology of Literature Review

To carry out a comprehensive literature review of seaport and airport adaptation to climate change, we have set up a systematic analysis for searching and selection of articles. With reference to Wan et al. (2017) and Luo and Shin (2016), we can divide the whole data collection process into three steps:

1. online database searching,
2. article screening, and
3. final refining and analyzing.

First, we collected papers on climate change adaptation of seaports and airports with a focus on flooding and storming from all of the peer-reviewed academic journals on Web of Science (All Database). It is one of the most comprehensive multidisciplinary searching platforms for academic research (Hosseini et al., 2016; Luo & Shin, 2016; Wan et al., 2017). We used different strings, such as the combination of the elements from the sets of (flooding or flood or adapt or adaptation or resilience), (airport or seaport or port), (flooding or flood), (resilience or adapt or adaptation), and (airport or seaport or port), as "Topic" items to perform the search process. Throughout the search process, we have used the "OR" function to finish the journals collection. The search was completed in October 2017, covering the period from 1970 to 2017; 501 relevant papers were collected.

Second, we conducted a two-stage screening process to secure the relevance and quality of the selected articles. In the first stage, we sorted out the peer-reviewed journals and eliminated the book chapters, conference proceedings, editorial materials, and non-peer-reviewed journals. Peer-reviewed journal papers were chosen for analysis because they are the most guaranteed type of research to be accepted by the scientific community (Bergström et al., 2015). We reduced the number of articles from 501 to 383. In the second stage, we studied titles, keywords, and abstracts of the chosen 383 articles to confirm their relevance. For example, articles related to ecosystem (Hirst et al., 2016) and other climate change impacts (Tham et al., 2011), which are irrelevant to flooding and storming, were eliminated. After the second screening, the number of selected articles was reduced to 105.

Finally, we carefully conducted a full-text review for the refined 105 articles. As a result, the articles that have no focus on flooding and storming impact on transportation were also eliminated. After the final refining process, 88 articles remained. We analyzed the articles by the distribution of their publication years, authors, journals, regions, transportation modes, and research methods. We identified research interests and the corresponding trends of different research themes. Furthermore, we analyzed the connection of leading authors through their collaborative papers. Finally, we compared the studies on seaports and airports to guide the directions of further studies.

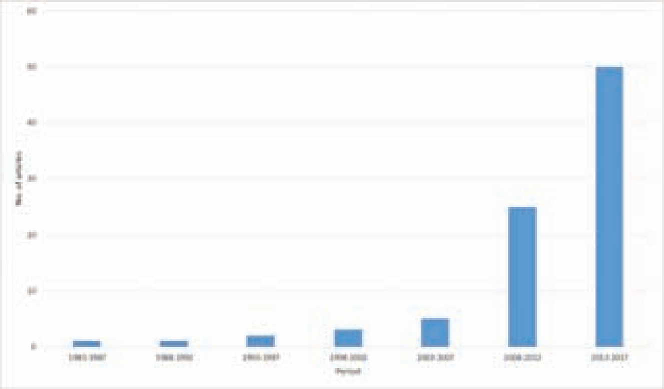
Analysis of Studies

Study Trends

The refined 88 journal articles are distributed from 1985 to 2017 and represented in Figure 1. The earliest refined journal is from 1985; 2012, 2015, and 2016 are the years with the highest number of journal articles, such as 12, 16, and 17, respectively. The number of corresponding papers is increasing rapidly. In the period of 2008–2012, the number of articles is four times more than that of 2003–2007, whereas in the period of 2013–2017, the number of articles doubles compared to that of 2008–2012 and is more than the total before 2013. Such growth clearly indicates the importance and urgency of the research topic and well reflects the fact that climate change involving both mitigation and adaptation is of high priority as both a national and international research agenda. It is foreseen that there will be more studies and relevant outcomes and publications in this field in the next decade, given the increasing effect of climate change on transportation and our social welfare.

FIGURE 1

Distribution by publication year.



Distribution by Journals

After assessing the trend of studies, we need to assess the articles by the prospect of journals. We list the top journals, indicating more than two articles, in Table 1. Among all articles, *Climatic Change* is the most contributed to journal as it published six journal articles that were related to the topic. Other leading journals include *Journal of Coastal Research, Natural Hazards, Coastal Engineering Journal, Journal of Geophysical Research, Ocean and Coastal Management, Ocean Engineering, Regional Environmental Change, Revista de Gestão Costeira Integrada,* and *Sustainability Science*. If the journals contain the same number of articles, we list them by alphabetic order in the journal list. It is clearly seen that the topic has diversified features and attracts attention and interest from a wider audience encompassing coastal research, geographical science, ocean engineering, and environmental and sustainability studies.

Distribution by Authors

This section evaluates the distribution of the leading authors. Table 2 shows the top authors. Among all articles, Austin Becker and Robert Nicholls are the most contributive scholars in the field. There are also 15 more authors contributing more than two articles. Analyzing their affiliations could also help us to identify the strong research groups/labs in the world in the investigated area. Statistical analysis of the papers of multiple authors from different research groups indicates that, so far, there is no significant critical mass being formed from the listed leading authors, which reveals that studies in the field are being carried out rather individually and the issues are being tackled from different perspectives based on the expertise possessed by different groups. Therefore, it shows a good potential to integrate complementary expertise from the leading authors to match the diversified features of climate adaptation research, involving hazard analysis, impact assessment, risk modeling, resilience engineering, geographical studies, and environmental and sustainability science.

TABLE 1

Top 10 journals.

No.	Journal Title	No. of Articles
1	*Climatic Change*	6
2	*Journal of Coastal Research*	4
3	*Natural Hazards*	4
4	*Coastal Engineering Journal*	2
5	*Journal of Geophysical Research*	2
6	*Ocean and Coastal Management*	2
7	*Ocean Engineering*	2
8	*Regional Environmental Change*	2
9	*Revista de Gestão Costeira Integrada*	2
10	*Sustainability Science*	2

TABLE 2

Top 17 authors.

No.	Author Name	No. of Articles
1	Becker, Austin	4
2	Nicholls, Robert	4
3	Corfee-Morlot, Jan	3
4	Fischer, Martin	3
5	Hallegatte, Stéphane	3
6	Chhetri, Prem	2
7	El-Raey, Mohamed	2
8	Esteban, Miguel	2
9	Frihy, Omran El Sayed	2
10	Gekara, Victor Ovaro	2
11	Hanson, Susan	2
12	Herweijer, Celine	2
13	Ng, Adolf K.Y.	2
14	Nursey-Bray, Melissa	2
15	Pugh, D.T.	2
16	Ranger, Nicola	2
17	Schwegler, Ben	2

Distribution by Regions

Apart from assessing the authorship of the journal articles, we investigate the regions of studies through analysis of the authors' affiliations. We evaluate the regions by the locations of the first authors' institutions, and the result is shown in Figure 2. Europe occupies 32%, involving 28 articles. It is followed by North America, Africa, Asia, Oceania, Latin America, and the Caribbean. In general, European and American academic institutions (49% of the total) remain in a world-leading position in climate change adaptation, with a focus on flooding and storming. This knowledge provides useful insights as to where the possible best practices and solutions to storming and flooding in seaports and airports are located in the world currently.

Distribution by Transportation Modes

In this section, we analyze the difference between relevant studies in seaports and airports. By reviewing all of the 88 papers, we conducted the analysis by separating them into three groups: seaports, airports, and combi. This is because some regional coastal assessments have not stated that they are uniquely defined by any transportation mode (e.g., airports or seaports); instead, they encompass large regions involving both seaports and airports. The result is shown in Figure 3. "Combi" has the largest ratio of 57%, involving 50 articles. "Seaport" and "Airport" have 39% and 4%, respectively. This reveals two important pieces of information that can trigger some interesting future studies. One is that, within the context of adaptation to flooding and storming, there are high synergies between airports and seaports, given that 57% of the investigated papers treat them together. The other is that seaports attract significantly more research attention. Research on the difference and similarity between airport and seaport adaptation planning to flooding and storming is needed, and the comparative analysis between them also needs to be conducted to find the reason why adaptation research in airports is less than that in seaports. Furthermore, there is a vast difference between the two in terms of research topics. Airports have more research focused on operation and climate risk assessment, whereas seaports are associated with other research topics as indicated in Figure 4. Research topics are detailed in the section on Distribution of Research Topics.

FIGURE 2

Distribution by regions.

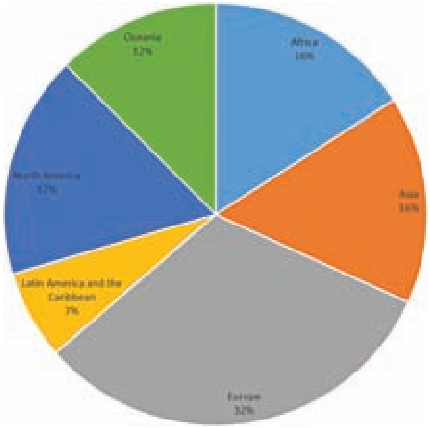
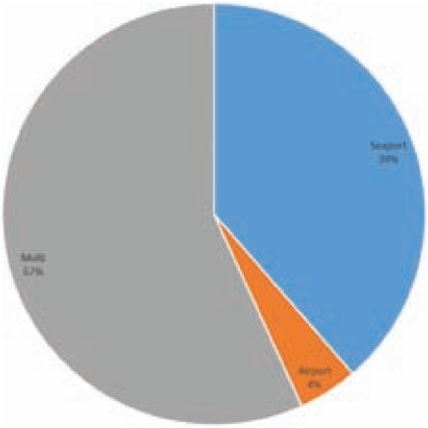


FIGURE 3

Distribution by transportation modes.

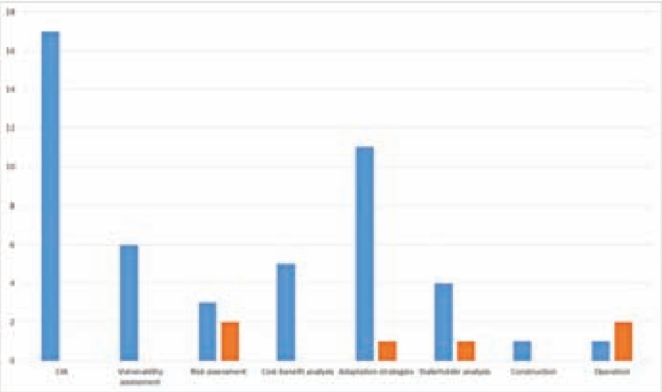


Distribution by Type of Research

We conducted a simple division between quantitative research and qualitative research by their basic characteristics. Quantitative research considers hard science, which consists of statistical analyses (Mugenda & Mugenda, 1999). On the other hand, qualitative research considers soft science, in which interpretation and narrative are more important throughout the whole research. The result is shown in Figure 5. Quantitative research takes an important role in these kinds of studies as it made up 59 articles and 67% in total. The remaining is qualitative research, which consisted of 29 articles and 33% in total. The main quantitative methods used include simulation and mathematical modeling. A simulation method is used to study the operation of a real-world or theoretical process/system under various preset circumstances for different purposes (e.g., numerical testing, observing behavior, optimizing performance, or exploration of new states). Mathematical modeling refers to those applying mathematical concepts and languages to describe and represent objective reality. Qualitative methods are conceptual works and case studies. Conceptual work includes analysis on concept issues, such as definitions, properties, theoretical framework, and conceptual modeling. A case study refers to an in-depth examination of a particular person, community, or situation, which usually can be achieved via interviews. By reviewing the 88 papers, it is also found that lack of data is a common problem discussed in both qualitative and quantitative

FIGURE 4

Distribution by research interests with split of airports and seaports.



studies. Therefore, how to address the unavailability and uncertainty in data to support rational decision in this area remains unclear, needing solutions from future studies.

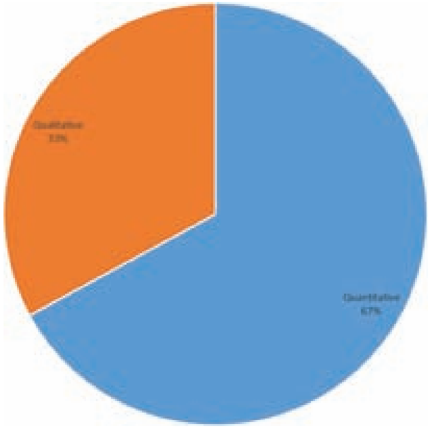
Distribution of Research Methods

Following the analysis in the preceding section, this section analyzes the detailed research methods in the 88 papers, including the following:

- Review
- Survey
- Framework
- Modeling
- Simulation

FIGURE 5

Distribution by research types.



The studies that involve more than one method are counted multiple times. The result is shown in Figure 6. The most common method is Modeling, representing 39 articles in total. The second and third most common methods are Framework and Review, where the numbers of articles are 32 and 29, respectively. Simulation and Review are at the bottom, relating to 10 and 4 papers, respectively.

Distribution of Research Topics

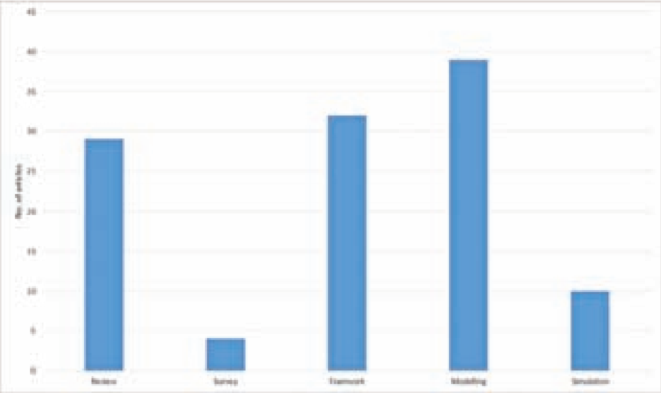
In terms of research topics, we have identified several different types:

- Climate impact assessment (CIA)
- Vulnerability assessment
- Risk assessment
- Adaptive strategies
- Cost-benefit analysis
- Stakeholder analysis
- Construction
- Operation

The definitions of CIA, vulnerability assessment, and adaptive strategies are in line with those from an Intergovernmental Panel on Climate Change report (IPCC, 2014). The report presents a fundamental adaptation planning framework containing such important concepts. CIA is a study describing the trend of climate change, where the impacts can be rising temperatures, sea level rise (SLR), and others. A vulnerability assessment for climate change is the process of identifying and quantifying the vulnerabilities in a specific region or infrastructure. Adaptation strategies mean the case study of local and regional transportation infrastructure by introducing the adaptive management of a particular region or transportation system. Besides, risk assessment requires the combination of studies of threat, vulnerability, and impact factors (Liu et al., 2012). Cost-benefit analysis based on the economic analysis of a system or infrastructure adaptation strategies means the case study of local and regional transportation infrastructure

FIGURE 6

Distribution by research methods.

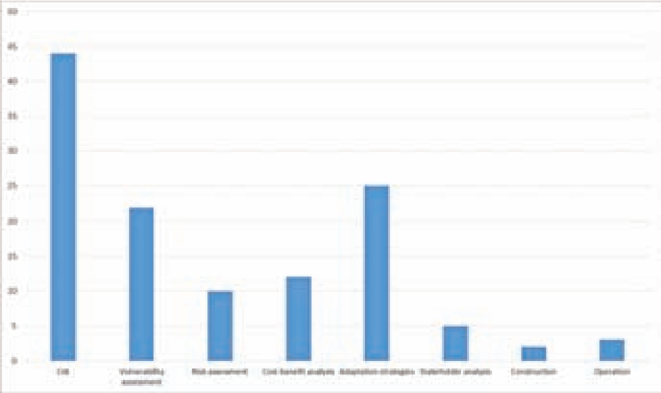


by introducing the adaptive management of a particular region or transportation system. Stakeholder analysis is a methodology to facilitate the reformation of institutional and policy processes by accounting and often incorporating the needs of those who have an interest in the reform under consideration (World Bank Group, 2001). Construction and operation mean the studies not in the adaptation planning process but in the postplanning process. Some investigated papers contain more than one topic and hence are counted multiple times in the statistics in Figure 7.

The result is shown in Figure 6. The most common research method is CIA, with 44 articles in the category. It is followed by adaptation strategies, vulnerability assessment, cost-benefit analysis, risk assessment, stakeholder analysis, operation, and construction. Obviously, studies in the adaptation planning process are far more than those in the postplanning stage and dominate the research on seaports and airports adaptation to flooding and storming. This indicates that current construction and operations of airports and seaports have not yet taken into account climate adaptation significantly. Adaptation strategies are made largely based on CIA, receiving more and more support from vulnerability assessment, risk assessment, and cost-benefit analysis to make the climate adaptation research in seaports and airports more systematically. Furthermore, stakeholder analysis shows a huge potential to grow in the next decade when more adaptation strategies are developed, requiring the balancing of different interests of multiple stakeholders for their implementation.

FIGURE 7

Distribution by research interests.



Evolution of the Studies

Because of the complexity of studies, the evolution of the studies is discussed from eight perspectives with respect to the eight topics in the Distribution of Research Topics section. The directions of the research are researched in a chronological order of the eight topics one by one after the comparison of the publication year of the first paper of each topic in Table 3.

Evolution of CIA

In 1985, Prasad and Reddy started to assess the sea level fluctuation monthly and annually in India and recorded in academic journals in the first time (Prasad & Reddy, 1985). In 1991, apart from SLR, Gornitz had designed coastal vulnerability index to raise high-risk coastal segments with a case study in the United States (Gornitz, 1991). A few years later, Dhaw and Forbes expanded the range of CIA from SLR to flooding and storming (Dhaw & Forbes, 1995). In 1999, Hubbert and McInnes designed a storm surge inundation model for coastal planning in Australia (Hubbert & McInnes, 1999). In 2000, Pirazzoli conducted a flooding statistical probability study on the Atlantic coast of France (Pirazzoli, 2000). In 2003, Hunter made a tailor-made SLR assessment for seaports in Tasmania (Hunter et al., 2003). In 2009, CIA was integrated with a Geographic Information System (GIS) for assessing digital elevation model (DEM) to make an Integrated Coastal Zone Management Plan by Snoussi and colleagues (2009). In other words, scholars started to combine CIA with vulnerability assessment by GIS spatial analysis. In 2010, Frihy contributed to the evolution by upgrading the SLR assessment from recording to forecasting its values in different scenarios (Frihy et al., 2010). In 2015, Becker combined CIA with vulnerability assessment and adaptation strategies from a whole climate adaptation planning perspective (Becker et al., 2015). In 2017, there are two special assessments for seaports. One is for harbor operability (Sierra et al., 2017), and one is for studying extreme wind events (Repetto et al., 2017).

Evolution of Vulnerability Assessment

In the late 1990s, El-Raey and colleagues undertook two vulnerability assessments of the coastal zone of Egypt, the Nile Delta, and Port Said

TABLE 3

The earliest years for different research interests.

CIA	Vulnerability Assessment	Risk Assessment	Cost-Benefit Analysis	Adaptation Strategies	Stakeholder Analysis	Construction	Operation
1985	1997	2008	2013	2008	2013	2016	2015

Governorate (El-Raey, 1997; El-Raey et al., 1999). They used remote sensing for GIS spatial analysis. After a decade, studies on vulnerability assessment arrived at a new stage. In 2008, Sterr integrated vulnerability assessment with adaptation strategies by clustering the assessment into a smaller region (Sterr, 2008). At the same time, GIS spatial analysis by DEM began to be widely used in vulnerability assessment (Gravelle & Mimura, 2008; Snoussi et al., 2009). In 2015, Akukwe and Ogbodo connected the studies of vulnerability assessment to emergency planning for setting up vulnerability indices and ranking these indices across the 13 costal zones they investigated (Akukwe & Ogbodo, 2015). At the same time, Musekiwa et al. (2015) set up a risk analysis table from vulnerability assessment to connect risks and vulnerabilities. Zanetti, de Sousa, and De Freitas (2016) proposed the climate change vulnerability index with a case study in Brazil.

Evolution of Risk Assessment

In 2008, Reid established a framework of climate risk analysis of seaports (Reid, 2008). In 2010, Briguglio connected risk assessment with adaptation suggestions (Briguglio, 2010). Keokhumcheng et al. (2012) assessed the flood risk in airports, using Bangkok Suvarnahumi Airport for the case study. In 2015, risk assessment became more systemic by linking to vulnerability assessment (Musekiwa et al., 2015). Furthermore, Yang et al. (2017) developed a new risk analysis model recently for climate risk quantification in a situation where objective data relating to risk parameters are not available.

Evolution of Cost-Benefit Analysis

In Nicholls et al., 2013 summarized the coastal planning experience from England and Wales. They started to include cost estimation. After that, there was vulnerability assessment including cost estimation (Musekiwa et al., 2015). Genovese and Green (2015) began to predict the damage of storm surge by modeling methods in 2015, and Hoshino commenced to estimate and compare the loss caused by future storm surges with and without adaptation strategies in the Greater Tokyo area (Hoshino et al., 2016). Cost-benefit analysis was formally integrated into the rational development of adaptation measures.

Evolution of Adaptation Strategies

The earliest article clearly presenting the climate change adaptation element in seaports and/or airports was published in 2008 (Sterr, 2008). Afterwards, many articles with adaptation measures and/or strategies were published (Briguglio, 2010; Becker et al., 2015; Hoshino et al., 2016). Between 2012 and 2013, there were several review papers published to address the use of adaptive measures. Osthorst and Mänz provided a preliminary typology of forms of sectoral adaptation to climate change by literature reviews (Osthorst & Mänz, 2012). At the same time, Wilby and Keenan identified evidence of different types of adjustment by following the flooding in Victoria, Australia (Wilby & Keenan, 2012). One year later, Becker et al. (2013) addressed a note for seaports on climate change adaptation. Furthermore, they discussed the needs and contributions of stakeholders of seaports. In Mutombo & Olcer, 2016 developed a three-tier (Policy-Management-Technology) framework for seaport infrastructure adaptation. At the same year, Burbidge stated a climate adaptation review on EUROCONTROL for European airports (Burbidge, 2016). In 2017, Becker used boundary objects, different adaptation scenarios, to stimulate ideas of storming resilience for seaports (Becker, 2017).

Evolution of Stakeholder Analysis

After developing adaptation strategies for several years since 2008, Becker et al. and Peirson et al. stated the importance of stakeholders' participation in the whole adaptation planning for seaports in 2013 (Becker et al., 2013) and especially for estuaries in 2015 (Peirson et al., 2015), respectively. Moreover, Burbidge recorded the consultation of European aviation stakeholders in climate change adaptation for airports in 2016. In 2014, Nursey-Bray studied how the port governance on negotiating climate adaptive management for facilitating regional, national and transnational networks, and governance flows (Nursey-Bray, 2014).

Evolution of Construction

In terms of construction in the postplanning process, the previous articles focused on new construction methods as one of adaptation measures. In 2016, Becker et al. developed a way to estimate climate sensitive construction materials applied to seaport protection (Becker et al., 2016). At the same year, Chow et al. designed a new coastal structural concept for climate change adaptation in Hong Kong and undertook a relevant cost-benefit analysis (Chow et al., 2016).

Evolution of Operation

As far as seaport and airport operations for climate adaptation, previous articles focused on extreme weather operations. In 2015, Herath et al. integrated spatial and temporal downscaling approaches to develop an intensity-duration-frequency model for assessing subdaily rainfall extremes for the Perth airport area (Herath et al., 2015). In 2016, Chhetri et al. used the container terminal operations simulator to simulate extreme weather event impacts on port operation (Chhetri et al., 2016). At the same year, Dun and Wilkinson invented a network graph approach to increase the resilience of air traffic networks (Dunn & Wilkinson, 2016).

Comparison of Airport and Seaport Climate Adaptation Studies

All "combi" articles were eliminated to ease the comparison of airports and seaports; there were 38 articles in this category. The distribution of transportation mode is shown in Figure 7. There were more contributions in seaports than those in airports. Seaports were 89% with 34 articles, and airports were only 11% with four articles.

Conclusion

This review paper discloses and allows scholars in the relevant areas to access the information on the trends and the characteristics of studies on seaport and airport adaptation to climate change with a particular focus on SLR and flooding. It describes the evolution of the studies of different research topics and shows the needs for a future research agenda along with the statistical analysis with respect to different criteria.

Studies of related topics developed rapidly in the previous decade. Research interests have been expanded from CIA, vulnerability assessment, and risk assessment to adaptation strategies and other specific studies, including cost-benefit analysis, construction, and operation. We can foresee that there will be more studies in more specific topics. Except the mentioned categories, land use planning (Morel et al., 2013) and management issues (Lam et al., 2013; Burbidge, 2016) will be among the new areas of specific studies. Also, storming and wind impacts have not been assessed comprehensively due to the complexity of wind forecasting. So, this area also has a great potential for further analysis.

Compared to seaports, airports attract fewer or no studies on some research topics within the context of their adaptation to flooding and storming. Obviously, there is a high demand for relevant studies to be carried out to ensure the climate resilience of airports, probably by referencing the studies undertaken in seaports given their similarity and synergy. Furthermore, more seaport studies in postplanning operations are expected. From the evolution analysis of each research topic, the established solutions to date have so far been largely piecemeal, at the level of individual research topics, despite the fact that more and more studies start to combine multiple topics together. Integrating all the research topics, from both planning and postplanning perspectives for an integrated climate adaptation framework, is highly desirable but requires the support of creating new models and methods in each topic and a holistic mechanism to combine the supporting models and methods in a systematic manner.

Another relevant emerging research area is the connection between climate adaptation and emergency management, which was initiated by Akukwe and Ogbodo in 2015. Well-established research in emergency management and relief logistic (Mostafavi & Inman, 2016; Hong et al., 2015, 2013; Meng et al., 2017; Bozorgi-Amiri et al., 2013) can be combined with risk-based climate adaptation planning to enhance the resilience of seaports and airport individually or in a combined way.

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PAPER

The Increased Risk of Flooding in Hampton Roads: On the Roles of Sea Level Rise, Storm Surges, Hurricanes, and the Gulf Stream

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ABSTRACT

The impact of sea level rise on increased tidal flooding and storm surges in the Hampton Roads region is demonstrated, using ~90 years of water level measurements in Norfolk, Virginia. Impacts from offshore storms and variations in the Gulf Stream (GS) are discussed as well, in view of recent studies that show that weakening in the flow of the GS (daily, interannually, or decadal) is often related to elevated water levels along the U.S. East Coast. Two types of impacts from hurricanes on flooding in Hampton Roads are demonstrated here. One type is when a hurricane like Isabel (2003) makes a landfall and passes near the Chesapeake Bay, causing a large but short-term (hours to a day) storm surge. The second type is when Atlantic hurricanes like Joaquin (2015) or Matthew (2016) stay offshore for a relatively long time, disrupting the flow of the GS and leading to a longer period (several days or more) of higher water levels and tidal flooding. Analysis of the statistics of tropical storms and hurricanes since the 1970s shows that, since the 1990s, there is an increase in the number of days when intense hurricanes (Categories 3–5) are found in the subtropical western North Atlantic. The observed Florida Current transport since the 1980s often shows less transport and elevated water levels when tropical storms and hurricanes pass near the GS. Better understanding of the remote influence of the GS and offshore storms will improve future prediction of flooding and help mitigation and adaptation efforts.

Keywords: flooding, sea level, hurricanes, Gulf Stream

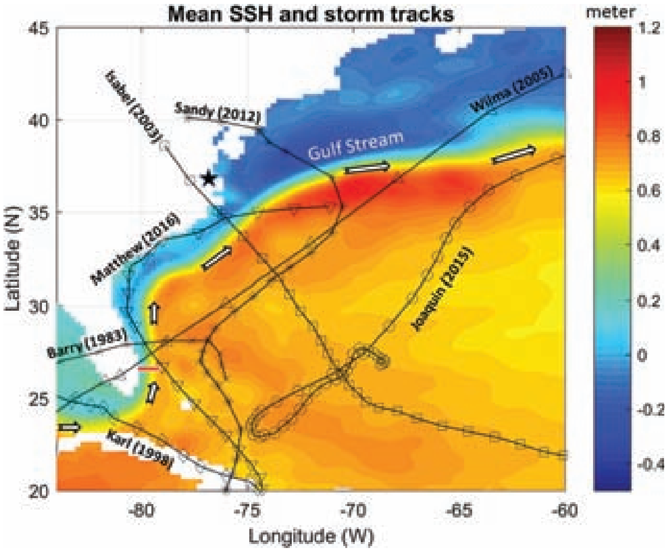
Introduction

The National Water Level Observation Network (NWLON) operated by National Oceanic and Atmospheric Administration (NOAA) (https://tidesandcurrents.noaa.gov/nwlon.html) provides an essential source of data to study both long-term sea level rise (SLR) and short-term water level variations and storm surges. These tide gauges data show that the rate of local SLR along some stretches of the U.S. East Coast (around the Chesapeake Bay and the Mid-Atlantic coast in particular) is much faster than the global SLR; this is mostly due to land subsidence (Boon, 2012; Mitchell et al., 2013; Ezer & Atkinson, 2015; Karegar et al., 2017), with a potential recent acceleration in SLR due to climatic slowdown of ocean circulation (Boon, 2012; Sallenger et al., 2012; Ezer & Corlett, 2012). Variations in wind patterns and atmospheric pressure (affecting sea level through the inverted barometer effect) can significantly contribute to coastal sea level variability along the U.S. East Coast (Piecuch et al., 2016; Woodworth et al., 2016), but these effects are outside the scope of this study.

Norfolk, VA, on the southern side of the Chesapeake Bay (see Figure 1 for its location), is a city that is already battling an acceleration in flooding frequency and intensity (Ezer & Atkinson, 2014, 2015; Sweet & Park, 2014). This study will focus on this city as an example that can apply to other coastal cities and communities in the Hampton Roads area, where efforts toward the development of options for adaptation, mitigation, and resilience to SLR have already been started (Considine et al., 2017; Yusuf & St. John, 2017). Local SLR in Norfolk from ~90 years of tide gauge records is ~4.6 mm/year (Ezer, 2013), but the rate is increasing (i.e., SLR is accelerating), so that the SLR over the last 30 years is ~5.9 mm/year compared to ~3.5 mm/year in the previous 30 years (Ezer & Atkinson, 2015); the recent local SLR is significantly larger than the global SLR obtained from satellite altimeter data, ~3.2 mm/year (Ezer, 2013). SLR can also escalate the damage from hurricanes, tropical storms, and nor'easters. When high sea level today is added to storm surges, weaker storms today

FIGURE 1

Mean sea surface height (SSH) from AVISO satellite altimeters are shown in color (in meters) and the location of the GS is indicated by white arrows. The location of the FC measurement across the Florida Strait is indicated by a red line, and the location of Norfolk, VA, is indicated by a black star. The tracks of several storms, discussed in the paper, are shown with markers representing the location of the eye of the storm every 6 h.



would cause as much flooding as much stronger past storms that happened when sea level was lower; this effect will be demonstrated here. There are some indications that warmer ocean waters may be related to an increase in the potential destructiveness of Atlantic hurricanes and tropical storms over the past 30 years (Emanuel, 2005). However, with strong interannual and decadal variability, finding a persistent trend in storm activities over the past century or predicting future changes in hurricane activities over the next century are challenging (Knutson & Tuleya, 2004; Vecchi & Knutson, 2008; Vecchi et al., 2008; Bender et al., 2010). Despite the difficulty of predicting the changes in the frequency and intensity of future storms, assessing the impact of SLR on storm surge is quite straightforward—if a storm with the same intensity and track that hit Norfolk 90 years ago were to come today, water level of a storm surge would be expected to be ~40 cm higher, and many more streets would be flooded. In addition to the impact of storm surges, Atlantic storms can also have an indirect impact on the coast by modifying ocean currents and causing more mixing. If such storms affect the Gulf Stream (GS), coastal sea level could be affected as well (Ezer & Atkinson, 2014, 2017; Ezer et al., 2017), and this indirect impact will be further investigated here. An additional indirect impact on coastal water level and coastal erosion is due to large swell from remote storms that can create wave runup (Dean et al., 2005). Impact from wave runup can, for example, increase coastal erosion of barrier islands and coasts along the Atlantic Ocean (Haluska, 2017). However, flooding in the Hampton Roads is not affected that much by waves and is mostly due to high water levels in the Chesapeake Bay and rivers (e.g., the Elizabeth River and the Lafayette River cause flooding in Norfolk).

The connection between the flow of the GS and sea level along the U.S. East Coast has been recognized early on from observations (Blaha, 1984) and models (Ezer, 2001), though due to the relatively short observed record of the GS identifying a persistent long-term trend in the GS transport is challenging (Ezer, 2015). Somewhat surprisingly, however, is the fact that this connection may be detected on a wide range of scales. On long-term decadal variability scales, for example, a potential climate-related slowdown of the Atlantic Meridional Overturning Circulation (AMOC) (Sallenger et al., 2012; McCarthy et al., 2012; Ezer et al., 2013; Ezer, 2013, 2015; Smeed et al., 2013; Srokosz & Bryden, 2015) may relate to accelerated SLR and increased risk of flooding along the U.S. East Coast (Boon, 2012; Ezer & Corlett, 2012; Sallenger et al., 2012; Mitchell et al., 2013; Yin & Goddard, 2013; Goddard et al., 2015; Ezer & Atkinson, 2014, 2015; Sweet & Park, 2014). On short-term time scales, there is now more evidence from data and models that even daily variations in the GS can cause variations in coastal sea level (Park & Sweet, 2015; Ezer, 2016; Ezer & Atkinson, 2017; Ezer et al., 2017; Wdowinski et al., 2016), including unexpected "clear-day" flooding (i.e., unusual tidal flooding with no apparent storm or local weather events). These variations in the GS can be due to natural variability and instability (Baringer & Larsen, 2001; Meinen et al., 2010) or variations in the wind pattern (Zhao & Johns, 2014), including impacts from tropical storms and hurricanes passing near the GS (Oey et al., 2007; Kourafalou et al., 2016; Ezer & Atkinson, 2017). Note that, on short-term scales, an important mechanism transferring large-scale oceanic signals onto the shelf may involve the generation of coastal-trapped waves (Huthnance, 2004; Ezer, 2016).

The mechanism that connects the GS and coastal sea level is as follows. The GS separates a lower sea level on its inshore side (blue in Figure 1) and a higher sea level on its offshore side (red in Figure 1). This sea level difference (~1 to 1.5 m) is proportional to the GS flow speed (i.e., the Geostrophic balance), so even a small and common daily change of say 10% in the GS flow may result in ~10 cm sea level change; in comparison, this amount of global SLR would occur over ~30 years. Therefore, a weakening in the GS flow is expected to raise coastal sea level and lower offshore sea level (the offshore impact has less important implications but can be detected from satellite altimeter data; Ezer et al., 2013).

In this paper, the latest research on various mechanisms that can cause flooding are summarized, using several data sets including tide gauge data, observations of the Florida Current (FC; the upstream portion of the GS, see Figure 1), and a data set of historical hurricanes and tropical storms.

Data Sources

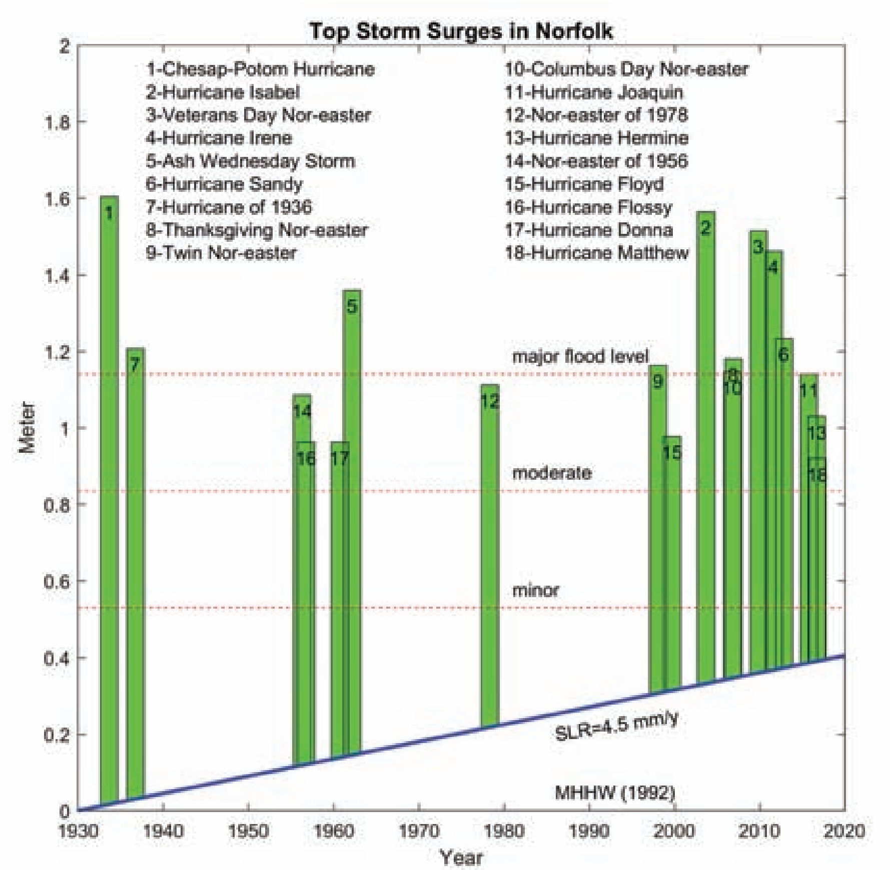
Hourly sea level records from tide gauge stations are available from NOAA (https://tidesandcurrents.noaa.gov/); here the focus is on the Sewells Point Station in Norfolk, VA (see star in Figure 1), which has the longest record in Hampton Roads. The estimated errors in measuring water level anomalies (say during a storm surge) are around ±5–10 cm. As a reference water level, the mean higher high water (MHHW) from the datum centered on 1992 is used. The definitions of minor (often called "nuisance"), moderate, and major flood levels relative to MHHW are consistent with NOAA's reports and recent studies of flooding (Ezer & Atkinson, 2014; Sweet & Park, 2014).

The daily FC transport from cable measurements across the Florida Strait at 27°N (Baringer & Larsen, 2001; Meinen et al., 2010) is obtained from the NOAA/Atlantic Oceanographic and Meteorological Laboratory website (http://www.aoml.noaa.gov/phod/floridacurrent/); see the location in Figure 1. Estimated errors are ±1.6 Sv (1 Sv = million cubic meter per second) with a mean transport of ~32 Sv. The data include the periods 1982–1998 and 2000–2016, with a gap of 2 years.

The Atlantic hurricane and tropical storm data set HURDAT2 (Landsea et al., 2004; Landsea & Franklin, 2013) is available from NOAA's National Hurricane Center (http://www.nhc.noaa.gov/). It provides the track data every 6 h for storms in 1851–2016, but only data since the satellite age from the 1970s are used here.

FIGURE 2

The maximum water level at Sewells Point (Norfolk, VA) relative to the MHHW (1992 datum) for the major storms passing the region. The impact of SLR relative to 1930 is demonstrated using the average rate of that period. Also shown in horizontal dashed lines are the estimated levels of minor (0.53 m), moderate (0.835 m), and major (1.14 m) flood levels in Norfolk.



Surface currents during hurricanes are obtained from NOAA's coupled operational Hurricane Weather Research and Forecasting model (Yablonsky et al., 2015; Tallapragada, 2016). The atmospheric model is coupled with the Princeton Ocean Model, which has horizontal resolution of 7–9 km and 23 vertical terrain-following layers with higher resolution near the surface; the model domain covers the western North Atlantic Ocean (10°N–47.5°N, 30°W–100° W). A recent study (Ezer et al., 2017) used this model to evaluate the impact of hurricane Matthew (2015).

The mean sea surface height in Figure 1 is obtained from the AVISO satellite altimetry data set that combines several available satellites; the data are now distributed by the Copernicus system (http://marine.copernicus.eu/). For comparisons between tide gauge and altimeter sea level data in the region, see Ezer (2013).

Results

The Impact of SLR on Flooding in Hampton Roads

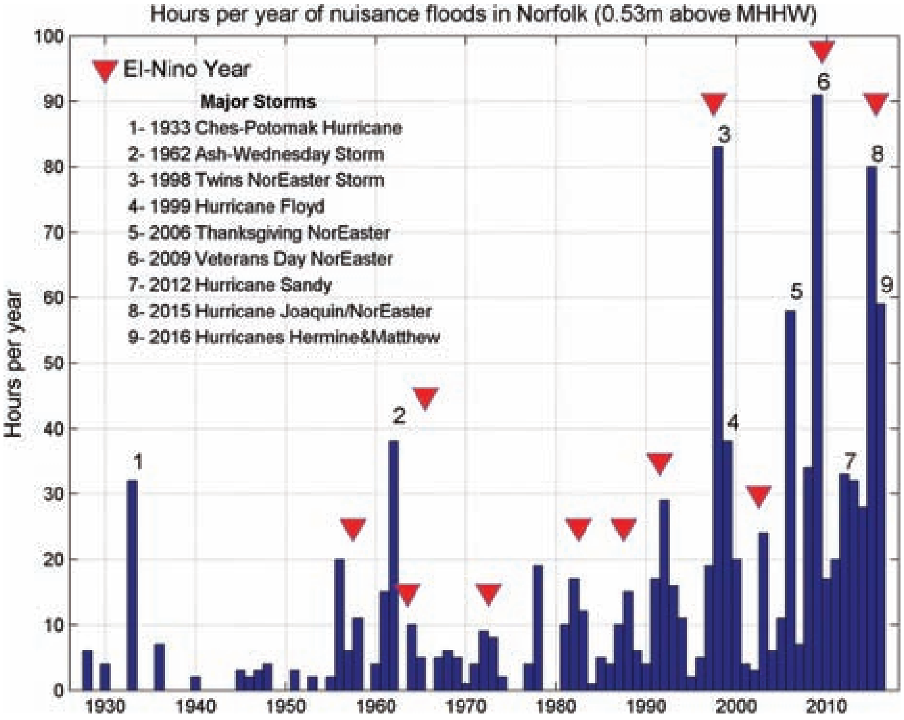
Figure 2 shows the maximum water level (relative to MHHW) that has been reached in Sewells Point (Norfolk, VA) during the major storms that affected the region since recording started in 1927 (the highest recorded storm surge was during the hurricane of 1933). To illustrate how much SLR would affect storm surges over the years, an average rate of 4.5 mm/year (Ezer, 2013) is shown relative to 1930. For example, if the 1933's hurricane happened today, water level would reach ~2 m, with unprecedented level of flooding and damage. Note the cluster of storms of the past two decades compared with the infrequent past storm surges. This may be partly due to decadal variations in storms but most likely is the result of SLR, as smaller storms plus SLR can have similar impacts as larger past storms. The frequency of minor flooding is also greatly affected by SLR. For example, if a storm surge of say 0.6 m caused some minor flooding in the 1930s, an equivalent flooding would occur today with just ~0.2 m water level over MHHW, so that even a slightly higher than normal tide would be enough to cause inundation without any storm. This is illustrated by the dramatic increase in the hours of minor flooding in Norfolk (Figure 3). Other cities have similar acceleration in flooding hours (Ezer & Atkinson, 2014; Sweet & Park, 2014). Note that seven of the top nine most flooded years happened since 1998. In addition to the clear impact of SLR and storms, there are interannual and decadal variations associated with more stormy years during El Niño and years with low North Atlantic Oscillation index or a weak AMOC (Ezer & Atkinson, 2014; Goddard et al., 2015). The main reason for the large increase in flood hours is that past floods occurred mostly for short periods of a few hours to a day or so during the passage of strong storms. Today, we often see longer flooding periods that occur for several tidal cycles, sometimes even without any storm in sight, but these are possibly due to a weakening GS or an offshore storm (see discussion later).

Examples of the Impact of Hurricanes on Flooding in Hampton Roads

There are three ways in which storms (tropical storms, hurricanes,

FIGURE 3

The number of hours per year that water level in Norfolk is at least 0.53 m above MHHW; this level corresponds to minor street flooding (also known as nuisance flooding). Major storms in the most flooded years are listed, as well as indication (red triangles) of years with El Niño.



or winter nor'easters) can cause flooding in Norfolk (and in other coastal cities): (1) Storm surges resulting from the direct impact of the low atmospheric pressure, winds, and waves; in this case, the storm piles up water against the coast or pushes water into the Chesapeake Bay and the Elizabeth River. (2) Indirect impacts from offshore storms that do not make landfall and do not pass near Norfolk; in this case, examples are storms that impact ocean currents like the GS (see discussion later). (3) Street flooding due to intense precipitation associated with the storm. Note that in many cases several of these mechanisms can apply simultaneously.

An example of Case 1 was Hurricane Isabel (2003), which resulted in the second higher water level ever recorded in Norfolk (Figure 2). This hurricane made landfall near Cape Hatteras, NC, and moved northwest south of the Chesapeake Bay (Figure 1). Wind gusts of ~30 m/s near Norfolk (Figure 4b) caused a large storm surge that lasted a few hours (Figure 4a); fortunately, the storm passed during the Neap tide period, so the addition of the high tide was minimal. An example of Case 2 is Hurricane Joaquin (2015), which looped in the South Atlantic Bight and stayed offshore for a long time without ever making a landfall (Figure 1). However, the storm winds disturbed the flow of the GS (winds west of the storm blowing southward against the GS flow), as seen in the low transport of the FC (blue line; Days 270 and 280 in Figure 5b). Because of the GS-coastal sea level relation discussed before (Ezer, 2016; Ezer & Atkinson, 2017; Ezer et al., 2017), sea level rose (red line in Figure 5b) when GS transport dropped, causing a couple of weeks with flooding in Norfolk almost every high tide (Figure 5a). An example of Case 3 is the impact of Hurricane Matthew (October 2016; see its track in Figure 1) on flooding in the Hampton Roads area (http://wavy.com/2016/10/08/deadly-hurricane-matthew-soaks-hampton-roads-north-carolina/). When elevated water levels were combined with enormous amount of rain, streets could not drain and stayed flooded for a long period of time (in other regions along the South Carolina coast direct storm surge was a major factor in the flooding). The disturbance that Matthew caused to the flow of the

FIGURE 4

Example of (a) water level and (b) wind in Sewells Point (Norfolk, VA) during hurricane Isabel in September 2003 (see Figure 1 for the track). Blue and green lines in (a) are for tidal prediction and observed water level (in meter relative to MHHW), respectively; blue and red lines in (b) are for mean wind and gusts (in m/s), respectively. Data plots obtained from NOAA NWLON Station at Sewells Point (https://tidesandcurrents.noaa.gov/nwlon.html).

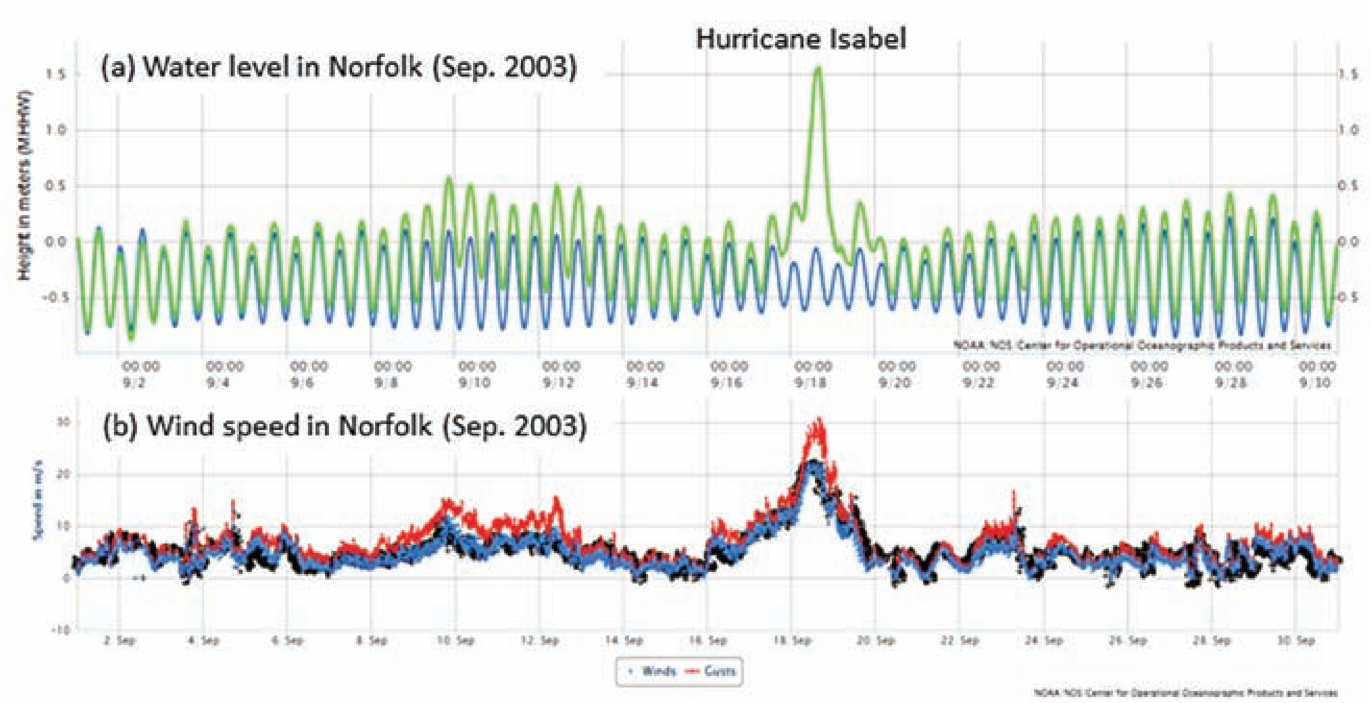
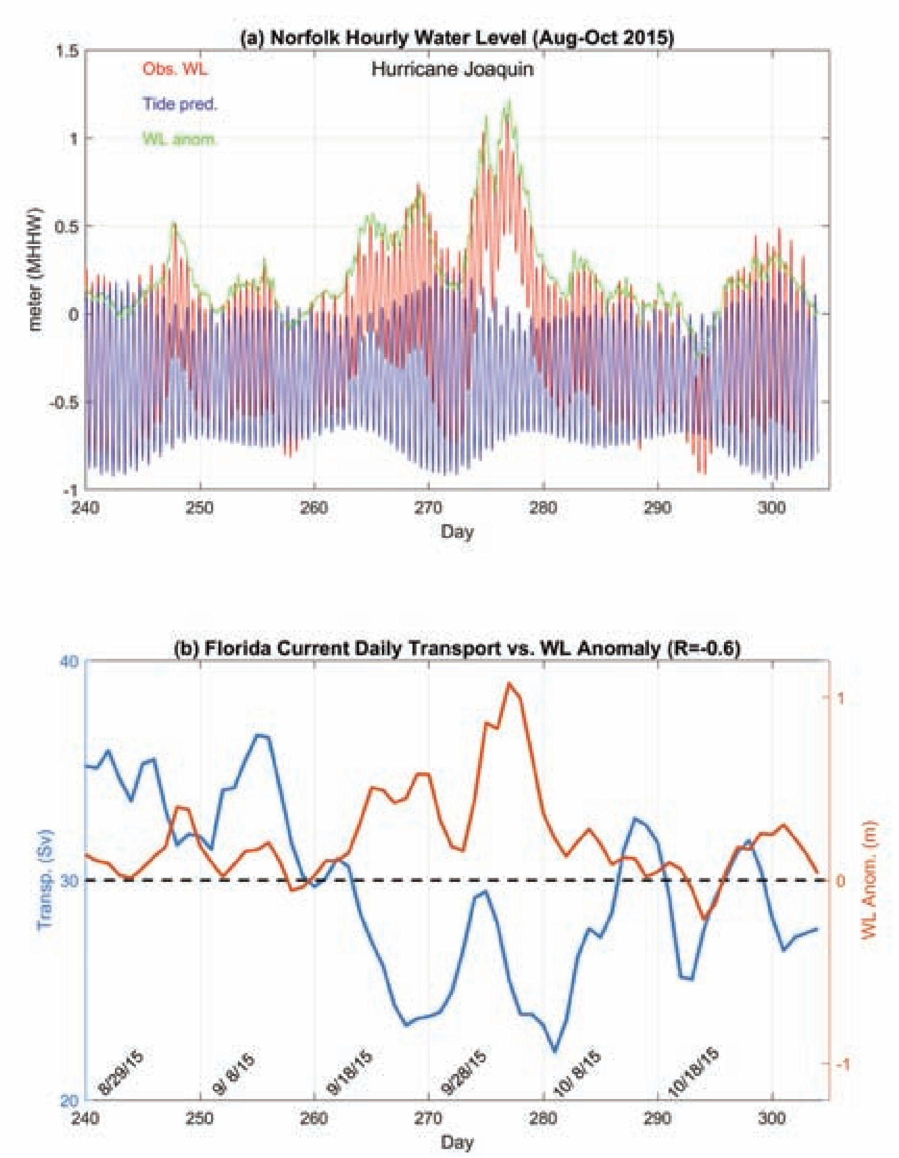


FIGURE 5

(a) Hourly observed water level (red) tidal prediction (blue) and residual anomaly (green) in Norfolk from late August to late October 2015, when Hurricane Joaquin was offshore the Atlantic coast (see Figure 1 for the track). (b) Daily FC transport (blue in Sv, 1 Sv = 10^6 m^3/s) and water level anomaly (red in meter).



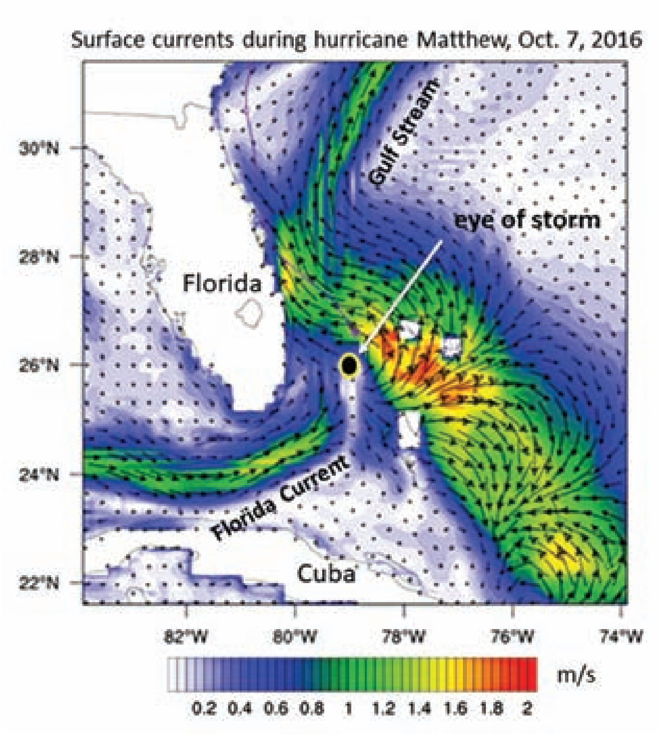
GS can be seen in Figure 6, from an operational atmosphere-ocean forecast model. When the eye of the storm was near the coast of south Florida, the storm broke the path of the flow, separating the FC exiting the Gulf of Mexico from the downstream GS. For more details on the impact of hurricane Matthew, see the recent study of Ezer et al. (2017). In the next section, analysis of many other storms will be examined to detect those that may have affected the GS.

The Impact of Tropical Storms and Hurricanes on the FC

Anecdotal examples of hurricanes affecting the GS (and its upstream portion, the FC) have been discussed above, so here a more quantitative approach is taken by analyzing the HURDAT2 data set of Atlantic hurricanes and tropical storms. The data set starts from the middle 1800s using ship observations and later satellite-based data (Landsea et al., 2004). Here, only the data from the satellite era (1970–2016), which are more reliable, were considered. From the 6-hourly records of storms' location and strength, the number of days per year when storms of different categories are found in the region 60°W–85°W and 20°N–40°N were calculated, and the distribution is shown in Figure 7. Many tropical storms and hurricanes that affect the U.S. East Coast pass through this region of the subtropical western North Atlantic, and the cyclonic oriented wind there can influence both the subtropical gyre flow and the GS. Sensitivity experiments with subtropical regions slightly different than that chosen above (not shown) yield very similar trends. Note that, instead of counting individual storms, the annual sum can include multiple counts of the same storm, so that storms that last longer have more weight than short-lived storms. The results appear to show that since the 1990s there is an increase in the occurrence of hurricanes in this region. For example, before 1995 no year had more than 10 days of Category 1–2 hurricanes or more than 3 days of Category 3–5 hurricanes in this region. However, since 1995 there were 8 years with more than 10 days of Category 1–2 hurricanes and 12 years with more than 3 days of Category 3–5 hurricanes. In other words, since 1995, there is over 50% chance that the strongest hurricanes (Categories 3–5) will be found in this region for at least 3 days (though only few of them will make landfall). Further statistical

FIGURE 6

Example of surface currents on October 7, 2016, when Hurricane Matthew was near the south Florida coast (the eye of the storm is indicated by a circle). The simulations are from NOAA's Hurricane Weather Research and Forecasting operational coupled ocean-atmosphere forecast system. See Figure 1 for the complete track of the storm.



analysis of Atlantic hurricanes as done before (Landsea et al., 2004; Vecchi & Knutson, 2008; Vecchi et al., 2008, and others) is beyond the scope of this study, which will focus on potential influence of the storms on the GS.

The daily transport of the FC has been measured by a cable across the Florida Straits since 1982 (with a large gap October 1998–June 2000 and a few smaller gaps; see Meinen et al., 2010). To evaluate if unusual transports are observed during the passage of storms, a subset of the cable data is created for only those days when storms are found in the region (as in Figure 7). Two properties are evaluated for these "stormy" days, the FC daily transport (Figure 8a) and the FC daily transport change (Figure 8b). The transport change is simply the daily change in transport from the observed transport of the previous day. Previous studies show that variations in coastal sea level are correlated with both the GS/FC transport and transport change (Ezer et al., 2013; Ezer & Atkinson, 2014, 2017). During "stormy" days, the FC transport can change significantly by as much as 5–8 Sv/day (see storms with significant impact in Figure 8b). For example, when Hurricane Matthew (2016) moved along the coast (Figure 1), the FC transport declined from ~35 Sv to ~20 Sv (last column of "x"s in Figure 8a) and the maximum daily decline was ~5 Sv (Figure 8b). For more analysis of the impact of Matthew, see Ezer et al. (2017).

The track of a hurricane relative to the location of the GS/FC can make a significant difference in the impact. For example, hurricanes that caused a large daily transport decline (Figure 8b), like Barry (1983), Karl (1998), and

FIGURE 7

The annual occurrence of tropical storms and hurricanes in the subtropical western North Atlantic region 60°W–85°W and 20°N–40°N during 1970–2016. For each year, the number of days when tropical storms or hurricanes are found in the above region are calculated according to three storm categories: tropical storms in blue (maximum wind $W_{max} < 33$ m/s), hurricanes Categories 1–2 in green (33 m/s $< W_{max} < 50$) and hurricanes Categories 3–5 in red (50 m/s $< W_{max}$).

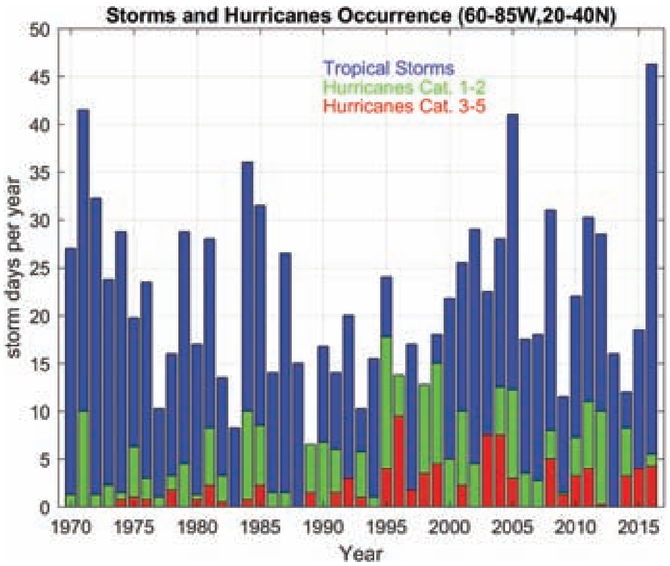
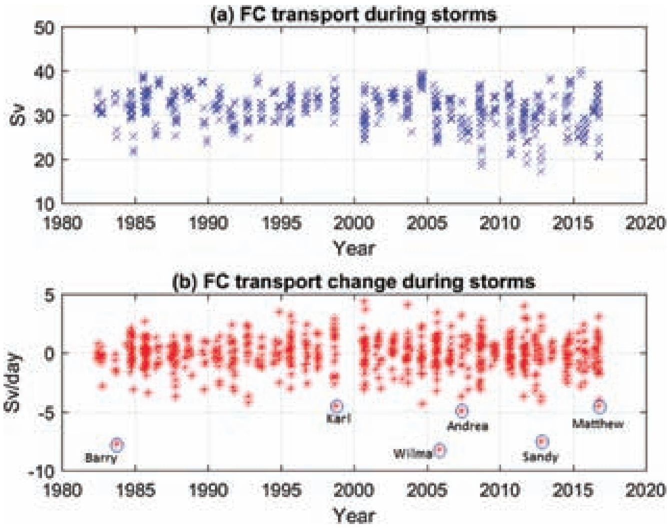


FIGURE 8

(a) FC transport (blue in Sv) and (b) transport change (red in Sv/day) during the time that a tropical storm or hurricane was recorded in the same region as in Figure 7. Each marker represents a day in which a storm was found in the region; some of the storms that caused the most decline in the FC transport are indicated in (b) and discussed in the text.



Wilma (2005), moved fast exactly over the FC not far from the Florida Strait (see their track in Figure 1). However, their influence on water level in Norfolk was minimal compared with hurricanes like Sandy (2012) or Matthew (2016), which moved slowly along the GS path (Figure 1) with enough time to influence the GS and coastal sea level.

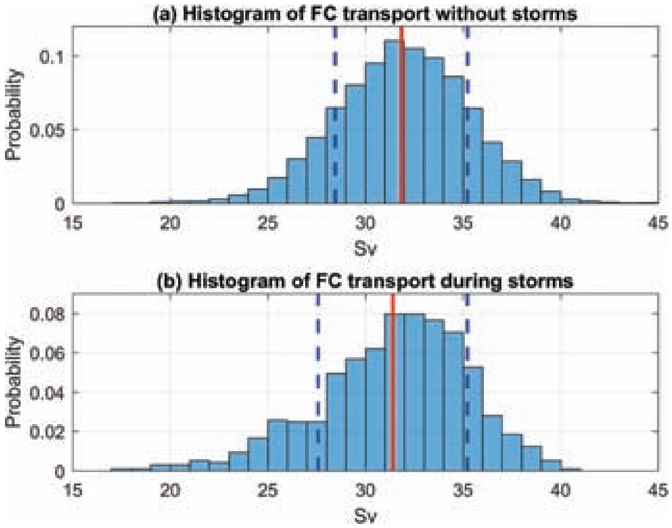
To look at the total impact of storms on the FC transport in a more quantitative way, the histogram of the FC transport for all the days without storms (Figure 9a) is compared with the histogram during days with storms (Figure 9b). Although the daily transport distribution looks Gaussian and symmetric around the mean during days with no storms, it is clearly asymmetrical with a lower mean flow and skewed probability toward low transports during storms (i.e., a longer "tail" of the distribution toward the left). Note that Figure 9a ("without storms") excludes days with tropical storms and hurricanes but may include other extratropical or winter storms that are absent from the HURDAT data set. This result confirms anecdotal observations (Ezer & Atkinson, 2014, 2017; Ezer et al., 2017) that storms can disturb the flow of the GS and thus in most cases increase the likelihood of weaker than normal GS—this weakening further contributes to higher than normal coastal sea level during particular periods. Ezer et al. (2017) showed, using satellite altimeter data, high-frequency radar data and models that, after an intense mixing of the GS water by a nearby storm, may take a few days for the current to recover. During those days, anomalously high water can be observed along the U.S. East Coast and minor tidal flooding increased as well.

Summary and Conclusions

The impact of the fast rate of local SLR in the mid-Atlantic region (Boon 2012; Sallenger et al., 2012; Ezer & Corlett, 2012; Ezer, 2013) has already been felt in the acceleration of flooding in low-lying cities like Norfolk,

FIGURE 9

Histogram of FC transport 1982–2016 for (a) all the days without hurricanes or storms and (b) days with recorded hurricanes or storms in the same region as in Figure 7. Red and blue vertical lines represent the mean and the standard deviation, respectively.



VA, and other coastal communities along the U.S. East Coast (Mitchell et al., 2013; Ezer & Atkinson 2014, 2015, 2017; Sweet & Park, 2014). Both minor tidal floodings and major storm surge floodings have significantly increased in recent decades, as demonstrated here for Norfolk.

This report discusses the different mechanisms that contribute to the increased flooding. Some mechanisms are quite straightforward; for example, it is easy to understand how SLR or increases in storms frequency or intensity would result in more flooding and a greater risk of damages to flooded properties. However, other mechanisms are more complicated; for example, floods associated with nonlocal factors such as offshore variations in the GS (other remote influences such as westward-propagating planetary waves, climatic variations in the North Atlantic Ocean, or variations in wind and pressure patterns were discussed in other studies). This study follows on the footsteps of recent studies that showed a connection between short-term weakening in the FC/GS transport and elevated coastal sea level (Ezer, 2016; Ezer & Atkinson, 2014, 2015, 2017; Ezer et al., 2017; Wdowinski et al., 2016), but here the analysis includes for the first time an attempt to evaluate the impact on the GS from all the hurricanes and tropical storms that passed through the region over the past few decades. There is some indication that the most intense hurricanes (Categories 3–5) can be found more often near the subtropical western North Atlantic region, which is consistent with some other studies that suggest that warmer waters would cause an increase in the destructiveness of Atlantic hurricanes (Emanuel, 2005; Holland & Bruyère, 2014). The consequence is that, due to warmer Atlantic waters, hurricanes may be able to sustain their intensity longer if they stay offshore (e.g., Hurricanes Joaquin, Matthew, and other recent storms) and thus may have larger impact on the GS. It was found that hurricanes that moved across the GS path or stayed in its vicinity long enough are indeed those that have the largest impact on the GS. This indirect impact of offshore storms that sometimes do not even make landfall can result in several days of elevated water levels and tidal flooding, until the GS recovers and returns to its normal variability (Ezer et al., 2017). When combined with storm-induced rain, these elevated water levels prevent proper draining of flooded streets and lengthening the impact, as was the case in the Hampton Roads during Hurricane Matthew (2016). This remote impact from storms and hurricanes is more long-lasting than cases of storm surges near the landfall area that can result in higher water levels but shorter-term impact of only a few hours, as was the case of Hurricane Isabel (2003).

Analysis of the FC transport since the 1980s suggests that the impact of tropical storms and hurricanes on the GS is not only detectable in a few isolated cases but has a significant signature in the long-term statistics of the flow variability. Therefore, during the time of the year when tropical storms are active, there is a greater probability of weaker than normal FC and higher than normal coastal sea level. Since remote/indirect forcing of coastal sea level variability is not easily accounted for in storm surge models, studies of this type can help to better understand the mechanisms involved and improve water level prediction.

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PAPER

Participatory GIS as a Tool for Stakeholder Engagement in Building Resilience to Sea Level Rise: A Demonstration Project

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ABSTRACT

This article describes a participatory geographical information system (PGIS) demonstration project used as part of the stakeholder engagement efforts undertaken by the Citizen Engagement Working Group of the Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Planning Pilot Project. The PGIS demonstration project was conducted in the Little Creek/Pretty Lake case study area in the Hampton Roads region of southeastern coastal Virginia. PGIS served as a deliberative and participatory mechanism to obtain local knowledge from residents about the location of valued assets within the community and locations challenged by increased flooding and sea level rise. The PGIS application, using the weTable tool, was found to be useful for soliciting and documenting local knowledge, such as by highlighting community assets and identifying community challenges. It was also found to be useful for facilitating community-wide discussion, visualizing the problem, and understanding the severity of sea level rise and flooding. The PGIS demonstration project showed how participatory mapping can directly engage residents in creating sociospatial data, build knowledge, and foster learning and deliberation in a complex issue such as resilience to flooding and sea level rise.

Keywords: Participatory mapping, weTable, Hampton Roads, sea level rise planning, whole-of-community

Introduction

The Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Planning Pilot Project (the Pilot Project) was a 2-year effort to identify and develop a "whole-of-government" and "whole-of-community" governance structure for holistic sea level rise and resilience planning in the Hampton Roads region of coastal Virginia. The Pilot Project was convened by Old Dominion University and led by a Steering Committee comprising influential leaders at multiple levels of government and from multiple sectors (such as business, nonprofits, and community organizations). The Pilot Project was structured along five working groups: a Legal Working Group, Infrastructure Working Group, Land Use Planning Working Group, Citizen Engagement Working Group, and Public Health Working Group.

This article focuses on the stakeholder engagement efforts of the Pilot Project, undertaken by the Citizen Engagement Working Group, utilizing a participatory geographical information system (PGIS) approach to solicit and codify residents' perspectives on community assets and to help residents assess how these assets and the communities they are embedded in are challenged and impacted by sea level rise and flooding. Regarding the latter, PGIS simultaneously promoted social learning among participating residents by providing an interactive mechanism for collaborative, joint learning about sea level rise and flooding, information exchange, and discussion and analysis of issues associated with building resilience.

Governments, businesses, and residents must work together to build resilience to sea level rise in a collaborative approach that spans multiple sectors and jurisdictional boundaries (Adger et al., 2005). Understanding the actual capacity of communities, businesses, and public institutions to respond and adapt to issues like sea level rise is critical (Moser, 2010), and a multisectoral approach is necessary for responding to sea level rise in an integrated way and for pursuing innovative solutions to more effectively adapt to sea level rise.

Such a multisectoral approach is consistent with the whole-of-community framework that underpins the Pilot Project. This approach emphasizes the involvement of a wide range of stakeholders beyond those in the governmental sector, such as those associated with businesses, nonprofit or nongovernmental organizations, academic institutions, faith-based institutions, communities, families, and individuals. Stakeholder engagement is crucial given a whole-of-community framework, and for the Pilot Project there was an explicit need to engage members of the community in a discussion of flooding, sea level rise, adaptation, and resilience.

The Pilot Project Phase 1 Report explicitly noted that "both community education and input are vital components of resiliency in Hampton Roads" (Steinhilber et al., 2015, p. 9). In the same vein, the Citizen Engagement Working Group highlighted the need to identify or develop strategies for effective two-way engagement with residents on the issue of resilience to flooding and sea level rise (Steinhilber et al., 2015). This emphasis on community engagement was not unique to the work of the Citizen Engagement Work Group, as the Infrastructure Working Group also emphasized in its findings "the importance of community planning and managing the perception of the community" (Steinhilber et al., 2016, p. 31).

Citizen Engagement, Participatory Mapping, and PGIS

There has been increasing emphasis on incorporating citizen engagement into governing (United Nations, 2014). For example, the United Nations Framework Convention on Climate Change (United Nations, 1992) called on countries to implement educational and public awareness programs, provide the public with access to information, and seek public participation in addressing climate change and its effects.

Environmental issues such as those related to climate change and sea level rise, however, are often considered too difficult to be understood by the average community member (Crow & Stevens, 2012; Fischer, 2000) and thought to be best left in the hands of experts and scientists (Rowe & Frewer, 2000). Nevertheless, there is also broad support for the need to improve public understanding of complex environmental issues such as sea level rise (Bord et al., 2000; Brown & Donovan, 2014; Crow & Stevens, 2012; Dickinson et al., 2012; Nisbet, 2009; Whitmarsh et al., 2013). Such public understanding, in turn, is an important precursor for public participation in environmental decision-making. Different engagement approaches have been suggested and used for various environmental issues. Participatory mapping is one category of techniques that has risen in popularity over the last three decades. GIS technologies have been widely used to support participatory mapping applications in environmental issues (Al-Kodmany, 2002; González et al., 2008; Jordan & Shrestha, 2000; Kingston et al., 2000) such as through PGIS. These concepts will be discussed next.

Participatory Mapping

Participatory mapping is defined as any process where individuals, especially local participants, share in the creation of spatial data such as a map (Goodchild, 2007). According to Levine and Feinholz (2015), participatory mapping has played a key role in obtaining critical sociospatial data that are relevant to ecosystem-based planning and management. As such, it is an important tool for helping to situate local observations in the wider geographic context, exploring the human dimensions of coastal management, and examining local participants' perspectives and priorities (Joyce & Canessa, 2009).

For environmental management and monitoring issues, local users can be the best sources of detailed information that is generally lacking in traditional monitoring data (Levine & Feinholz, 2015). Participatory mapping puts human experiences into a spatial context and is a process-driven, vibrant, and vital way of knowing that fosters deliberation on complex issues (Tschakert et al., 2016). The mapping process is considered more important than the resulting map itself because it provides an opportunity for participants to meet and engage with each other in new ways, learn from each other, and share concerns held by different stakeholders (Levine & Feinholz, 2015).

Participatory mapping has been used in monitoring, reporting, and verifying environmental policies and problems, including applications in the areas of environmental degradation (Agyemang et al., 2007; Chagumaira et al., 2016), marine and coastal ecosystem management (Andrade & Szlafsztein, 2015; Frazier et al., 2010), marine spatial planning (Stelzenmüller et al., 2013), disaster management (Gaillard & Pangilinan, 2010; Kaul & Thornton, 2014; Levine & Feinholz, 2015; Villagra et al., 2014), and sustainable management of natural resources (Lubis & Langston, 2015).

The benefits of using participatory mapping for building resilience include introducing new and varied perspectives, creating usable information, promoting active learning, and surfacing unexamined assumptions. By having stakeholders collectively define the problem and identify possible solutions and strategies, it also allows for the coproduction of practice- and policy-relevant knowledge that is grounded in stakeholder values and the local context, enabling the design of adaptation processes with context-specific information (Fazey et al., 2010; Few et al., 2007; Preston et al., 2011). This is particularly relevant when the problem and solutions span multiple jurisdictions and affect various agencies, organizations, and communities.

PGIS

Technological advancements have made GIS increasingly accessible to ordinary citizens (Ganapati, 2011). Because of decreasing computing costs, low-cost GPS technology, and open data access over the Internet, GIS has become more widely used in community initiatives. The integration of GIS technology and community initiatives has led to PGIS that uses geospatial information as a vehicle for interaction, discussion, and analysis in support of advocacy and decision-making (Corbett et al., 2006).

PGIS developed out of participatory approaches that combined a range of geospatial information management tools and methods to represent participants' spatial knowledge, either virtual or physical, using two- or three-dimensional maps. These maps are used as interactive mechanisms for spatial learning, information exchange, discussion and analysis, and ultimately decision-making and advocacy (Rambaldi et al., 2006). Through PGIS, mapping exercises are carried out with local stakeholders to document local spatial knowledge (Baldwin et al., 2013). The mapping exercise can be carried out with individuals or small groups using semistructured or nonstructured interviews (see, e.g., Asare-Kyei et al., 2015; Baldwin et al., 2013; Pozzebon et al., 2015), during formal or informal meetings or focus groups (see, e.g., Bracken et al., 2016; Cinderby et al., 2008), using brainstorming sessions (see, e.g., McBride et al., 2017), or even by recording oral history (see, e.g., Cullen, 2015).

Often the first round of the PGIS mapping exercise is used to create a base map and later iterations of mapping exercises are used to add details such as identifying the distribution of resources and areas of interest or threat (Baldwin et al., 2013; Cullen, 2015). In other examples, the first mapping cycle can be aimed at identifying the preexisting concerns or historical occurrence of events such as floods, and the second iteration at identifying where solutions must be implemented (Bracken et al., 2016). The initial base maps can also be created in advance of the PGIS mapping exercise using existing aerial and spatial data and then further refined using local input (Sletto et al., 2010).

Some PGIS applications use validation exercises with the wider community to refine and finalize the map (Bracken et al., 2016; Cinderby et al., 2008; Sletto et al., 2010). This stage of PGIS may address issues such as relevant geospatial data types (e.g., ArcGIS, Google Earth) or visualization techniques such as color intensity; supplementary products (e.g., atlases/maps, reports, DVDs) and means of accessing resulting data (Baldwin et al., 2013; Cinderby et al., 2008). The final stage involves use of the PGIS products for evaluation and assessments, including to assess coastal vulnerability, identify areas of concern for planning or environmental protection, and obtain stakeholders' evaluation about the PGIS process and products (Baldwin et al., 2013; Cinderby et al., 2008; Cullen, 2015; Jordan & Shrestha, 2000).

PGIS has been used globally, in locales ranging from the Caribbean Islands (Baldwin et al., 2013; Baldwin & Oxenford, 2014; Sletto et al., 2010) to Africa (Asare-Kyei et al., 2015), to the United Kingdom (Bracken et al., 2016; Cinderby et al., 2008), and to the United States (Brehme et al., 2015; McBride et al., 2017). For example, PGIS has been applied to address issues such as effective transboundary marine resource governance (Baldwin et al., 2013), mapping marine habitats (Baldwin & Oxenford, 2014), validating community level flood hazard maps (Asare-Kyei et al., 2015), and coastal planning (Brehme et al., 2015). Across different applications, PGIS has been found to be effective at coproducing knowledge by eliciting high-quality local experiential information compatible with experts' knowledge and for generating spatial products that are understood by locals, while simultaneously promoting learning and capacity building to access and use information produced by a variety of users and decision makers (Torres et al., 2014; Baldwin & Oxenford, 2014; Bracken et al., 2016; Cinderby et al., 2008; Cullen, 2015; McBride et al., 2017; Rambaldi et al., 2006; Young & Gilmore, 2013).

The Pilot Project Citizen Engagement Working Group

The Pilot Project Citizen Engagement Working Group had several objectives, one of which was to develop engagement and communications strategies that enhanced the capacity of Hampton Roads communities to (a) plan for flooding emergencies, (b) prepare for sea level rise contingencies, and (c) strengthen social capital and resilience (Steinhilber et al., 2016). To incorporate a whole-of-community framework into the Pilot Project, the Citizen Engagement Working Group focused its efforts on engaging local residents in addressing issues of sea level rise, adaptation, and resilience.

Adapting to and building resilience for sea level rise requires stakeholder engagement processes that help communities reduce their risks by identifying threats to not only human life and personal property but also to the social fabric of the community. Understanding how residents perceive threats and prioritize their concerns so that communities can respond appropriately is an important part of building resilience. The Pilot Project Citizen Engagement Working Group was driven by the understanding that (a) involving citizens and other stakeholders would improve the quality of information, expand the range of adaptation and resilience solutions, and enhance public support for potential solutions and (b) doing so simultaneously improves the community's capacity to adapt and be resilient, as social learning changes the way residents understand and engage with their environment.

Case Study Area and Demonstration Project

The Citizen Engagement Working Group utilized the Little Creek/Pretty Lake area of Norfolk and Virginia Beach as a case study area to conduct a demonstration project using PGIS as a stakeholder engagement tool for incorporating local knowledge into an assessment of risks from flooding and sea level rise. The Little Creek/Pretty Lake case study area was selected because its ecological boundaries extend across two municipalities (the cities of Norfolk and Virginia Beach) and a federal military installation (Joint Expeditionary Base Little Creek–Fort Story).

The City of Norfolk has two watersheds that drain into the Little Creek/Pretty Lake case study area. The Lake Whitehurst watershed drains approximately 4.5 square miles of area and contains one of Norfolk's 11 fresh water reservoirs and the Pretty Lake watershed drains approximately 4 square miles of area. On the Virginia Beach side, the Little Creek watershed, which contains Lake Lawson and Lake Smith, drains approximately 8.1 square miles of area into the case study area. The Joint Expeditionary Base Little Creek–Fort Story is located near the center of the Pretty Lake/Little Creek case study area and adjacent to the inlet of the system to the Chesapeake Bay, covering approximately 3.3 square miles.

PGIS Demonstration Project

The Citizen Engagement Working Group utilized the Action-Oriented Stakeholder Engagement for a Resilient Tomorrow (ASERT) framework, which was developed by Old Dominion University researchers as an approach to facilitate the engagement of stakeholders from across multiple sectors in building resilience (Considine et al., 2017). The ASERT framework emphasizes the presentation of relevant and accessible information, coupled with the use of two-way communication and deliberative and participatory mechanisms. The deliberative and participatory components of the ASERT framework build on the Structured Public Involvement approach that has been applied in high-conflict decision-making contexts such as environmental and transportation planning (Bailey et al., 2002, 2007, 2011).

The ASERT framework was operationalized through a demonstration project in the Little Creek/Pretty Lake case study area. The demonstration project used PGIS as a deliberative and participatory mechanism to obtain local knowledge from residents about the location of valued assets within the community and locations challenged by increased flooding and sea level rise. The purpose of PGIS was to solicit and codify residents' perspectives on community assets and to help residents assess how these assets and the communities they are embedded in are challenged and impacted by sea level rise and flooding. Information collected through PGIS could be used to inform decision-making by providing context-specific local knowledge. However, for the demonstration project, the goal was to apply PGIS as an engagement and data collection tool and to assess the usefulness of the tool. The sociospatial data collected through the PGIS exercise was shared with local decision makers, but the PGIS exercise was not embedded in any formal decision-making process.

For the PGIS application, the demonstration project team used the weTable tool (Messmore, 2013; Mikulencak & Jacob, 2011) for (a) identification of community assets and challenges and (b) visualization of the flooding impacts of sea level rise. The weTable served as the platform to present maps and geospatial data representing the physical features of the community and the impacts of coastal inundation due to sea level rise and/or storm surge. The geospatial data highlighted the impacts of flooding, such as on critical infrastructure and personal safety, and provided the starting point for residents to identify vulnerabilities to sea level rise and flooding. As shown in Figure 1, the weTable uses Nintendo Wii technology to create an interactive tabletop that allows participants to simultaneously visualize sea level rise scenarios while collaboratively exploring and identifying assets and vulnerabilities. A laptop computer with GIS software is connected to a projector and Nintendo Wii remote. The computer screen showing the GIS software is projected onto a tabletop surface. Participants interact with GIS map using a light pen connected via Bluetooth to the laptop via the Nintendo Wii remote.

A key function of the weTable exercise is to focus participants' attention to sea level rise and coastal flooding by using maps to visually convey the extent of the impacts. Such visualization promotes individual and group understanding because it provides shared references and objects to talk and think about and use as a basis for coordinating actions and perspectives, moving from individual perceptions to a shared perception (Aggett & McColl, 2006; MacEachren & Brewer, 2004). Participants used the weTable to interact with maps to analyze risks and vulnerabilities; for example, indicating specific areas that might be at risk or showing how some areas may be more vulnerable than others (Lieske et al., 2015). The weTable also allows for social learning among participants, which was an important contribution of PGIS, as social learning offers a process through which individuals can learn from one another in ways that can benefit the wider community (Bandura, 1971; Reed et al., 2010). Social learning promotes self-reflection within the community and attitudinal change, which is key for building community resilience to increasing flooding due to sea level rise (Medema et al., 2014).

FIGURE 1

weTable set-up.

The demonstration project research team used the Google Earth application to present spatial data and maps to weTable participants. During the weTable exercise, participants interacted with maps of the Little Creek/Pretty Lake area. They also used flood maps associated with the scenario identified by the demonstration project research team involving 1.5 feet of sea level rise combined with a 100-year storm surge scenario. Community data from participants were collected electronically via Google Earth map layers.

Participants were asked to respond to two primary questions. First, they used a base map for the Little Creek/Pretty Lake case study area and were asked to identify assets in the community, such as schools, roads, and parks. Follow-up prompts asked them to consider: (a) Why are these assets particularly useful? (b) Which assets should be prioritized and why? Figure 2 shows the Google Earth map that includes some community assets identified by weTable participants.

Participants then used a map overlay of flooding projections under the scenario of 1.5 feet of sea level rise and a 100-year storm surge. Figure 3 shows the Google Earth map with this flood layer. Participants were posed a second question: With this map as an aide, tell us what kinds of challenges you see. Two follow-up prompts were also offered to participants: (a) Tell us more about the specific challenges in the areas you have

FIGURE 2

Google Earth map showing community assets.

FIGURE 3

Google Earth map showing the sea level rise and flood scenario.

identified, and (b) What areas would be more challenged than others and why?

Results of the weTable Exercise

Over a period of 3 months in spring 2016, 43 residents of the case study area participated in three exercises utilizing the weTable component of the PGIS demonstration project. The research team solicited participants for the PGIS demonstration project by sending invitation e-mails to neighborhood associations and civic leagues. Flyers were also posted in area businesses, community centers, senior centers, and public libraries. Residents self-selected to participate in the demonstration project and received $20 gift cards for attending the 90-min sessions.

Participants came from a wide range of backgrounds and experience with flooding and adaptation. For example, almost half of participants (47%) indicated being engaged in their neighborhoods or communities at high or extremely high levels. About equal percentages of participants were neutral in their engagement (26%) or had low or extremely low levels of engagement (28%). Their perceived vulnerability to flooding also varied. More than half (59%) perceived their personal vulnerability at high or extremely high levels, while a remaining 26% were neutral and 15% perceived low or extremely low vulnerability. Subsequent discussion with participants also indicated that there was diversity in their experiences with adaptation and mitigation activities.

Through the weTable exercises, participants identified key community assets such as parks and recreational centers, churches and faith-based facilities, restaurants and grocery stores, and transportation infrastructure. weTable participants also identified community assets related to health, such as clinics, medical and dental centers, and pharmacies, in addition to public safety services such as fire stations. Several elementary, middle, and high schools were also identified during the PGIS exercise as being important assets in the community. In addition to these assets, weTable participants also pinpointed several challenges in the community such as flooded bridges and roads, sewage backups, flooded homes, and isolation of community assets due to lack of access during flooding situations.

An important aspect of the weTable as a PGIS tool is its ability to surface collective local knowledge and to engage local participants in better understanding the impacts of sea level rise and flooding. As part of the demonstration project, the research team

TABLE 1

Mean scores and standard deviations for participants' responses to questions regarding weTable usefulness.

	Mean	Std. Dev.
Visualizing the problem of sea level rise	4.6	0.7
Highlighting community assets	4.4	0.9
Identifying community challenges associated with sea level rise and flooding	4.3	0.7
Understanding severity of sea level rise and flooding	4.5	0.8
Facilitating community-wide discussion about sea level rise and flooding	4.6	0.9

Note. Response scale 1-Not at all useful, 2-Slightly useful, 3-Somewhat useful, 4-Moderately useful, 5-Extremely useful.

collected data from participants about the usefulness of the weTable exercise. At the conclusion of the weTable session, participants were asked to respond to the following evaluation questions, providing answers using a scale from 1 to 5, with 1 being *not at all useful* and 5 being *extremely useful*:

- How useful was the weTable for visualizing the problem of sea level rise?
- How useful was the weTable for highlighting community assets?
- How useful was the weTable for identifying community challenges associated with sea level rise and flooding?
- How useful was the weTable for understanding the severity of the problem of sea level rise and flooding?

Results of participants' evaluations are summarized in Table 1. This table shows the mean ratings for each question on the 5-point scale (1 = *Not at all useful,* 2 = *Slightly useful,* 3 = *Somewhat useful,* 4 = *Moderately useful,* and 5 = *Extremely useful*). Overall, participants found the weTable exercise between moderately and extremely useful. They gave the highest ratings (mean ratings greater than 4.5) to weTable usefulness for facilitating community-wide discussion, for visualizing the problem, and for understanding severity of sea level rise and flooding. Interestingly, the primary utility of PGIS in terms of soliciting and documenting local knowledge, such as by highlighting community assets and identifying community challenges, was rated slightly lower (mean ratings of 4.4 and 4.3, respectively). This is consistent with the literature on participatory mapping that points to the mapping process being more important than resulting map, as the former provides the mechanism for participants to interact while

FIGURE 4

Challenges entry form on the web-based community map.

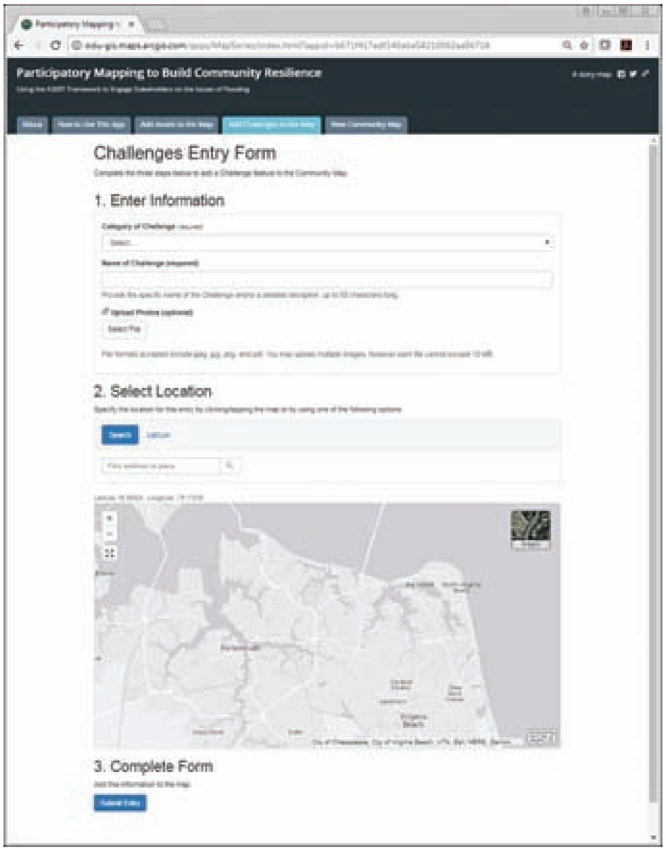
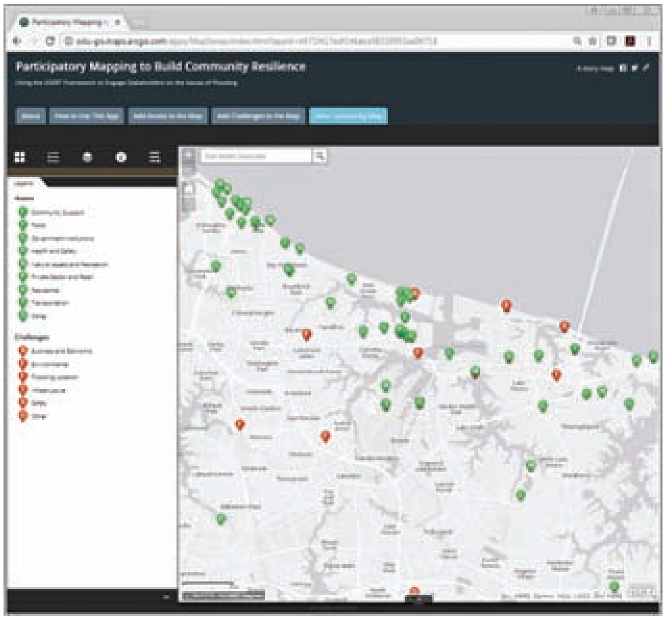


FIGURE 5

Community map displaying assets and challenges.



learning from each other and refining their knowledge and opinions about resilience.

Combined, the results of the weTable exercise in terms of collection of local data and participants' perceptions of weTable usefulness point to a successful PGIS demonstration project. The PGIS demonstration project showed how participatory mapping can, by directly engaging residents in creating sociospatial data, be a process-driven and vital way of building knowledge and fostering learning and deliberation in a complex issue such as resilience.

Taking the PGIS Demonstration Project to the Next Level

The Pilot Project concluded in July 2016, but the work started by the Citizen Engagement Working Group has continued and the PGIS demonstration project has been extended. In summer 2017, the PGIS demonstration project was taken to the next level with the development of a web-based community mapping application that can be deployed over a wider geographic area. This web-based PGIS application builds on the weTable exercise and provides local residents the opportunity to identify and input assets and challenges in their community. For example, as shown in Figure 4, the community map offers a web-based form for local residents to enter a community challenge by selecting a type of challenge (such as flooding location, infrastructure, business and economic, etc.), naming the challenge, and specifying it on the map. Users also have the option of uploading photos associated with the community challenge.

The web-based community map also supports the PGIS goals of codifying, documenting, and disseminating local knowledge about flooding and sea level rise. Users of the community map can, as shown in Figure 5, view the community assets and challenges that have been identified and added by other local stakeholders. Furthermore, the data collected through this PGIS approach can be analyzed in more detail and then disseminated to a wide range of stakeholders to support discussion, deliberation, and decision-making (see Figure 6 for a sample analyses).

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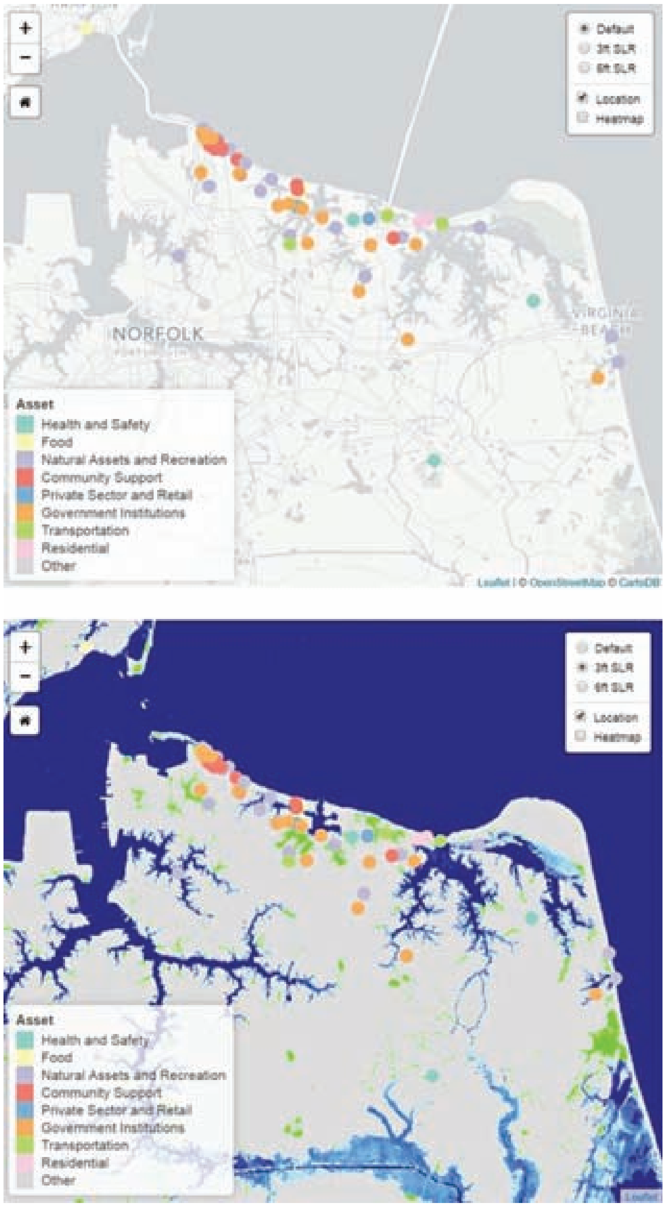
FIGURE 6

Sample analyses of data collected through the PGIS application.



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PAPER

StormSense: A New Integrated Network of IoT Water Level Sensors in the Smart Cities of Hampton Roads, VA

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ABSTRACT

Propagation of cost-effective water level sensors powered through the Internet of Things (IoT) has expanded the available offerings of ingestible data streams at the disposal of modern smart cities. StormSense is an IoT-enabled inundation forecasting research initiative and an active participant in the Global City Teams Challenge, seeking to enhance flood preparedness in the smart cities of Hampton Roads, VA, for flooding resulting from storm surge, rain, and tides. In this study, we present the results of the new StormSense water level sensors to help establish the "regional resilience monitoring network" noted as a key recommendation from the Intergovernmental Pilot Project. To accomplish this, the Commonwealth Center for Recurrent Flooding Resiliency's Tidewatch tidal forecast system is being used as a starting point to integrate the extant (NOAA) and new (United States Geological Survey [USGS] and StormSense) water level sensors throughout the region and demonstrate replicability of the solution across the cities of Newport News, Norfolk, and Virginia Beach within Hampton Roads, VA. StormSense's network employed a mix of ultrasonic and radar remote sensing technologies to record water levels during 2017 Hurricanes Jose and Maria. These data were used to validate the inundation predictions of a street level hydrodynamic model (5-m resolution), whereas the water levels from the sensors and the model were concomitantly validated by a temporary water level sensor deployed by the USGS in the Hague and crowd-sourced GPS maximum flooding extent observations from the sea level rise app, developed in Norfolk, VA.
Keywords: Hurricane Maria, Hurricane Jose, King Tide, hydrodynamic modeling, Internet of Things

Introduction

The modern smart city of today is tantamount to a complex system. Such systems are frequently subjected to innumerable nonlinear influences on how to efficiently allocate their limited resources (Rhee, 2016). The protocols by which these cities respond to emergency inundation conditions in the near future could be adapted using models informed and validated by an expanded water level sensor network to advise how best to prepare for the imminent flood-related disasters of the future (Figure 1). Analysis of the local sea level trend from the longest period record in Hampton Roads at Sewells Point in the City of Norfolk depicts a long-term linear increase in mean sea level of 4.59 ± 0.23 mm/year since its establishment in 1928 (Figure 2). The data from a new sea level trend study conducted at the Virginia Institute of Marine Science (VIMS) focuses on trends since the Anthropocene (1969 to present) to suggest that rising sea levels will inevitably exacerbate flooding conditions from storm events in the nearer future than initially projected by the Intergovernmental Panel on Climate Change's fifth assessment report, leading to a linear increase in mean sea level of 0.29 m by 2050 (Mitchell et al., 2013; NOAA Tides & Currents, 2017). When considering

FIGURE 1

Map of 57 publicly streaming water level monitoring stations throughout Hampton Roads, VA. The StormSense sensor network has contributed 28 sensors to the 29 existing sensors maintained by federal entities. Of these, NOAA has six (marked in blue), and USGS maintains 19 (noted in green). Additionally, VIMS has one, and WeatherFlow has three (also marked in red). Click figure or http://arcg.is/14aCe1 for interactive station map.

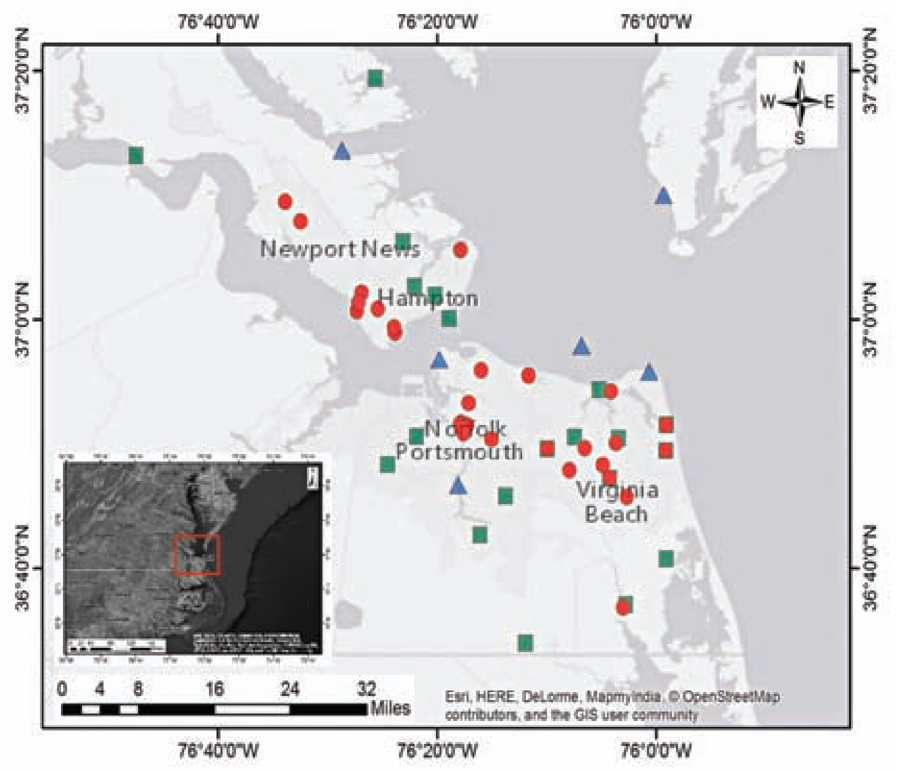

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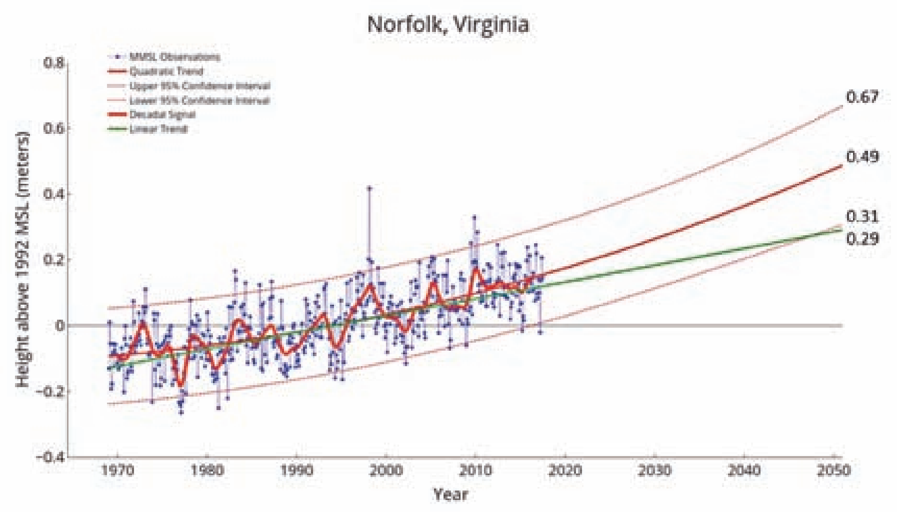
FIGURE 2

Hampton Roads Sea Level Rise Projections for Sewells Point through 2050 from VIMS Anthropocene Sea Level Change Report at http://www.vims.edu/test/dlm/slrc/index.php (Boon et al., 2018).



a quadratic fit of these data, the curve suggests an elevated trend of 0.49 m by 2050 (Figure 2; Boon et al., 2018). Cities, counties, town governments, local institutions, and private contractors provide myriad solutions, each of which must be evaluated in its own way. However, provision of these serviceable flooding solutions often impacts the availability of other services citizens rely upon.

Many existing smart cities solutions are designed to have a measurable impact on specific key performance indicators relevant to their communities. Because many of today's smart city/community development efforts are isolated and customized projects, the National Institute of Standards and Technology (NIST) launched the Global City Teams Challenge (GCTC) to encourage collaboration and the development of standards for smart cities. The GCTC's long-term goal is to demonstrate a scalable and replicable model for incubating and deploying interoperable, adaptable, and configurable Internet of Things (IoT)/Cyber-Physical Systems technologies in smart cities/communities. This program aims to help communities benefit from working with others to improve efficiency and lower costs. NIST also created the Replicable Smart City Technology (RSCT) cooperative agreement program to provide funding to enable awardee city/community partners to play a lead role in the team-based GCTC effort to pursue measurement science for replicable solutions (RSCT, 2016). The RSCT program was designed to support standards-based platform approaches to smart cities technologies that can provide measurable performance metrics. Together these two programs work to advance state-of-the-art of smart city standards.

The StormSense project brings together municipal governments in Hampton Roads, Virginia, including Newport News, the RSCT grant recipient, Norfolk, Virginia Beach, Hampton, Chesapeake, Portsmouth, Williamsburg, and York County along with the VIMS to develop a regional resilience monitoring network, with the installation of 28 new publicly broadcasting water level sensors. This was a notable recommendation from the Intergovernmental Pilot Project's working group (Steinhilber et al., 2016). StormSense is poised to develop the network as Phase 1 and develop a street level flood forecasting and monitoring solution across the entire region for Phase 2, which begins with integration of observed water levels into VIMS' Tidewatch tidal forecasting system, which now operates under the Commonwealth Center for Recurrent Flooding Resiliency (CCRFR; Figure 1).

Hampton Roads, VA, experiences nuisance flooding fatigue with such frequency that it is easy to forget that flooding events cost our cities, their first responders, and their residents time and money (VanHoutven et al., 2016). In one neighborhood in the City of Newport News that is subjected to frequent flooding, typically many emergency responders were required to assist in evacuating the complex (Lawlor, 2012; Alley, 2017). However, by remotely alerting residents that the water was rising quickly on the local stream, the past two flooding events have not required any emergency responders to assist in evacuating and were subsequently able to dedicate their emergency services elsewhere (Smith, 2016; Alley 2017). The goal of establishing a flood monitoring network can be expensive, but in the long term, the anticipated benefits of improved quality of life for a region's citizens are monumental. The goal is to replicate this level of success throughout the cities of Hampton Roads by providing a greater density of water level sensors. As an added benefit, more publicly available water level sensors empower property owners to take responsibility for their assumed risk of living adjacent to floodplains. This has resulted in a marked spike in the number of residents who have opted for flood insurance, with 2,231 claims totaling $25 million in damage attributed to 2016 Hurricane Matthew (FEMA, 2016). Many of these properties are insured through the Federal Emergency Management Agency's (FEMA) National Flood Insurance Program (NFIP), but many properties outside of the designated floodplain do not have preferred risk policies (VanHoutven et al., 2016).

A stakeholder workshop conducted on January 19, 2016, with representatives from Hampton Roads regional emergency management, storm water engineering and planning municipal staff, as well as academic and nongovernment organization partners uncovered a need for near-term, locally scaled, and "realistic" scenarios to communicate risk (Flooding Mitigation Stakeholder Workshop, 2016). Emergency managers are currently limited in their communications tools and know them to be inadequate (CoreLogic, Inc., 2015; Yusuf et al., 2017). A better understanding of the decisions people are making to adapt to flooding is needed. Differences are expected in both flood perception and behavior between urban and rural audiences (Bannan et al., 2017). A pilot study conducted in 2015 examining information logistics for drivers on flooded roads in Norfolk found that decisions made about driving were strongly situational based upon the importance, timing, and location of the driving plans, but that a regional approach to communication was needed and lacking (CoreLogic, Inc., 2015). Time living in Hampton Roads was an important factor in risk perception and that information comes from local knowledge, recognized sources of information, and sometimes a haphazard mix of both. Examining these issues in Hampton Roads and these recent studies, the context of flood communication and further elucidating the currently vague appropriate flood model parameters for accurate inundation prediction using hydrodynamic models at the street level scale in a broader context is needed. This leads to the following flood research questions:

- How should bottom friction be appropriately parameterized for high-resolution street level subgrid inundation models?
- How should percolation/infiltration of rainwater through different density surfaces present in urban and rural environments be accurately accounted for in a high-resolution subgrid model?
- How should model results be disseminated to enhance flood preparedness, and what communication methods and messages influence flood risk decision-making and behaviors (including information seeking and adaptive response)?

To attempt to address these questions, examples from a recent installment of 10 water level sensors by the United States Geological Survey (USGS) in the City of Virginia Beach, along with five new street inundation sensors and one tide gauge in Norfolk, and seven new water level sensors in Newport News through

StormSense will be compared during Hurricanes Jose and Maria in Hampton Roads in September 2017.

Study Area and Model Inputs

Hampton Roads, VA, is the second largest population center at risk from sea level rise in the United States. The region has more than 400,000 properties that are exposed to flood or storm surge inundation (Sweet et al., 2014). The region has a population of over 1.7 million people, living and traveling on roads exposed to both severe and increasing frequent chronic "nuisance" flooding (Ezer & Atkinson, 2014, 2017). Existing flood communication and messaging systems have not yet responded to the changing risk patterns brought by sea level rise and have not been able to meet the diverse needs of a growing populous in an expanding floodplain. A better understanding of flood-risk perception, information-seeking behavior, and decision-making can inform the development of new communications tools and flood-risk messaging (Wahl et al., 2015). This is the percieved intersect between new IoT technologies and emerging flood model validation methods. For each storm event, water levels driven via 36-h Tidewatch forecasts provided by VIMS at Sewells Point were used to drive surge and tides, alongside wind and pressure inputs used to drive the model atmospherically, similar to Loftis et al. (2016b). VIMS employs a street level hydrodynamic model, which incorporates a nonlinear solver and variable subgrid resolutions, capable of being embedded with lidar-derived topography to scale resolution for inundation where it is needed down to 5-m or even 1-m resolution in known areas where flooding frequency is high. The model has been used to simulate every major storm event in Hampton Roads that has occurred in the last 20 years and has been used in many other places along the U.S. East and Gulf Coasts as well (Loftis, 2014; Wang et al., 2014, 2015; Loftis et al., 2016a, 2017). For more information on the model, please refer to these cited studies.

Groundwater Inputs

Recent advancements in hydrodynamic computation have enabled models to predict the mass and movement of flood waters to predict water velocities at increasingly finer scales. However, the current version of the subgrid inundation model VIMS has developed does not fully incorporate a comprehensive groundwater model that slowly returns flood waters that infiltrate through the soil back to the nearest river (Loftis, 2014). This is a valuable aspect of flooding relevant for city planning perspectives using subgrid hydrodynamic modeling that has been successfully developed and employed throughout the Netherlands, Germany, and Italy (Casulli, 2015). There is an array of groundwater wells that exist in the Hampton Roads Region, bored and monitored by the USGS (USGS Groundwater Monitoring Sites, 2017). These temporally varying values for hydraulic conductivity could provide some valuable input information for the hydrodynamic model via Richard's equation (Loftis et al., 2016a). However, this does not currently account for the standard practice of near-surface groundwater displacement via pumping prior to anticipated flooding events conducted by cities with residents in the floodplains where a high water table regularly exacerbates even minor rainfall events (Loftis et al., 2017). Nevertheless, values observed near these sites prior to forecast simulations were used as the model's initial condition to estimate infiltration through pervious surfaces to counterbalance precipitation inputs, similar to Loftis et al. (2016a).

In forecast approaches, groundwater influence is usually neglected, since typically storm surge is a short-term event, and groundwater recharge is more of a delayed and long-term process; however, it is becoming increasingly important to also consider in forecasting longer-term extratropical flooding events such as nor'easters where flooding and high winds can persist for five or more tidal cycles. VIMS has been incorporating different forms of percolation of flood waters through different types of ground cover ranging from vegetated to impervious within the subgrid model in recent years (Loftis et al., 2013, 2016a, 2016b). It is worth noting that there are potential applications for storm water systems that could be manually added to the existing subgrid model version to account for surge flooding backups through storm water drainage without sufficient backflow prevention (Loftis et al., 2017).

Precipitation Inputs

The inundation model could be used to guide decisions related to storm water management by using existing sensor-derived precipitation data in several cities. This could be expanded to include data observations from rain gauges that are currently operating on sewer and storm water pump stations in the localities and from the Hampton Roads Sanitation District (HRSD), which combined currently amounts to ~130 sensors.

With an iteratively interpolated series of precipitation measurements, further research could also be conducted with these sensors and the new water level sensors to model the impacts of localized microburst precipitation events, like those experienced during 2016 Hurricane Matthew, or most recently on August 29, 2017, in some neighborhoods in southside Hampton Roads. This could aid researchers to help model ways that the city's systems could potentially be augmented for greater resilience to precipitation-induced flooding threats in the future. In the simulations presented herein, model results are calculated with temporally varying precipitation inputs from the currently private rain gauge data provided by HRSD.

Water Level Sensors

StormSense has recently deployed 28 IoT-bridge-mounted ultrasonic and microwave radar water level sensors in Newport News, Virginia Beach, and Norfolk, as outlined on the StormSense project's website at: http://www.stormsense.com. These sensors will complement the previously installed array of six gauges operated by NOAA, 19 relatively new gauges recently installed in 2015–2016 via Hurricane Sandy relief funds operated by the USGS, and one gauge operated by VIMS in Hampton Roads. Although the extant remote sensors in the region are largely radar sensors transmitting data through satellite signals, the new StormSense IoT sensors enlist the use of ultrasonic sensors and transmit data via cellular transmission protocols or Long Range (LoRa) Wireless Area Networks (WAN), with the focus of creating a replicable cost-effective network of sensors. Some realized utilities for a dense network of water level sensors are noted as follows:

1. Archiving of water level observations for flood reporting
2. Automated targeted advance flood alert messaging
3. Validation/inputs for hydrodynamic flood models

Sensor Types and Applications

A collaboration between VIMS and the partner cities of Newport News, Hampton, Norfolk, Virginia Beach, Portsmouth, Chesapeake, Williamsburg, and York County, in Hampton Roads, VA, will provide a prototype for strengthening emergency response times by providing spatial flood extent predictions in interactive map form at 5-m resolution. The plan for integrating the inundation model into a more permanent warning system involves planned connection with the new sensors to the cities' current Everbridge notification systems for alert messaging when the sensor observes flooding at user-specified elevations and integration with model predictions for timely forecasted tidal inundation alerts through Tidewatch once the sensors are tidally calibrated. Figure 3 shows an internal look at some sensors in Newport News, VA. The city employed a mix of two radar sensors (Figure 3A) and six ultrasonic sonar sensors (Figure 3B) from Valarm, a California-based sensor vendor with a cloud-based virtual alarm messaging platform. The

FIGURE 3

Internal look at Newport News' sensor from Valarm: (A) a standard bridge-mounted remote radar sensor control box configuration on the 16th St. Bridge over Salters Creek versus (B) a pole-mounted ultrasonic sonar sensor on a solid breakwater at Leeward Municipal Marina. (C) The internal view of the control board and the sensor in A.

FIGURE 4

(A) Map of Norfolk's LoRaWAN ultrasonic sensor network established in The Hague. The group currently consists of one tide monitoring sensor mounted over The Hague Walking Bridge near where the USGS mounts their temporary RDG and five inundation sensors strategically positioned over frequently flooded streets. (B) One such street is featured at the intersection of Boush St. and Olney Rd. during the King Tide flooding on the morning of November 4, 2017. (C) The sensor data are currently publicly reporting water level observations in Tidewatch and the user interface provided by the manufacturer, Green Stream, Inc. (https://greenstream.io/Dashboard).

Valarm Tools cloud platform will use the newly installed sensors to provide subscriber-based alerts (Figure 3C) based upon water level observations (and eventually tidal forecast predictions once incorporated into Tidewatch) to provide a unique flood preparedness service to their citizens and potentially bolster the flood warning portion of their FEMA NFIP application to participate in the Community Rating System (CRS). This is important, as each higher participation level the city achieves in the hierarchical CRS program is commensurate with an additional 5% decrease in flood insurance premiums for the citizen homeowners in participating communities.

This approach demonstrates the benefits of replicating shared smart city solutions across multiple cities and communities that are facing similar flood challenges, and it aligns with the goals of GCTC and RSCT programs. For a different innovative example, Figure 4A shows a map of Norfolk's LoRaWAN ultrasonic sensor network established in The Hague, in August 2017. The sensor network is currently composed of one tide monitoring sensor mounted over The Hague walking bridge near where the USGS mounts their temporary rapid deployment gauge (RDG) and five inundation sensors, strategically positioned over frequently flooded streets (Figure 4B). The LoRaWAN sensors were purchased through a Norfolk-based vendor, GreenStream, Inc., and use long-range WiFi instead of cellular data transmissions and like the Newport News sensors. They are currently publicly reporting water level observations in Tidewatch, as depicted in Figure 4C. Public Application Programming Interface URLs are available at http://www.vims.edu/people/loftis_jd/HRVASensorAssets/index.php.

It is the hope that the recent installation of water level sensors provided by the efforts of the USGS can be used as an opportunity to demonstrate some of the benefits of added water level sensors using these ultrasonic sensors will be evaluated as reputable and replicable monitoring methods after a longer-term study. In pursuit of this, Figure 5 shows three examples of temporary StormSense ultrasonic sensors deployed on the same bridges as the USGS' radar sensors over tidal rivers and creeks throughout the city of Virginia Beach. A later paper will evaluate the differences between these sensor accuracies and types, fault tolerance in data transmissions, and solar power management schemes. An initial comparison with a temporary RDG established by the USGS allowed for a favorable short-term data comparison with Norfolk's LoRaWAN sensor collocated there during a 9-day overlap period during Hurricane Maria in Figure 6.

Sensor Configurations, Accuracies, and Costs

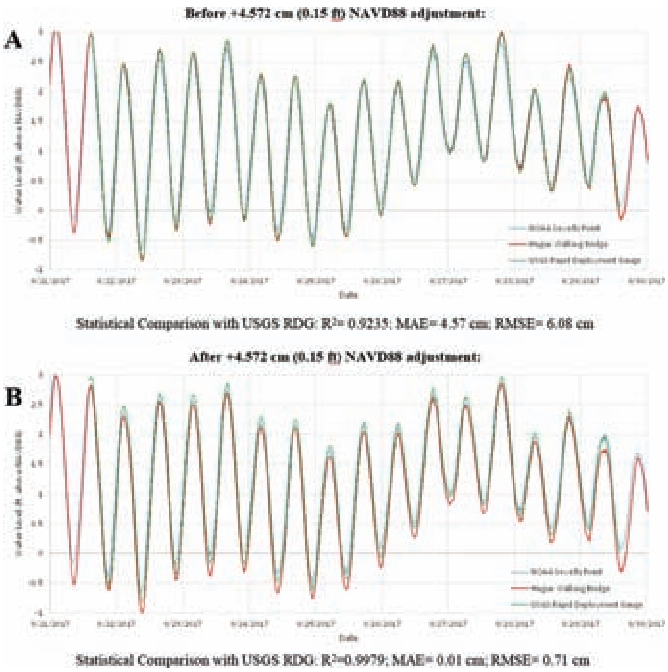
After an evaluation period of 6–9 months, these sensors will be relocated to unique monitoring locations in Virginia Beach. A small number of white papers and vendor brochures evaluate the accuracies of the ultrasonic and radar sensors in laboratories

FIGURE 5

Examples from three StormSense ultrasonic sonar sensors colocated in the field adjacent to USGS radar sensors in Virginia Beach for direct comparison of monitoring accuracy. These sensors will temporarily be stationed adjacent to each other for a period of 6–9 months to provide a long-term data record for comparison of water level measurements, data transmission speeds, and solar power efficiency.

FIGURE 6

Comparison of Norfolk LoRaWAN ultrasonic tide sensor (in red) with temporary RDG (in green) installed by the USGS measuring water levels via radar at Hague Walking Bridge from September 21 to September 29, 2017, during the passage of Hurricane Maria. Results in A depict measurements recorded prior to a vertical adjustment of +4.572 cm (0.15 feet), which was applied for future reporting and improves results in B after the sensor was consistently lower than the USGS sensor, temporarily mounted to the same bridge at the same site. Observations from NOAA's Sewells Point sensor (in blue) represent the water levels at the mouth of the Elizabeth River as the next nearest tide gauge from the Hague located 12.39 km (7.7 miles) downriver.



or for the application of level monitoring of water treatment reservoirs or chemical vats. However, these are not comparable to tidal water bodies or areas with significant wave action, such as during the extratropical storm surge events presented in this study during Hurricanes Jose and Maria.

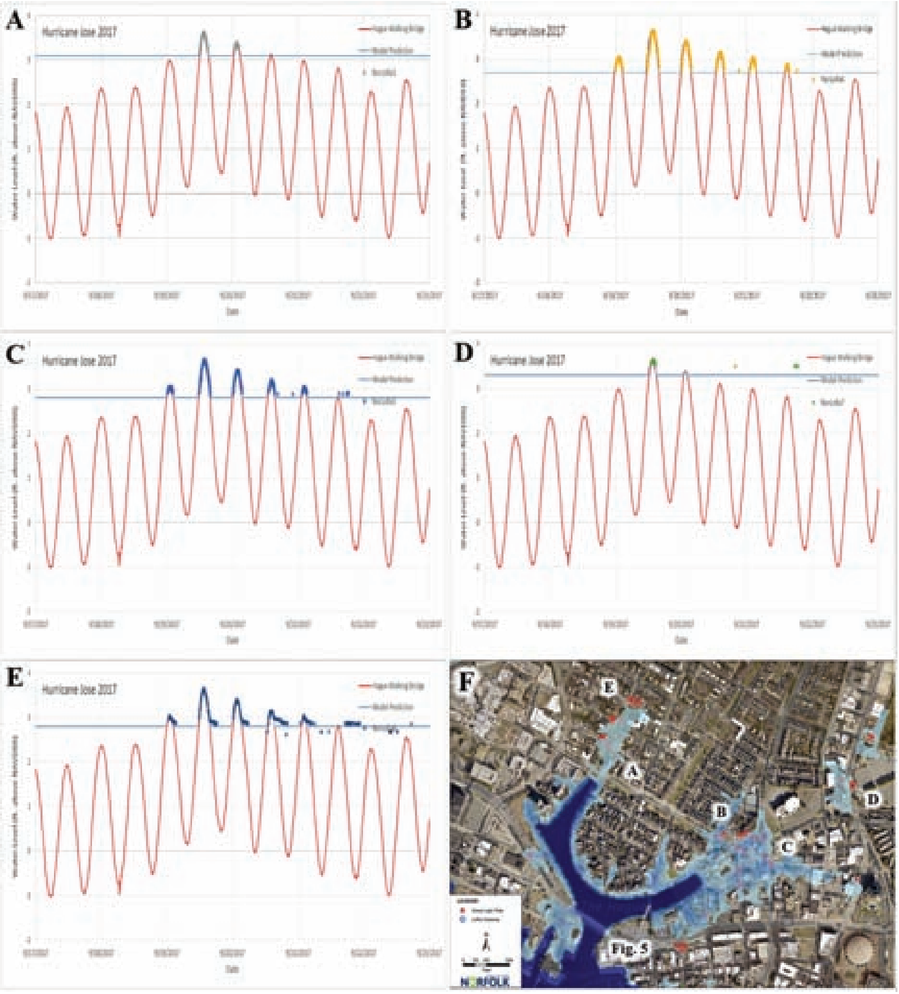
A cursory comparison from the initial deployments of the sensors in Summer 2017 revealed that the ultrasonic sonar units are from Valarm are accurate in the lab to a root mean square error (RMSE) of ±5 mm and accurate in the field to an average of ±18 mm, whereas the two radar sensors in Newport News are accurate in the lab to ±1 mm and accurate as deployed in the field to ±9 mm. The costs to purchase a solar-powered cellular transmission station were approximately $3,000 each for the ultrasonic sensors and $4,400 each to purchase the radar units. The street inundation sensors employed in Norfolk through the vendor Green Stream are accurate in the lab to approximately ±15 mm and accurate in the field ±45 mm, and sensors were purchased for $400 each, plus the cost of the LoRa transmission gateway, which has an effective transmission range of approximately 1 mile, less the distances occluded by high rises and buildings (Loftis et al., 2017).

Water Level Sensor Data Comparisons

A comparison of the five new street inundation sensors and one water level sensor in Norfolk, and eight new water level sensors in Newport News were used to temporally and vertically validate a street level hydrodynamic model's predictions during the offshore passage of Hurricanes Jose and Maria, which detected increased water levels in Hampton Roads by 76.2 cm (2.5 feet) and 60.9 cm (2 feet), respectively. These six gauges resulted in an aggregate vertical RMSE of ±8.93 cm over a 72-h Hurricane Jose model forecast simulation (Loftis et al., 2017). The time series plots shown in Figures 7A–7E compared well with the maximum period of spatial inundation extents predicted by the model at 19:00 UTC on September 19, 2017, in Figure 7F. The labeled location for each of the sensors in The Hague in Figure 7F also shows the surface elevations of city-maintained light poles in feet above NAVD88, which accounts for relative depths of flood waters and puddles detected by the sensors and the model. Interestingly enough, the sensor in Figure 7E detects latent ponding of water on the outskirts of the intersection for several hours after the nearby overwater sensor at the walking bridge in The Hague shows the tidal-driven surge subsiding after the peak of several tidal cycles. This is likely a result of storm water drainage backup in the storm drains nearest to the sensor.

FIGURE 7

Norfolk LoRaWAN ultrasonic street inundation sensor comparisons from September 17 to September 23, 2017, during the passage of Hurricane Jose. Each sensor's observations featured in A–E are compared with the nearby LoRa tide gauge featured in Figure 5 (in red) and the street level hydrodynamic model's predictions (in blue) at five locations in Norfolk's Hague region. F depicts the spatial inundation extents predicted by the model at 19:00 UTC on September 19, 2017, with the labeled location of each inundation sensor alongside surface elevations of city-maintained light poles in ft above NAVD88, which were used to aid decision-making for sensor placement.



The seven gauges present during Hurricane Maria (including the USGS RDG installed from September 21 to September 29, 2017) yielded a more favorable aggregate RMSE of ±6.28 cm when compared with the model. Both storms produced minimal surge-related coastal flooding, yet inundation impacts were equally profound in some tidal-connected inland areas, making the comparison with Norfolk's new street inundation sensors interesting to observe and practical for verification of inland inundation extents and depths. Figure 6A shows how the USGS RDG measurements temporarily colocated (similarly to Figure 5) at the same site during Maria's passage were used to apply a vertical adjustment of +4.5 cm (0.15 feet), based upon the mean absolute error (MAE) as an offset, to improve the RMSE metric for this event and likely many events in the future. This change resulted in an improvement in sensor-estimated RMSE from 6.08 to 0.71 cm, a difference of 5.37 cm (0.17 feet).

Crowdsourced GPS Flood Extents During Hurricane Jose

Hurricane Jose had a more significant storm surge measured by water level sensors in Hampton Roads and less rain, whereas the opposite was true for Hurricane Maria. The relatively new citizen science "Sea Level Rise" mobile app provided 393 points of geospatial data for use with validating predicted flood extents in the Larchmont Neighborhood of Norfolk during Hurricane Jose (Figure 8) with a favorable mean horizontal distance difference (MHDD) of ±3.36 m (Loftis et al., 2018). This indicates that the modeled maximum flooding extents calculated by the street level hydrodynamic model in the flood-prone Larchmont neighborhood of Norfolk compared reasonably well with these observations during the event and the average depth of inundation in this area reported by the model (and the underlying digital elevation model's contour) was 24.4 cm (0.8 feet).

The street level model's Lidar-derived Digital Elevation Model, embedded in the model's subgrid, was recently scaled to 1 m resolution in the Larchmont, Chesterfield Heights, and The Hague neighborhoods in Norfolk as part of an ongoing NASA Mid-Atlantic Resiliency Demonstration Study. Larchmont is positioned on a peninsula bounded by the Elizabeth River to the west and the Lafayette River to the north and east, and the area frequently experiences tidal "nuisance" flooding. By measuring the horizontal distances from the GPS-reported points of maximum flooding extents from the Sea Level Rise app to the edge of the model predicted maximum flooding extent contour line, an assessment of geospatial accuracy may be reached with minimal processing effort using the standard distance formula (Loftis et al., 2016b, 2017). An inherent caveat of this geospatial MHDD approach is that it is only a relevant metric in areas with minimal surficial slope, like those that characterize Hampton Roads, VA. In areas with steeper slopes immediately adjacent to the shoreline, model overprediction of several inches or even feet in the vertical may only manifest in minuscule increments of change on the horizontal scale (Loftis et al., 2016b).

FIGURE 8

Street level model flood prediction at 14:00 UTC on September 19, 2017, while Hurricane Jose was hovering offshore of just outside of the Chesapeake Bay mouth. The blue dots represent 393 high water marks tracing the extent of inundation collected via citizen science volunteer users of the Sea Level Rise mobile app between 9:50 and 10:17 EDT (13:50–14:17 UTC).

Discussion

The hydrodynamic model in Hampton Roads, VA, was effectively validated using five street inundation sensors and two water level sensors during the passage of Hurricanes Jose and Maria in September 2017. An aggregate of the results in Newport News during Hurricane Jose yielded an RMSE of ±6.2 cm as a primary time-honored model validation method that has been embraced by the hydrodynamic modeling community as a staple for determining the uncertainty of their predictions. The USGS provided a valuable service in the form of surveying and installing a temporary RDG during Hurricane Maria that provided an additional form of data validation not present during Hurricane Jose the previous week. The data from this sensor, positioned on the same walking bridge in The Hague, compared quite well between the new ultrasonic sonar sensor and this temporary radar gauge, with R^2 = 0.9235, MAE = 4.57 cm, and RMSE = 6.08 cm. It was noted that an offset using the sensor's MAE during Jose could be applied as a minor vertical adjustment of +4.5 cm (0.15 feet) to improve the statistical comparison during Jose to R^2 = 0.9979, MAE = 0.01 cm, and RMSE = 0.71 cm, along with likely improving future observations at the site, as suggested in the examples from Figure 4. This minimal, yet consistent, bias of +4.5 cm (1.8 inches) is likely due to minor measurement error or differences in vertical datum measurements at this specific site relative to the bottom of the sensor's emitter to NAVD88, as its application to the other sites in Norfolk made inconsistent changes in results.

Typically, the USGS collects valuable high water marks after major flood events. However, as none of these events were truly catastrophic flood events in Hampton Roads, VA, relative to if they had made landfall, high water marks in the form of GPS maximum flood extent points from the citizen science app Sea Level Rise were compared with the model instead as a secondary form of model validation. Results from 393 data points at one site in the western peninsula side of the Larchmont neighborhood in Norfolk during Jose yielded a favorable MHDD of ±3.36 m. This characterized the relative error as equivalent to approximately 2/3 of a single 5 × 5 m subgrid cell pixel from the model's perspective.

Conclusions

In the future, smart city systems could evaluate tenable candidate blueprint solutions for flood-related problems, whether they be attributed to storm surge, heavy rainfall, and tides, as was the case during the offshore passage of Hurricanes Jose and Maria, using a decision matrix. This could help key decision makers make informed decisions regarding how flood-related solutions could be best addressed with the new StormSense water level sensor network being integrated into Tidewatch to creating a resilience monitoring network throughout Hampton Roads, VA, to directly address a key recommendation from the Intergovernmental Pilot Project. Ways the new sensors could be used to drive a street level inundation model and be parameterized for specific flooding scenarios are *noted in italics* below:

- Combinations of gray and green infrastructure opportunities can be tested by *changes to spatially varying soil infiltration values in areas where modified green infrastructure lie.*
- Increase in storm water "holding" management systems can be modeled by *Digital Elevation Model modification and adding sources/sinks for new holding reservoirs/ponds.*
- Reduction of impervious surfaces can be addressed by *changes to spatially varying soil infiltration values.*
- Land use changes can be addressed by the *model grid mesh modification to remove/add buildings/infrastructure AND changes to spatially-varying soil infiltration values.*

In cases of heavy rainfall, the street level subgrid hydrodynamic modeling approach also performs the function of a hydrologic transport model to predict flow accumulation and aid in identification of areas that are most susceptible to flooding. This is useful for resilient building practices, as the model could also identify potential areas where development of green infrastructure could commence, with the understanding that a subgrid model represents infrastructural features and many city lifelines better than most conventional hydrodynamic models.

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PAPER

Integrated Ocean, Earth, and Atmospheric Observations for Resilience Planning in Hampton Roads, Virginia

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ABSTRACT

Building flood resilience in coastal communities requires a precise understanding of the temporal and spatial scales of inundation and the ability to detect and predict changes in flooding. In Hampton Roads, the Intergovernmental Pilot Project's Scientific Advisory Committee recommended an integrated network of ocean, earth, and atmospheric data collection from both private and public sector organizations that engage in active scientific monitoring and observing. Since its establishment, the network has grown to include monitoring of water levels, land subsidence, wave measurements, current measurements, and atmospheric conditions. High-resolution land elevation and land cover data sets have also been developed. These products have been incorporated into a number of portals and integrated tools to help support resilience planning. Significant challenges to building the network included establishing consistent data standards across organizations to allow for the integration of the data into multiple, unique products and funding the expansion of the network components. Recommendations to the network development in Hampton Roads include the need to continue to support and expand the publicly available network of sensors; enhance integration between ocean, earth, and atmospheric networks; and improve shallow water bathymetry data used in spatial flooding models.

Keywords: sensor, flood, water level, monitoring, StormSense

Introduction

The Hampton Roads, Virginia, area has experienced increasing vulnerability to flooding due to high rates of relative sea level rise (Ezer & Atkinson, 2014) and a long history of human waterfront settlement. For many years, flood management strategy has focused on reducing vulnerabilities by addressing impacted infrastructure while maintaining the status quo (i.e., elevating houses to prevent flood damage but still allowing people to live in the same places). However, the rising social and economic costs from increased flood frequency and the recognition that sea level rise will exacerbate these costs (Boon & Mitchell, 2015) have led to the understanding that the government needs to address regional resilience, rather than continue with the *ad hoc* patching of vulnerabilities.

A key component of resiliency planning is the recognition that management strategies should address the nonlinear nature of changing systems as well as the inherent uncertainty in our understanding of it (Folke, 2006). Effectively incorporating predictions of near-term and future flooding with mitigating strategies into resiliency planning requires a precise understanding of the temporal and spatial scales of current flooding, coastal dynamics, and precipitation patterns (Boon et al., 2018). This level of detail allows for an inventory of infrastructure currently at risk, the development of flood early warning systems (reducing current vulnerabilities) and high-resolution hydrodynamic models (increasing our resilience to future storm surge and sea level rise), and improved predictions of future risk.

Collaborative planning is critical in areas (such as Hampton Roads) where flood-prone regions cross jurisdictional boundaries. Locality-specific adoption of different strategies can lead to a coastline without cohesive protection measures and where the failure of protection measures in one community may impact the success of protection measures in an adjacent community. Collaborative planning efforts require cooperation on multiple levels, including the generation of seamless data sets. In Hampton Roads, the Intergovernmental Pilot Project (IPP; http://digitalcommons.odu.edu/odurc_pilot/) was established to coordinate a "whole of government" approach to regional resiliency planning (Toll, 2018). Their three key recommendations were (1) to establish, maintain, and institutionalize relationships to support collaboration and information sharing; (2) to standardize methods for integrating and sharing data; and (3) to apply the "Whole of Government and Community" approach to the watershed level as opposed to jurisdictional boundaries (Steinhilber et al., 2016).

Within the IPP, a Scientific Advisory Committee (SAC) comprising representatives from both private and public sector organizations engaged in a review of active scientific monitoring and observing within the Hampton Roads area. This committee is responsible for ensuring that member organizations work together to integrate a network of ocean, earth, and atmospheric data collection. This network includes private companies; academic institutions; and local, state, and federal government organizations. Although the IPP's efforts have technically been concluded, integrated collaborations on this issue continue under three main initiatives, including the following:

1. the Commonwealth Center for Recurrent Flooding Resiliency (CCRFR; http://www.floodingresiliency.org/), a state-funded virtual research center established between the Virginia Institute of Marine Science (VIMS), the Old Dominion University, and the Virginia Coastal Policy Center at the William and Mary Law School and serves as a source of scientific, socioeconomic, legal, and policy analyses aimed at building Virginia's resiliency against flooding;
2. the Climate Change and Sea Level Rise Initiative and Old Dominion University's Resilience Collaborative (http://www.odu.edu/impact/initiatives/resiliencecollaborative); and
3. the Hampton Roads Adaptation Forum supported by Virginia Sea Grant and the Hampton Roads Planning District Commission (https://sites.wp.odu.edu/HRAdaptationForum/). Between these groups and the region, the key challenge in the collaboration, thus far, has been to ensure that data standards are consistent across organizations to allow for the integration of the data into multiple products with unique management focuses. In this paper, we document all the publicly available environmental observations in the region and the resulting models and portals for efforts to integrating the observations into formats useful for resiliency planning.

Observation Networks and Integration

Many different companies, academic institutions, federal, commonwealth, and city governments make environmental observations in the region. There is also much collaboration between these organizations to facilitate dissemination and archiving of the data. The main types of observations are water level, subsidence, topographic, wave/current measurements, and weather observations. All of these observations are critical for the modeling of past and future precipitation- and wave-driven flood impacts that feed into resilience planning. Coverage of the different observation systems varies, creating unique challenges for the integration of the data into robust tools. The extent and format of each observing system are described in this section. In addition, nascent efforts to develop citizen science observations are ongoing, including a recent crowdsourcing effort using a mobile application developed in Norfolk called "sea level rise" to measure a king tide event in early November 2017. Sponsored by the nonprofit Wetlands Watch and promoted by the regional *Virginian-Pilot* newspaper, among other media partners, the "Catch the King" event portends increased awareness and potential scientific observations from the community that could prove valuable to mapping and model validation as well as public awareness (Loftis, 2017). This section's subsections outline all known available observations for (1) water level, (2) subsidence, (3) elevations, (4) waves, (5) currents, (6) atmospheric data, and (7) Gulf Stream dynamics.

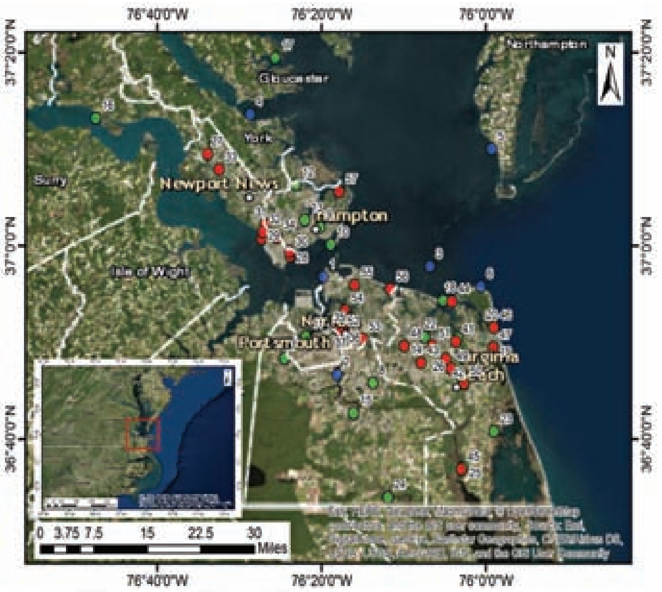
Water Level Observations

There are many different types of sensors that provide different utilities of value, depending on particular focus for measuring water level extremes. Water level sensors directly report the water elevations using a standard vertical datum above the North American Vertical Datum of 1988 (NAVD88) or mean sea level (MSL). By default, the National Oceanic and Atmospheric Administration (NOAA) reports these water levels relative to MSL with numerous other tidal and geodetic datum options, whereas the U.S. Geological Survey (USGS) exclusively reports their levels relative to NAVD88, with both reporting water levels every 6 min. Water levels are presently publicly monitored in 57 locations throughout the region by NOAA, USGS, VIMS, WeatherFlow, and StormSense, each comprising 6, 19, 1, 3, and 28 sensors in their respective portfolios (Figure 1). There also exist nonpublic sensor data collected by cities, which are somewhat limited for dissemination due to aging Supervisory Control And Data Acquisition (SCADA) architecture or limited communications functions. NOAA, the National Weather Service (NWS), and Tidewatch provide tide predictions at some of these gauges.

The National Ocean Service (NOS) of NOAA provides the most long-term and accurate water level observations. More recently, USGS and regional cities have installed more gauges. Most water level sensors in Hampton Roads are mounted to piers over open waterways or in sheltered marinas, as these sites accommodate a broad range of water level measurements from very low water events along with high water flood events. However, there are also inundation sensors in use, such as the temporary battery-powered rapid deployment gauges the USGS deploys in advance of substantial flood events over land or the new ultrasonic street inundation sensors the City of Norfolk installed as part of the StormSense Project in August 2017 (Loftis et al., 2017a).

FIGURE 1

Map of 56 publicly streaming water level monitoring stations throughout Hampton Roads, VA. Among federal entities, NOAA has six (marked in blue), and USGS maintains 19 (noted in green), whereas among local entities, VIMS has one, WeatherFlow has three, and StormSense has 28 (all marked in red). Click Figure or http://arcg.is/14aCe1 for interactive station map.



Water level observations have been made in the region since the installation of the Sewells Point Gauge by NOAA in 1927 on Naval Station Norfolk. The long-term measurements, such as those at Sewells Point, are critical for determining the long-term relative sea level rise rates and potential changes in rates, that is, the acceleration of sea level rise seen in the region (Boon, 2012; Ezer & Corlett, 2012). Since the initial installation, many more have been installed to improve flood forecasting, navigation, and delineation of the regional variability in sea level rise rates. As technology has advanced and associated hardware costs have become more affordable, a higher-density network of sensors is more tenable and affordable for the Hampton Roads community. The proliferation of Internet of Things (IoT) sensors and communications technologies has made these water level measuring technologies more affordable to local and regional entities in Hampton Roads. This development in sensor availability is critical, as the predictive capabilities of flood forecasting through hydrodynamic models (like those being developed at VIMS) have begun extending into the urban street-scale and could benefit from denser validation data sets. Ultimately, validations in more places throughout a city are needed to ensure a model's efficacy and aid improvement.

In 2008, NOAA published a gaps analysis in a technical memorandum reviewing relative coverage of regions with their sensors and originally identified few locations with need for data coverage in Chesapeake Bay and its tributaries (Gill & Fisher, 2008). No gaps were noted in Hampton Roads in Figure 11 of their report. However, NOAA's directive has a national viewpoint, and projected sea level rise trends and decreased costs for monitoring technology have enabled the region to respond more proactively to more frequent flooding. Due to the dendritic shape of the many estuaries of Hampton Roads, changes in prevailing wind directions combined with estuarine circulation contribute to flooding in ways that cannot be best understood by a single sensor at each major river mouth.

In a recent presentation to the Hampton Roads Planning District Commission's Regional Resilience Working Group, a more regionally resolute simulated gaps analysis review of 85 new suitable bridge-mounted water level sensor locations throughout Hampton Roads was presented (Loftis et al., 2017b). Suitability was determined by Lidar-detected deck heights for all bridges over open tidally connected waterways. The sites were identified by using hydrodynamic modeling simulations compared with the existing sparse network of sensor observations, and then a list was exported favoring sites that were <85% match in predictions, when compared with the next nearest suggested location during heavy wind conditions, and <95% match during regular tidal conditions. Of the 85 sites reviewed, 22 new suggested sensor sites were discovered as priority locations with bridges of sufficient elevation with consideration of projected sea level trends (Loftis et al., 2017b). A map of those suggested sites are presented in Figure 2, and a small number of these sites have since had sensors installed nearby by StormSense or the USGS. StormSense's data portal is accessible at http://aws.vbgov.com/stormsense, and the project's water level data are viewable at http://www.stormsense.com.

FIGURE 2

Analysis map of 85 bridges in the Hampton Roads region with sufficient deck height for installation of new water level sensors (in gray). Twenty-two sites were identified as priority sites (in red), where new sensors would be of research value. Existing NOAA and USGS water level monitoring stations are shown in blue and green, respectively, and were also considered in this analysis. Click Figure or http://arcg.is/1TWO49 for dynamic map.

NOAA CO-OPS

The NOS Center for Operational Oceanographic Products and Services (CO-OPS) has two NOS programs that support observations in the region: The National Water Level Observation Network (NWLON) and the Physical Oceanographic Real-Time System (PORTS®).

Long-term water level measurements are made at the NWLON stations. They are critical components for observing sea level rise in the region. There are 10 NWLON stations in Virginia and six in Hampton Roads (shown in blue in Figure 2). These stations are, in order of priority by length of data record, (1) Sewells Point, (2) Chesapeake Bay Bridge Tunnel (CBBT), (3) Money Point, (4) Yorktown U.S. Coast Guard Training Center, (5) Cape Henry, VA, and (6) CBBT Chesapeake Channel: https://tidesandcurrents.noaa.gov/stations.html?type=Water+Levels#Virginia. It should be noted that the gauge at (2) above has been moved nearly 6 miles northeast to the Chesapeake Channel of the CBBT (6) due to construction, and some NOAA sites show (5) as having water levels, but these simply show data from (6), thus (5) only has unique meteorological data.

USGS National Water Information System

The USGS National Water Information System has 28 water level stations in Virginia, 19 of which are located in the Hampton Roads region (shown in green in Figure 2; including one recurring temporary monitoring site in Norfolk's Hague). All of the USGS Hampton Roads assets were established in the last 2 years through cooperative agreements with localities through Hurricane Sandy Relief funds that had to be appropriated and spent by the end of 2016. Thus, the Richmond Field Office has no immediate plans for further development. In 2015, four sensors were installed in Hampton, three in Chesapeake, one in Portsmouth, one in Suffolk, one in Gloucester, and one in Virginia Beach, with eight more sensors installed in Virginia Beach in 2016: https://waterdata.usgs.gov/va/nwis/current/?type=tide&group_key=basin_cd

Tidewatch

VIMS operates and maintains a water level monitoring and prediction service called Tidewatch, which now operates under the CCRFR. Many of the individuals involved in the IPP SAC are now involved in advising, operating, and modeling at this new state-funded flood center. In its present state, Tidewatch mostly ingests Web service data streams for NOAA-monitored water levels in Chesapeake Bay for eight of its locations. However, Tidewatch will be used as a starting point to integrate sensors throughout the region to create a resilience monitoring network. Within its present installation of 10 sites, two monitoring locations are unique to the network owned and operated by the CCRFR. One is a new 2017 installation outside of Hampton Roads at Tangier Island, VA, whereas the other is within Hampton Roads in Back River's Dandy Haven, available at http://www.vims.edu/bayinfo/tidewatch/stations/brdh/index.php.

WeatherFlow, Inc.

WeatherFlow is a company that collects extensive wind and selected water level observations. WeatherFlow installed its first microwave water level sensor on the Wythe Creek Bridge in Poquoson, VA. This sensor fills a gap in the area between NWLON sites at Yorktown and Sewells Point and can be seen on the WeatherFlow DataScope Web portal (http://datascope.weatherflow.com/). Their data are accessible on a subscription basis. WeatherFlow also provides forecasts, nowcasts, and continuous wind data to subscribers via sector-specific portals (e.g., iWindsurf.com, iKitesurf.com, FishWeather.com, and SailFlow.com).

StormSense

StormSense is an IoT-enabled inundation forecasting research initiative and an active participant in the Global City Teams Challenge seeking to enhance flood preparedness in the smart cities of Hampton Roads, VA, for flooding resulting from storm surge, rain, and tides (Loftis et al., 2017a). In this study, we present the results of the new StormSense water level sensors to help establish the "regional resilience monitoring network" noted as a key recommendation from the IPP. To accomplish this, the Commonwealth Center for Recurrent Flooding Resiliency's Tidewatch tidal forecast system is being used as a starting point to integrate the extant (NOAA) and new (USGS and StormSense) water level sensors throughout the region and demonstrate replicability of the solution across the cities of Newport News, Norfolk, and Virginia Beach within Hampton Roads, VA (Loftis et al., 2018). StormSense's network employs a mix of ultrasonic and radar remote sensing IoT technologies to record water levels in 6-min intervals at 28 locations around Hampton Roads established in 2017. More details on data and locations of sensors are listed on the project's website, http://www.stormsense.com.

Subsidence Observations

Approximately one half of the relative sea level rise in Hampton Roads is caused by land sinking (Eggleston & Pope, 2013). Thus, it is imperative that the rates and spatial variability of subsidence be well known. Subsidence is measured using GPS, Synthetic Aperture Radar satellites, and extensometer techniques. The most comprehensive subsidence measurements for the area cover the time period from 1940 to 1971, depicting subsidence across the region that is relatively constant spatially at a level of approximately 2–3 mm/year. This subsidence is assumed to be due to the presence of large-scale subsidence signals associated with the glacial isostatic adjustment, groundwater withdrawal, and ongoing shifts associated with the Chesapeake Bay meteor impact crater. Until recently, this assumption was made, in part, because of the lack of higher-resolution information on vertical land motion for Hampton Roads. However, new methods employing a combination of the technologies in the ensuing subsections have enabled us to gain some slight insight into subsidence in Hampton Roads (Bekaert et al., 2017). This section provides details on the technologies, programs, and methods used to obtain and access subsidence data.

GPS CORS

The NOAA National Geodetic Survey manages a network for Continuously Operating Reference Stations (CORS). The CORS provide Global Navigation Satellite System data through the United States, including Hampton Roads. There are a total of six CORS in the Hampton Roads region, although generally located around the fringes with no current coverage in Norfolk, Hampton, or Newport News. The longest record provided by these stations extends back only to 2006, with most CORS having records spanning less than a decade in length.

InSAR

Using interferometric synthetic aperture radar (InSAR) analysis, it is possible to generate higher spatial resolution (20–30 m) estimates of subsidence in coastal areas (Jones et al., 2016). Several SAR satellites have collected imagery over Hampton Roads in the past decade, although few with enough acquisitions and a long enough record to provide the level of uncertainty needed to obtain useful results from InSAR analysis. The ALOS-1 SAR satellite collected data from 2007 to 2011 over Hampton Roads. In total, 12 acquisitions were obtained over this time period, although several of these acquisitions were made during 2010 and 2011. The ALOS-1 data are freely available from the Alaska Satellite Facility. The data have been processed and used in a recently published study to provide a first look at InSAR-estimated subsidence for the region (Bekaert et al., 2017). Compared to the previous survey from USGS from 1940 to 1971, significant spatial variability was seen in the estimates of vertical land motion for the region, although coupled with relatively large uncertainty as a result of the poor GPS coverage and limited data set that was used. COSMO-SkyMed has provided SAR coverage of Hampton Roads since approximately 2011, although these data are not freely available and subsidence estimates using these data have not been published to date.

For ongoing and future monitoring of Hampton Roads using InSAR, there are other data possibilities. Since 2015, the Sentinel-1 satellite has been acquiring data over Hampton Roads. Starting in September 2016, the satellite began acquiring data over the region every 12 days. Sentinel-1 also samples in the C-band, leading to dramatic reductions in uncertainty introduced by ionospheric noise when compared to the L-band measurements of ALOS-1. Importantly, the European Union Commission has committed to continuing and adding to the Sentinel Constellation until at least 2030, ensuring the ability to monitor subsidence over Hampton Roads. This will eventually lead to dramatic reductions in uncertainties as the time series continues to increase.

Extensometers

The Hampton Roads Sanitation District (HRSD) will, as part of its Sustainable Water Initiative for Tomorrow (SWIFT) project, install several extensometers. These devices measure surface motion relative to bedrock using a cable which extends through a steel pipe beneath the Potomac aquifer. The data will be available from HRSD or USGS. HRSD's site at www.swiftva.com includes further details regarding the SWIFT initiative.

Topography and Bathymetry

The inherent need for accurate and resolute topography and bathymetry to build efficient models for prediction and estimation of flood impacts are self-evident. Models are only of value if their input data enable them to address the concern adeptly, and elevation data are the most integral input of both nonconservative topography-based bathtub models and hydrodynamic models. If the shape, elevation of an inundated landform, and any impediments to fluid flow are not correctly accounted for in a model, the results will fail to accurately represent reality (Loftis et al., 2016). The provision of these data products involved implementation of a combination of remote sensing technologies to retrieve—mostly Lidar for topography and Sonar for bathymetry.

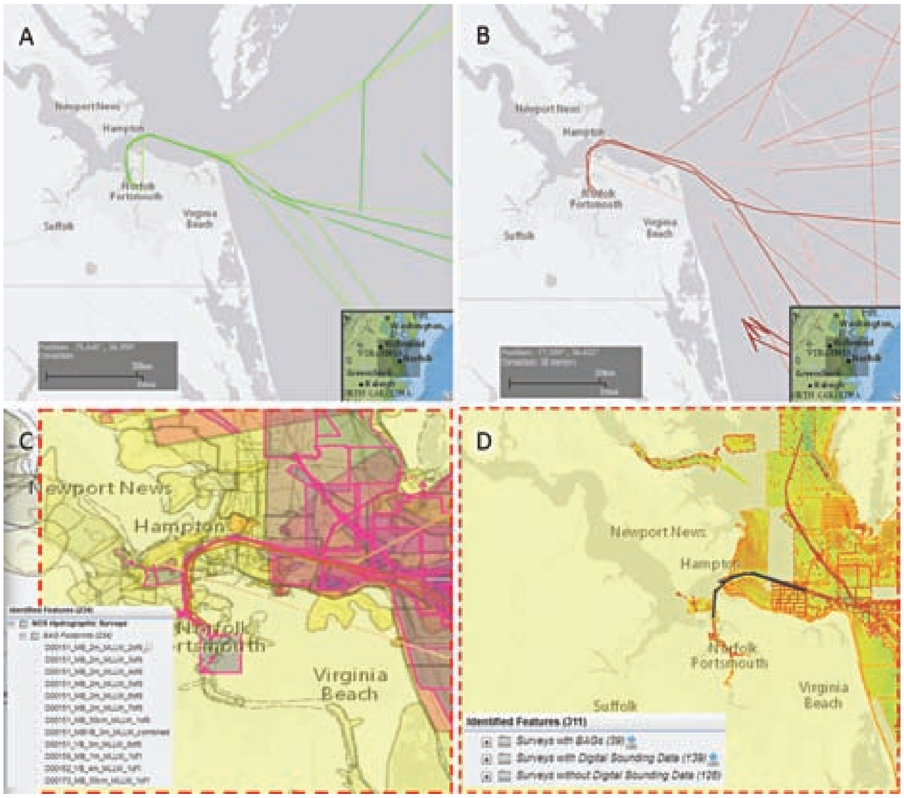
NOAA NCEI

The National Center for Environmental Information (NCEI), formerly the National Geophysical Data Center (NGDC), provides a wide variety of Bathymetry Surveys and Topography data. Bathymetry offerings in Hampton Roads range from raw point returns in the form of (1) multibeam sonar, (2) single-beam (trackline) sonar surveys, to (3) NOS hydrographic surveys or gridded points in the form of (4) bathymetric attributed grids (BAGs) (Figure 3).

1. Multibeam surveys provide six valuable data sets available in Hampton Roads and mostly cover the Norfolk Shipping Channel as depicted in Figure 3A. Surveys occurred on the following dates, listed in reverse chronological order: (1) MGL1409

FIGURE 3

Spatial coverage of NOAA-surveyed bathymetry data via (A) six multibeam sonar surveys, (B) four single-beam sonar surveys, (C) 311 NOS hydrographic surveys, and (D) 234 BAGs in Hampton Roads, VA. Of these data, only one multibeam sonar survey was newer than 2010, whereas <30 digitized hydrographic surveys and <30 BAGs were newer than 2010. URL: https://www.ngdc.noaa.gov/maps/bathymetry/.



(2014), (2) EW0008 (2000), (3) EW9901 (1999), (4) EW9808 (1998) (after dredging Norfolk Channel), (5) EW9804 (1998) (before dredging Norfolk Channel), and (6) EW9803 (1998) (before dredging Norfolk Channel).

2. Single-beam (trackline) sonar surveys comprise four useful data sets in Hampton Roads and, like the multibeam products, mostly cover the Norfolk Shipping Channel, shown in Figure 3B. The surveys were conducted, as noted in reverse chronological order: (1) EW9901 (1999), (2) EW9803 (1998), (3) LY73A (1973), and (4) OPR425D (1968).
3. Hydrographic surveys account for 311 data offerings, collected and archived by the NOAA NOS. These surveys are truly critical data sets, as they cover all of the navigable waterways of Hampton Roads. In many shallower tributaries to the Chesapeake Bay, these surveys are the only bathymetry data that exist in these systems. In many cases, the surveys are several decades old, and the point spacing or resolution is low: 20–30 m at best. The data from these hydrographic surveys are often included in derivative merged topobathymetric Digital Elevation Model (DEM) products noted in the next section.
4. BAG data surveys account for 234 variable extent surveys within the Hampton Roads region along the coasts of Virginia Beach, Norfolk, and Hampton, and parts of York and Gloucester Counties. BAG surveys also cover deeper channels of the James and Elizabeth Rivers in Hampton Roads.

NOAA's NCEI also provides combined topobathymetric merged data sets ranging from (in increasing resolution) Global ETOPO5 (5 min), ETOPO2v2 (2 min), ETOPO1 (1 min), satellite measured topography, alongside the global land 1-km base elevation product (30 arc-second), to the Southeast Atlantic region of the Coastal Relief Model (3 arc-second), down to the Hampton Roads Region's Virginia Beach DEM (1/3 arc-second): https://www.ngdc.noaa.gov/maps/bathymetry/, https://ngdc.noaa.gov/mgg/bathymetry/relief.html.

NOAA Digital Coast

This resource has a plethora of coastal and topobathymetric Lidar data with significant point spacing between returns. The data are available as LAS cloud and GeoTIFF rasters: https://coast.noaa.gov/digitalcoast/data/. Digital Coast has additional data sets that may be relevant for modeling efforts, including land cover data sets of variable resolution that are of value in establishing spatially varying friction and soil permeability parameterization for hydrodynamic models. NOAA also has two tsunami inundation model gridded Digital Elevation Models (DEMs) for Virginia. There are three nested Virginia Forecast Model grids, which provide bathy-metric data strictly for tsunami inundation modeling with the Method of

Splitting Tsunami model (https://data.noaa.gov/dataset/virginia-beach-tsunami-forecast-grids-for-most-model) and the Virginia Beach 10 m topobathymetric DEM, also available from the NOAA NGDC portal (Taylor et al., 2008; https://www.ngdc.noaa.gov/dem/squareCellGrid/download/423).

USGS NED

The USGS National Elevation Dataset (NED) has been a mainstay for surface topography data in the region for a long time. Their product offerings include variable formats of DEMs ranging from 1 min to 1/9 arc-second in resolution throughout Hampton Roads. Their more recent 1/3 and 1/9 arc-second DEMs offer some limited hydrocorrection for large culverts and large ditches (Evans, 2010; https://lta.cr.usgs.gov/NED). In addition, the USGS has developed a 1-m resolution merged DEM composed of the "best available data" (Evans, 2010) from the above-listed topography and bathymetry data sources for the entire Chesapeake Bay watershed, including all of Hampton Roads (Danielson et al., 2016; Thatcher et al., 2016).

VITA VGIN

The Virginia Information Technologies Agency's (VITA) Virginia Geographic Information Network (VGIN) provides elevation data throughout parts of the Commonwealth where available. Currently, their digital topography holdings cover all of coastal Virginia, including Hampton Roads. These elevations were obtained through Lidar surveys over an 8-year acquisition period and are downloadable as LAS point cloud data and bare earth Lidar DEMs (Scrivani, 2016). Lidar DEMs are available through VGIN's data portal and through ArcGIS Online feature services, and like the USGS NED layers, these Lidar holdings have limited hydrocorrection. VGIN also includes other flood risk-related shape files including Building Footprints and Parcel layers, where available. VITA's goals in providing services through VGIN will be extended to include Lidar throughout the rest of Virginia by 2020 according to their current 2015–2020 plan (VGIN VITA, 2015).

Wave Measurements

Observations of ocean waves in the region are important to predict overtopping of and impact loads on coastal structures, quantify shoreline erosion, and understand the storm risk to residential buildings in the coastal zone and to maritime safety. Since waves, either wind waves or boat wakes, are high-frequency water surface motions, wave measurements are carried out by sensors that can measure water level at high temporal resolution. The subsequent sections outline wave measurements from Scripps, NOAA, and sporadic alternative sources.

CDIP

The Coastal Data Information Program (CDIP) at the Scripps Institute of Oceanography, University of California, San Diego, leads an extensive nationwide network for monitoring waves. In collaboration with regional partners, CDIP operates five Datawell Directional Waverider Buoys in the expanded region. Two buoys are located near the mouth of the Chesapeake Bay. To the north, a buoy is deployed off Wallops Island, and to the south, two more are deployed off Duck, NC. The wave buoy data are provided on the CDIP web page at http://cdip.ucsd.edu and to the National Buoy Data Center (NDBC) and CO-OPS for further dissemination. These Datawell buoys are exclusively designed to observe waves with high accuracy and are often used for model validation (Hanson et al., 2014) (Figure 4).

NOAA's CBIBS

Additional wave measurements are provided by buoys within the Chesapeake Bay (Figure 5) as part

FIGURE 4

(A) The CDIP at Scripps is funded by the U.S. Army Corps of Engineers to maintain an array of Datawell wave buoys. (B) Datawell wave buoys are designed specifically to provide high-quality wave observations. The wave buoy data are provided on the CDIP Web page at http://cdip.ucsd.edu and to NDBC and CO-OPS for further dissemination.

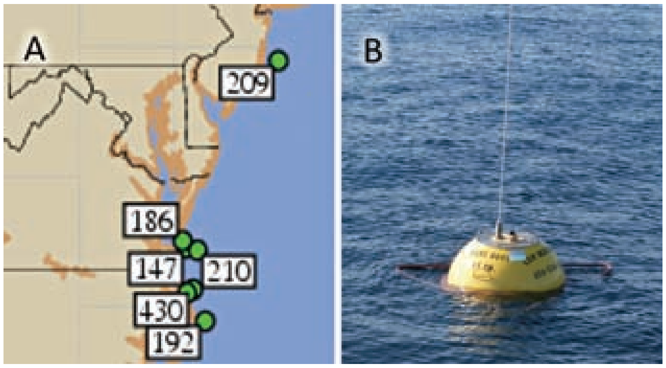
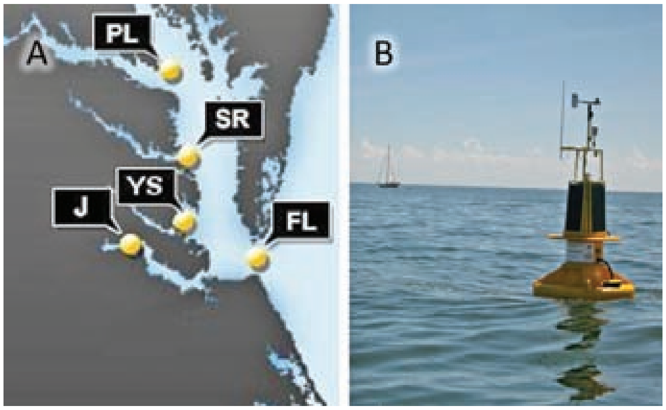


FIGURE 5

(A) NOAA's CBIBS maintains an array of buoys within the Bay. (B) CBIBS buoys support a variety of sensors, providing wave, current, water quality, and meteorological observations. Data are available at: https://buoybay.noaa.gov.



of NOAA's Chesapeake Bay Interpretive Buoy System (CBIBS; https://buoybay.noaa.gov). The wave observations are obtained from buoys that have a superstructure supporting meteorological observations. Within the vicinity of Hampton Roads, CBIBS buoys are located at First Landing, Jamestown, York Spit, and Stingray Point. The data are made available for viewing and download on their website.

Other Wave Measurements (Bottom-Mounted Sensors and ADCPs)

Although wave buoys are suitable to measure waves in deep waters, wave measurements in shallow waters (less than ~10 m depths) are commonly carried out using bottom-mounted instruments. Bottom-mounted sensors include pressure gauges that measure water level at high temporal resolution and acoustic sensors such as acoustic Doppler current profilers (ADCPs) that can measure waves in addition to currents. Single-pressure gauges can only obtain nondirectional wave measurements, whereas multiple-pressure gauges or an acoustic Doppler current profiler can obtain directional wave spectra. Several previous and ongoing research activities in the region have resulted in local measurements of waves in shallow waters.

For instance, in a recent study, Boswell and Tahvildari (2017) deployed a set of pressure sensors and an ADCP in a sheltered subestuary in the Southeast branch of the Severn River in Mobjack Bay, VA. The purpose of the study was to quantify wave attenuation rate by low-crested stone breakwaters that were constructed as a component of a marsh-sill living shoreline system to reduce shoreline erosion. A total of seven pressure sensors were deployed shoreward and channel-ward of three breakwaters and in an interstructure gap to quantify wave dissipation at different beach transects. Two pressure gauges have the capability to measure waves of up to 16 Hz frequency, whereas the rest can measure oscillations of up to 2 Hz. The ADCP measured directional waves in deeper waters (~6 feet) channel-ward of the structures. Future work will include wave and current measurements around artificial oyster reefs as well as turbidity measurements around stone breakwaters and oyster reefs. The data sets, a map of the sites, and information on layout of the gauges can be found at www.odu.edu/coastal/living_shorelines. The value of these data increase as sea levels are projected to rise and wetlands in the intertidal zone begin to drown and retreat landward. In the context of resilience, the measured wave intensity at sensors can help support longevity of investment claims with regard to seeding potential and root strength of vegetation for living shorelines over gray infrastructure alternatives in the face of current and future storms.

Current Measurements

Ocean current measurements are made to support real-time models, search and rescue, and engineering projects. Currents are measured directly by ADCPs attached to buoys or, indirectly, by high-frequency radar. These models could be interpolated products using streamflow and ADCP measurements near river mouths to estimate velocities at various stream segments using mathematical tree models and Geographic Information System (GIS). Hydrodynamic models could also use these data to verify cross-sectional transport estimates near sensors, calculate residence time, or verify flow intensity during aperiodic storm events. The following sections review resources for ADCPs and high-frequency radar gauges measuring currents in Hampton Roads.

ADCP Current Measurements

NOAA's PORTS program operates current meters attached to aids-to-navigation buoys at three locations in the lower Chesapeake Bay. These Doppler profilers provide data in the Thimble Shoals and Chesapeake shipping channels. A description of the operation of these instruments is found in NOAA Technical Report NOS CO-OPS 043 titled "Test, Evaluation, and Implementation of Current Measurement Systems on Aids-to-Navigation" (Bosley et al., 2005). Three more current meters provide velocity data in the lower James River. One of those, located at Dominion Terminal, has a horizontal orientation in order to measure currents in bins referenced to distance from the pier. These PORTS currents data are collected on a 6-min time interval, and data may be accessed through https://tidesandcurrents.noaa.gov/ports/index.html?port=cs. The current observation record in the lower Bay is further enhanced by a current profiler attached to the First Landing (FL) CBIBS buoy near Cape Henry (36.9981°N, −76.0873°W). Data from this buoy are available at https://buoybay.noaa.gov/locations/first-landing#quicktabs-location_tabs=0.

High-Frequency Radar Surface Current Measurements

The Center for Coastal Physical Oceanography (CCPO) at Old Dominion University (ODU) maintains six high-frequency radar stations with funding from NOAA's Integrated Ocean Observing System office and the Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS). Three high-resolution radar systems operating at 25 MHz measure surface currents in the lower Chesapeake Bay. Station data are combined to produce hourly maps of current vectors on a grid with 2-km spacing. Data coverage extends from the Bay mouth to the mouth of the James River and north of Kiptopeke, VA. The antennas are located at Ocean View Community Beach in Norfolk, Joint Expeditionary Base Little Creek-Fort Story in Virginia Beach, and Sunset Beach Resort in Cape Charles. There are also three long-range radar systems operating at 5 MHz, which are located on Atlantic Ocean beaches. They measure coastal ocean currents out to a maximum range of 200–250 km offshore. The long-range data are combined to create hourly maps of current vectors on a 6-km spaced grid. The antennas are installed at Little Island Park in Virginia Beach, VA, on the north end of Cedar Island off of Wachapreague, VA, and at the Assateague Island National Seashore, MD.

The ODU radar stations contribute to a regional, national, and global high-frequency radar network, and data are output in near real-time for public use. The data are freely available for visualization and download (THREDDS servers) on the National HFRadar Network website http://cordc.ucsd.edu/projects/mapping/), hosted by the Coastal Observing Research and Development Center at University of California, San Diego. The data are also available on the Global HF Radar Network (http://global-hfradar.org/). The 6-km gridded data product is automatically sent to an Environmental Data Server for use in the U.S. Coast Guard search and rescue planning tool. NOAA generates tidal current predictions using lower Chesapeake Bay radar currents and displays those forecasts on its CO-OPS website (https://tidesandcurrents.noaa.gov/hfradar/Hfscm.jsp?port=CHES). For more information on local and regional products, visit the CCPO HF radar project website (http://www.ccpo.odu.edu/currentmapping) and the MARACOOS HF radar website (https://maracoos.org/node/146).

Weather Observations

Observations of weather parameters, such as air temperature, barometric pressure, wind speed, and relative humidity, are routinely made by the National Weather Service with regional organizations and companies providing additional data. There is a relative paucity of observations over water, which could impede more accurate forecasting and understanding of future impacts. The following sections outline resources provided by the National Weather Service, NOAA, and WeatherFlow.

National Weather Service

The regional Weather Forecast Office (WFO) nearest to Hampton Roads is located in Wakefield, Virginia. This WFO covers southeastern Virginia, northeast North Carolina, and the eastern shore of Virginia (http://www.weather.gov/akq/). They maintain surface weather observations in the region and the Nexrad radar system. Land and ocean observations, forecasts, and climatology data are listed at their website.

NOAA PORTS

The PORTS observing system in Hampton Roads makes a variety of wind, current, temperature, salinity, and atmospheric observations to serve the maritime community (https://tidesandcurrents.noaa.gov/ports/index.html?port=cs). NOAA produces, through their PORTS program, Automated Real-Time Narrative Summaries (ARNS) for each station, which may prove useful for audible summary data for each station or a group of stations via voice-activated querying, which is becoming increasingly popular via Amazon Alexa, Google, Apple's Siri, and Microsoft's Cortana. Limited documentation on

ARNS is here: https://tidesandcurrents.noaa.gov/arns.html.

WeatherFlow, Inc.

WeatherFlow, Inc., recently instrumented the Chesapeake Light Tower, located 14 miles off the shore of Virginia Beach after the site was abandoned by NOAA. The site now includes atmospheric and water level observations. WeatherFlow colocated sensors as part of the Virginia Offshore Wind Energy Development. Data are currently privately available for this and other sites on the WeatherFlow DataScope site (http://datascope.weatherflow.com/). WeatherFlow, Inc., operates approximately 20 proprietary weather stations in the Hampton Roads area. Data from those stations are available through several WeatherFlow apps, with some of the data being visible to free users of those apps and the remainder of the data being visible only to users who pay a subscription fee to get an upgraded version of those WeatherFlow apps.

Gulf Stream Dynamics

On long-term time scales, weakening of the Gulf Stream has been linked with acceleration in sea level rise along the U.S. East Coast, especially north of Cape Hatteras (Boon, 2012; Ezer, 2015; Ezer et al., 2013; Sallenger et al., 2012). On short time scales of days to weeks, variations in the Gulf Stream transport that can be detected by the daily cable measurements of the Florida Current are linked with unpredictable anomalous water level elevation that can cause "clear day" tidal flooding (Ezer & Atkinson, 2017; Ezer et al., 2017). Gulf Stream transport is measured daily across the Straits of Florida and reported at http://www.aoml.noaa.gov/phod/floridacurrent/index.php.

Data Integration Services (Web-Based Data Consolidators)

For resiliency planning, a critical component of integrated data collection is the dissemination of the data in a digestible format for decision makers. The variety of data that is available in the region combined with a variety of user needs has led to a variety of websites that integrate various parts of the overall observing system. Many of the data integrating sites have a nationwide scope, whereas others are specific to the region. All provide a valuable service. Some examples of data integration sites that are ingesting data from the Hampton Roads observation network are described below.

Integrated Data Portals and Viewers

These provide the ability to access different types of data through a single server. Portals are typically aimed at users who want to do their own analyses and provide information to unsynthesized data. Viewers provide mapped and synthesized data tools for resilience planning. The geographic scope of the data portals and viewers varies from national to local, and some examples of prominent portals and viewers are noted below (although a more exhaustive list is provided in Appendix B):

- NOAA's Sea Level Rise viewer allows the user to visualize potential impacts from sea level rise through interactive maps and photos in landmark locations that have been digitally altered to create an oblique view of flooding at thresholds up to 6 feet above MSL: https://coast.noaa.gov/digitalcoast/tools/slr.
- Climate Central's Surging Seas viewer (http://www.ClimateCentral.org) covers most of the U.S. coastal states and allows integrated mapping of social, economic, and flood risk factors. It allows easy comparison of different scenarios to facilitate decision-making up to ~32 feet above MSL.
- AdaptVA (http://www.AdaptVA.org) is a site dedicated to providing climate-related data specifically curated for adaptation efforts in Virginia. It provides both a data portal (a geoportal) and synthesized information, targeting different users with each. The geoportal is primarily built to deliver Virginia specific data but will also search ArcGIS.com for global data. All of the synthesized data tools are specific to Virginia.
- Part of the U.S. Integrated Ocean Observing System, the MARACOOS (http://www.MARACOOS.org) serves as a portal for data from the coastal region extending from Cape Cod, MA, to Cape Hatteras, NC. MARACOOS integrates, analyzes, and applies information to best serve their diverse stakeholder communities and to meet end-user needs. They provide marine, atmospheric, and hydrodynamic data from multiples sources and list their priorities for data inclusion as follows: maritime safety, ecological decision support, water quality, coastal inundation, and energy. Much of the observational data, satellite data, and forecast models are available for viewing, download, and analysis through their OceansMap Viewer and tool: http://oceansmap.maracoos.org/.

Forecast Services

These provide water level forecasts based on integrated water and atmospheric observations. NOAA National Weather Service and the Virginia Institute of Marine Science's Tidewatch both have water level forecasting systems (http://water.weather.gov/ahps/ and http://www.floodingresiliency.org/water-level-predictions/, respectively) for the Chesapeake Bay region. Although the algorithms are slightly different, they both use wind forecasts and water level observations to graph forecasted water levels at tide gauges and water sensors. Both provide an effective way to measure, visualize, and predict the magnitude and impacts of coastal flooding at locations within the Chesapeake Bay and along Virginia's seaside Eastern Shore. These systems can be used to prepare for storm tides and minimize potential flood impacts. On a longer temporal scale, sea level forecasts are also provided by VIMS (http://www.vims.edu/slrc) for a number of stations. These forecasts are based on relative sea level rise trends at tide gauges throughout the United States and are updated semiannually.

Public Web Service URLs

Web services from water level sensors and other flood-relevant monitoring assets are often ingested by the viewers and forecast services previously noted in this section. The main three water level monitoring groups with publicly accessible Web services in Hampton Roads are NOAA, USGS, and StormSense.

- NOAA's Tides and Currents site provides a sizable number of integrative services through a variety of interoperable data formats including XML, JSON, and CSV formats for the six sensors in/around Hampton Roads. These stations (in order of length of data record) are noted in the dynamic digital Appendix A (http://www.vims.edu/people/loftis_jd/HRVASensorAssets/index.php) in the following order: (1) datum, (2) water levels, (3) tide predictions, (4) air temperature, (5) barometric pressure, and (6a) wind speed with (6b) direction, (7) conductivity, and (8) water temperature (https://tidesandcurrents.noaa.gov/api/).
- USGS employs public Application Programming Interfaces (APIs) to share the data services they provide. Aggregation links for water levels (and additional parameters, if the city co-opted for other sensors) in Virginia Beach, Hampton, Gloucester, and Chesapeake are available for the 27 sensors the USGS maintains in the region. Other stations can also be retrieved this way if their station names are known and queried within the URLs noted in Appendix A.
- StormSense in Hampton Roads includes the 28 new water level sensors noted in the Water Level Observations section, which are currently publicly broadcasting their water levels under the public API URLs presented in Appendix A. StormSense also provides the tools to accept data streams from various other sources with disparate data formats, as recently displayed before and during Hampton Roads' 2017 king tide forecast and sizable coordinated monitoring event, "Catch the King" (Loftis et al., 2017c): http://www.vims.edu/people/loftis_jd/Catch%20the%20King%20Forecast%20Nov%205th/index.php. In this instance, Tidewatch was used as a starting point to integrate StormSense and NOAA sensors throughout the region in pursuit of creating a resilience monitoring network to directly address a key recommendation from the IPP.

Summary and Recommendations

The IPP Science Advisory Committee had a number of recommendations in the final report. The third recommendation was directly relevant for sensor observations and stated that "…the SAC provide a mechanism to assure that the sea level rise science needs and requirements of regional stakeholders are addressed" (Steinhilber et al., 2016; Toll, 2018). They further advised that this could be accomplished through coordination between all levels of government and relevant private organizations for data collection and the delivery of data through integrated Web portals. These goals have been accomplished; however, there were a number of challenges that needed to be overcome. Both establishment of data standards and funding of network sensors have been major concerns. It should be noted that federal funding to NOAA, USGS, and NASA who maintain the land, ocean, and remote sensing instruments is crucial, yet it is expected that network funding may continue to be a concern.

Challenges for Establishing an Integrated Network of Measurement Assets

Data Communications Standards

Most of the cities in the region are installing their own water level gauges employing a broad range of sensor types ranging from (1) K_a-band radar, as used by NOAA and USGS, to the cheaper (2) ultrasonic sonar, as remote sensing observation methods, to (3) *in situ* pressure transducers, which tend to biofoul in the fall tidal floods when harmful algal blooms are more frequent. With industrial IoT technologies, cost savings are realized in communities by eschewing the more costly Iridium Satellite uplink communication methods NOAA and USGS use in favor of 4G cellular broadband signals, 2G machine-to-machine through Ingenu, and long range wireless area networks. These IoT communication methods, combined with cheaper ultrasonic sensors, result in a reasonably accurate (~10 cm) affordable water level monitoring alternative for modern smart cities at a cost of ~10× cheaper, per sensor (Loftis et al., 2017a).

The reality is that, although cities may have ample Public Works and Data Scientists capable of installing and managing their own data, the data types, collection intervals, formats, and error metrics should be standardized. Thus, this approach is still likely to be out of the realm of affordability in rural localities for at least the next decade. It should also be noted that IoT approaches, though cheaper, are potentially more susceptible to interrupted communications during heavy flood events coincident with power outages. Although IoT water level sensors are powered by large solar panels and batteries, their communications are still subject to the same overburdened cellular Internet and data channels most denizens rely on when the power and Internet are offline.

Funding and Resource Sustainability

For the engaged cities installing sensors in Hampton Roads, most are either collaborating via cooperative agreement with the USGS Richmond Field Office or VIMS through the Smart Cities StormSense Project to locate suitable sites, procure and install the sensors, and make the data public. It is important to assure that the observations are of sufficient accuracy and that they are made public in near-real time. To be sure of this, StormSense is funded through a Replicable Smart City Technologies Cooperative Agreement awarded to the City of Newport News and VIMS, who have been directly advised by the National Institute of Standards and Technology. The data streams coming from the StormSense sensors emulate USGS' data standards by collecting data in 6-min time intervals and reporting their water levels relative to NAVD88 while broadcasting their data via public APIs in a variety of digestible data formats. By making all new water level sensors public in near-real time, the observations can be used for forecasting, emergency management, and research projects.

Creating Integrated Data Products

The frequency at which different types of data are upgraded can significantly impact the integration of multiple data into a single model or data product. For example, bathymetry is rarely updated, whereas the water level sensors are updated on 6-min time scales. This means that storm surge models are working with detailed changes in water level, but the water levels may be superimposed on inaccurate depths, hampering the improvement of the models.

In Hampton Roads, bathymetric surveys outside of the dredged primary shipping channels are relatively outdated and somewhat sparse in terms of point spacing. Given that shallower streams' hydrographic surveys are frequently integrated as the only digitized bathymetry source, shallow stream systems, such as the Lynnhaven, Nansemond, Back, and Lafayette Rivers do not have the best possible bathymetry data for adequate consideration of flood risk in Hampton Roads. Refined bathymetry would result in an immediate improvement of flood forecasting.

Recommendations

In completing this inventory of observations and data formats, a number of key determinations can be formulated into recommendations for filling gaps, leveraging historical continuity of observations, and integrating systems for improving situational awareness in emergencies as well as broad-based information needs for resilience planning. An overall premise is that integration of diverse observing systems into a network is vital for resilience planning, which inherently crosses sectors and space-time scales. First, as each observing network arose out of a particular sector or scientific or geotechnical discipline, it is prudent to inventory and define data standards early when inputs are sought across networks. Interoperability issues comprise technical issues of communications and data formats, standards of unit measurements, and application requirements in temporal and spatial collection needs (extent, resolution, and temporal frequency). We find that shallow-water bathymetry continues to be a constraint on hydrodynamic modeling, and efforts to systematically map and update this parameter will result in better forecasting and planning process inputs. Likewise, topographic data, already greatly enhanced by Lidar DEMs, could be further improved with finer resolution, use of hydrocorrection in disjunct, low-lying areas, and leverage research on subsidence for developing future topographic representation (and inundation models) for relative sea level rise (combining eustatic rate scenarios and subsidence trends). In addition, the growing network of real-time water level sensors ought to be expanded to allow forecasting to better predict storm surge impacts as well as wind tides and nuisance flooding. Finally, overall integration of ocean, earth, and atmospheric observations should be sought to enhance situational awareness in emergency events as well as promote scientific analysis and prediction. With these recommendations in mind, these sensor data should be used to help the public, stakeholders, and policy makers in the near term by recognizing when their home or vehicle is in danger of flooding in near-real time and validate predictive model results for future improvement. Simultaneously, this integrated network of sensors will aid in resilience efforts through research into compounding effects of sea level rise and subsidence in Hampton Roads in the long term.

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Appendix A

Hampton Roads, VA, Sensor Assets and Public Web API URLs for Near-Real Time Water Level Data (http://www.vims.edu/people/loftis_jd/HRVASensorAssets/index.php)

Appendix B

Coastal Flooding Products Available Near Hampton Roads, VA, *from Illuminating the Challenges: Flood Data to Local Action Workshop*, September 2016 (https://wm1693.box.com/s/a8vgidonn4wmhkzx2l287n7t3zp8srgl)

PAPER

Improving Public Health Readiness for Sea Level Rise: A New Initiative in Coastal Virginia

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ABSTRACT

Sea level has been rising around the world, and in recent decades, the rate has been accelerating. Because rising seas have the potential to directly or indirectly affect the health of vast numbers of coastal communities and inhabitants, public health agencies and professionals—in conjunction with other fields—have a pivotal role to play in helping to protect populations, reduce and prevent health impacts, and foster resilience. This article discusses a novel effort that has been undertaken in Coastal Virginia to help prepare the next generation of public health professionals to grapple with sea level rise issues. The effort grew out of discussions of the importance of public health issues that took place through the Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Pilot Project. The new training effort focuses on public health graduate level training and incorporates both classroom and practice-based components. Though still in its early stages, the sea level rise and public health training effort has already achieved significant successes and continues to grow. The article begins by examining sea level rise as a public health issue. This is followed by a discussion of the new public health training initiative in Coastal Virginia. The article closes by exploring future directions.

Keywords: sea level rise, public health, resilience, intergovernmental pilot project

Introduction

It is now widely understood that sea level is rising around the world. Over the past century, global mean sea level has already risen approximately 8 inches (Levy & Patz, 2015). But this represents a global average; the sea is actually rising "much more in some places than in others" (Sobel, 2014). In the Miami area, for example, sea level is estimated to have increased by significantly more than the global average, rising about a foot in the past 100 years. Similar increases have been experienced in New York and Charleston (New York City Panel on Climate Change, 2015; City of Charleston, 2015). Furthermore, the rate of sea level rise has not remained steady; rather, there is strong evidence that it is speeding up significantly (NOAA, 2017a; Nerem et al., 2018). For example, it has been reported that the sea has risen nearly 4 inches in Miami in just the past two decades (McNoldy, 2015).

With the scope and urgency of the problem of global sea level rise becoming more apparent every year, a host of disciplines and professions are now working to better understand this emerging threat and its implications. From biology, ecology, and environmental science to ocean science, coastal engineering, and underwater robotics, a variety of fields are helping to further illuminate the dynamics of the problem, identify current and future challenges, and begin to fashion effective responses.

Because some of the most significant impacts of rising sea level are those directly or indirectly affecting human health, another field that has a pivotal role to play is public health. The field of public health "promotes and protects the health of people and the communities where they live, learn, work and play" (APHA, 2017). Whereas a medical doctor can be thought of mainly as treating and healing sick individuals, public health deals with the health of entire populations (APHA, 2017). "These populations can be as small as a local neighborhood, or as big as an entire country or region of the world" (CDC Foundation, 2017).

The need for a major public health role in addressing sea level rise stems from the fact that rising seas have the potential to affect vast numbers of coastal communities and inhabitants. From a global perspective, "eight of the top ten largest cities in the world are located by the coast" (UN, 2016). In the U.S. context, approximately 40% of the nation's population resides in counties directly on the shoreline (NOAA, 2017b). In other words, rising seas have the potential to directly or indirectly impact the health of millions of people.

The health impacts of sea level rise are expected to grow in the coming decades, creating significant challenges for local and state public health departments; regional, national and international health agencies; and other components of the public health field. As such, it will be vital for public health professionals to be involved and prepared. This article discusses a novel effort that has been undertaken to help prepare "the next generation of public health professionals to grapple with sea-level rise issues" (IPP, 2016). Launched in Coastal Virginia in 2015 and focusing on public health graduate level training, the effort is still in its early stages. But it has already achieved significant successes and continues to grow. The article begins by examining sea level rise as a public health issue. This is followed by a discussion of the new public health training initiative in Coastal Virginia. The article closes by exploring future directions.

Rising Seas and Public Health

Sea level rise has the potential to directly or indirectly affect the health of coastal populations in a multiplicity of ways. Rising seas can result in increased salinity of estuaries and aquifers, harming vital drinking water supplies upon which communities depend. Changes in salinity can also foster the growth of microorganisms, including those associated with human illness. In addition, rising seas can raise water tables and greatly exacerbate drainage problems. Pools of standing water can accumulate, facilitating the growth of mosquito populations and increasing the risk of disease spread. Sea level rise is also associated with increases in the frequency and severity of flooding. Indeed, in recent decades, there has been a dramatic increase in "minor" flooding events (also sometimes described as "nuisance" flooding) on all three U.S. coasts—Atlantic, Pacific, Gulf (NOAA, 2014a). This phenomenon is clearly illustrated by the experience of Atlantic City, New Jersey, where the average number of flood days has gone from 3.1 per year in the period between 1957 and 1963 to 24.6 a year in the period between 2007 and 2013. Another particularly striking example is Annapolis, Maryland, where the average number of flood days has gone from 3.8 per year in the period between 1957 and 1963 to 39.3 a year in the period between 2007 and 2013. This represents a 925% increase (NOAA, 2014b).

The term "minor" (or "nuisance") flood can be quite misleading, because these flooding events can result in a host of significant hazards. Such floods can render roads impassable, isolating individuals and neighborhoods. Water-covered roads can make it difficult for people to get to important medical appointments, stop individuals from going to pharmacies to obtain medicines, and impede emergency vehicles trying to respond to calls for help. Minor floods can also damage vehicles, homes, and infrastructure (Spanger-Siegfried et al., 2014). Meanwhile, building materials left damp by minor floods provide an excellent environment for the rapid growth of mold. According to public health experts, "the spores of some varieties can begin to germinate in as little as 4 to 12 hours" (Parrot, 2009) and "significant mold growth can occur" within 48 h of materials being exposed to water (Johanning et al., 2014). Depending on the type of mold involved, this can increase the risk of allergy, asthma, and respiratory problems in sensitive populations (Parrot, 2009; EPA, 2016). Finally, in some situations, recurrent flooding may even require people and communities to relocate (Spanger-Siegfried et al., 2014). In short, so-called "minor" flood events can constitute a serious problem with significant public health consequences, particularly as the scope, frequency, and severity of such flooding events increases over time.

If "minor" flooding represents a significant and growing problem, major flood events linked to storms and storm surge can constitute a grave threat. Storm surge is the additional ocean water that is pushed onto shore by a storm (Miles, 2014). It comes on top of whatever water is normally already there. Thus, if an area is experiencing a regular high tide at the time of a storm, the amount of water pushing onto land will be the high tide plus the surge (Miles, 2014). Sea level rise adds another component. When an area has been affected by significant sea level rise, any storm surge that occurs comes on top of the regular tide and on top of the already elevated sea level. The result can be massive, destructive flooding events.

The public health consequences can be serious and widespread. At the most obvious level are deaths due to drowning. Superstorm Sandy provides a powerful illustration. In New York City, the number one direct cause of death from Superstorm Sandy was drowning associated with the storm surge (Lane et al., 2013). The "majority of deaths occurred in Queens and on Staten Island, and most people perished at the height of the storm, drowned by the surge" (NYT, 2012). According to Sobel (2014), some people drowned in their homes, whereas others perished in vehicles as they tried to escape.

People can also die as a consequence of having to evacuate. Particularly for individuals who are ill, frail, or in care, the process of having to move or be moved can be difficult and traumatic. For some, the result can be premature death. A 2012 study looked at records for more than 36,000 nursing home residents who had experienced Gulf hurricanes (Katrina, Rita, Gustav, and Ike). The analysis concluded that the process of evacuation had compounded morbidity and mortality (Dosa et al., 2012).

Other public health impacts result from the effect of floodwaters on infrastructure. Floodwaters and surge can cause sewers to back up or overflow, collapse or break sewer lines, overtop or engulf sewage treatment facilities, and even completely overwhelm the treatment network. During Superstorm Sandy, for example, "11 billion gallons of sewage flowed into the floodwaters engulfing New York and New Jersey" (Miles, 2014). Floodwaters polluted with human and animal waste can carry high levels of fecal bacteria, which can lead to intestinal and other illnesses (Esworthy, Schierow, Copeland, Luther, & Ramseur, 2006). Rising waters can also damage underground storage tanks, causing hazardous materials to leak into soil, groundwater, and floodwaters and posing a threat to people and the environment (EPA, 2010). Commercial and industrial operations, landfills, and other key facilities can be compromised, potentially releasing biological, chemical, and other contamination into communities (Few & Matthies, 2007).

Flooding events can also affect key healthcare and public health facilities, causing impacts not only to the facilities themselves but impairing the capacity of the system to provide services and assistance to people in affected areas. For example, during Superstorm Sandy, storm surge flooded key radiology facilities at NYU Langone Medical Center. Four MRI scanners, some CT systems and X-ray equipment were destroyed (Knaub, 2013; Godt, 2013). Likewise, at Bellevue Hospital, "millions of gallons of contaminated water pooled in the basement." The morgue flooded, forcing medical personnel to look for other places to keep bodies of the deceased (Miles, 2014, p. 327).

This broad array of potential health impacts makes the sea level rise issue a quintessential public health problem and makes it vital for public health professionals to be involved. The central aim of public health professionals—whether they work for local or state health departments, federal agencies such as the CDC, nongovernmental organizations, laboratories, the hospital and healthcare system, or other agencies —is to "prevent people from getting sick or injured in the first place" (APHA, 2017). Public health responsibilities and initiatives range widely. They include vaccinating children and adults to protect them from serious infectious diseases, programs to reduce tobacco use among young people, efforts to prevent childhood lead poisoning by reducing exposure to lead paint and other sources of lead, monitoring bacteria levels in beach water and issuing swimming advisories, community screening for chronic and communicable diseases/conditions, licensing and inspecting medical and dental X-ray machines and similar devices, and working to ensure the safety of food through such measures as monitoring shellfish for pathogens/toxins and conducting inspections of restaurants and other food establishments (ASTHO Profile, 2017; NACCHO, 2017; Salinsky, 2010; Washington State Department of Health, 2018). Public health also plays a critical role in preparedness and response to health emergencies (Stoto et al., 2005). When foodborne illness outbreaks involving such pathogens as *Escherichia coli*, listeria, and salmonella occur, it is public health epidemiologists, environmental health specialists, laboratorians, and others who track the outbreak, identify the pathogen and the affected foods, and respond to protect members of the public. For example, public health professionals responded to a major, multistate outbreak of *E. coli* O157:H7 infections that killed four children and left hundreds of other people ill, tracing it to consumption of contaminated hamburger patties (MMWR, 1993). Likewise, public health professionals help prepare for, assess, and respond to natural disasters, hazardous materials emergencies, pandemics, terrorism incidents, and ecological disasters (Falk & Ashkenazi, 2012; ASTHO Profile, 2017; NACCHO, 2017; Salinsky, 2010; Washington State Department of Health, 2018). For example, after the Deepwater Horizon disaster in 2010, public health professionals played an important role in assessing chemical air monitoring results, analyzing the safety of seafood, monitoring the health of cleanup workers and people living in affected communities, and providing health information to the public (see, e.g., Michaels & Howard, 2012; LDHH, 2010, 2012).

The health consequences of sea level rise touch upon many of the aforementioned core concerns, responsibilities and activities of public health professionals. With respect to flooding situations, for example, public health concerns might range from ensuring the safety of food and drinking water supplies after flood events to testing floodwaters for biological, chemical, and other contaminants and from identifying and managing mold problems to assessing the immediate and longer-term health implications of evacuation or relocation. Clearly, then, public health has a critical role to play in helping to protect populations, foster resiliency, and reduce or prevent impacts from sea level rise. As such, it is essential for public health to be "an integral part of current and future sea level rise adaptive planning efforts" (IPP, 2016).

Preparing the Next Generation of Public Health Professionals

To help prepare the next generation of public health professionals to meet the growing health challenges posed by rising seas, a new training initiative was launched in the Hampton Roads region of Southeastern Virginia. Begun in 2015 and continuing to expand today, the effort is being led by Old Dominion University (ODU) in conjunction with Eastern Virginia Medical School (EVMS). The effort incorporates both classroom-based and practice-based activities and includes content on sea level rise and public health in the region and beyond.

The new training initiative grew out of discussions of public health issues that took place through the Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Pilot Project or IPP. Convened at ODU and operating from 2014 to 2016, the IPP's purpose was to bring together a broad range of stakeholders to create a fully comprehensive, integrated approach to sea level rise preparedness and resilience planning in the Hampton Roads region that can also be used as a template for other regions in the United States (IPP, 2015, 2016). Hampton Roads, which has a population of some 1.7 million people, is made up of 17 localities, including the independent cities of Norfolk, Virginia Beach, Chesapeake, Newport News, Hampton, Portsmouth, Suffolk, Poquoson, and Williamsburg. The area has hundreds of historic sites, a long coastline, and beautiful beaches, making it a popular tourist destination.

In addition, the region is one of considerable strategic importance, being home to numerous industries and research facilities, the Port of Virginia (the third biggest U.S. East Coast container port) and a variety of important defense facilities. These include Joint Base Langley-Eustis, Naval Air Station Oceana, Joint Expeditionary Base Little Creek-Fort Story, and Naval Station Norfolk (the largest naval base in the world). The Hampton Roads area and the Chesapeake Bay region more generally are situated at a low land elevation, are undergoing significant subsidence of land, and (like other coastal areas) are experiencing the effects of rising seas (Maryland Sea Grant, 2015). In addition, the city of Norfolk has been identified as one of nine high-risk areas of the North Atlantic Coast in terms of coastal flood risk (NACCS, 2015). Given the region's importance, future sea level rise could have both immediate effects and bigger implications that extend well beyond Hampton Roads.

Employing a "whole of government" and "whole of community" approach, the IPP successfully engaged representatives from a variety of federal agencies, the Commonwealth of Virginia, many localities, elected officials, the Port of Virginia, academia, the Navy, the Coast Guard, the Air Force, the Army Corps of Engineers, private industry (e.g., Newport News Shipbuilding), the legal profession, nongovernmental organizations, infrastructure, vulnerable communities, the real estate community, and other sectors (IPP, 2015, 2016). In 2015, the IPP identified public health as another crucial area needing attention. In April of that year, ODU faculty briefed the IPP Steering Committee on the crucial links between sea level rise and public health. Shortly thereafter, the Steering Committee, by consensus, established a new Public Health Working Group as the fifth working group of the Pilot. (The other four working groups were legal, infrastructure, land use planning, and citizen engagement.) This established public health as a core component of the IPP's work. One significant need identified in discussions with public health professionals was to find new and innovative ways of incorporating sea level rise issues into public health education and training (IPP, 2015, 2016).

Informed and encouraged by the IPP's work, faculty in ODU's School of Community and Environmental

Health moved to create new education and training opportunities for developing public health professionals. The aim: to provide developing public health professionals with a broad understanding of sea level rise and its many public health implications so that they can (1) help identify potential health impacts; (2) contribute to the creation of public health strategies for preventing, reducing, or responding to such impacts; and (3) help to foster more resilient communities.

The new effort centers on the Masters of Public Health (MPH) program. Public health professionals typically gain their foundational professional education and first practical public health training through the multidisciplinary MPH degree. This is where developing public health professionals learn the field and begin to practice it. Thus, the MPH provides an ideal setting in which to incorporate content and activities to enhance public health understanding and readiness for sea level rise.

Although MPH programs can vary, it is typical for the first year in the 2-year degree program to focus on providing foundational knowledge across all areas of public health (including epidemiology, biostatistics, health promotion and health behavior, health policy and health administration, and environmental health). The second year of the degree provides more specialized knowledge (e.g., in such areas as environmental science, toxicology, emergency management, health communication or infectious disease) and an opportunity for real-world application and training.

To ensure that all graduating MPH students—regardless of track or specialty—would be provided with significant knowledge of sea level rise issues, a decision was made to incorporate substantial coverage of sea level rise issues into a first-year core course. The course that was chosen was ODU's foundational course in environmental health that is taken by all MPH students. The three-credit course, entitled Principles of Environmental Health Science, has a typical enrollment of about 60 students per year.

Coverage of sea level rise and public health has been incorporated into the course through a 2-week module. One week introduces the problem of sea level rise and its public health implications. Topics include historical and recent data on global mean sea level rise, sea level rise in relation to the United States, minor flooding, storm surge, direct and indirect health impacts of sea level rise, vulnerable populations, challenges for public health infrastructure and the healthcare system, and implications for public health planning and training.

Students are also provided with the opportunity to consider public health lessons learned from recent flood events. To help illustrate the issues and identify key lessons, students learn from case studies and watch and discuss documentaries. For example, in 2016–2017, students watched two PBS NOVA programs on Superstorm Sandy. NOVA, the award-winning science series on PBS, is produced by WGBH Boston. One of the programs provides extensive information about the effects of storm surge, enabling students to gain a better understanding of the range of issues and impacts (NOVA, 2012). The second program provides information about different approaches for dealing with sea level rise, helping students to consider what changes may be needed to make cities more resilient in the future (NOVA, 2013).

Augmenting the first week of coverage is a second course week that focuses on local sea level rise impacts and issues in relation to public health. Here, noted experts in such areas as oceanography and vulnerability assessment examine flooding patterns in Norfolk and other nearby areas and discuss a range of adaptation, mitigation, and resilience measures. Meanwhile, other modules in the course (e.g., public health emergency preparedness, environmental risk communication) provide opportunities for students to relate sea level rise issues to other aspects of public health. In the second year of the MPH curriculum, students with a continuing interest in the health aspects of sea level rise have the opportunity to reinforce and expand their knowledge through some elective courses that include additional relevant content. For example, in the second-year course entitled Environmental Emergencies and Disasters, students examine historical and recent disaster trends, examine the health implications of community disruption and evacuation, learn more about special populations in disaster, and participate in problem-solving disaster teams.

Whereas the course-based components are intended to provide a basic working knowledge of sea level rise and public health to all MPH students, it is also important for students choosing to focus on this topic to have a way to gain much more in-depth knowledge of the issues as well as practical experience. To achieve this aim, the region's first "community practicum" focusing specifically on sea level rise and health was created in 2015. The 200-h practicum provides students with an in-depth supervised practical public health experience. Under the guidance of an on-site preceptor and an academic adviser, students work on real-world public health issues using the knowledge and skills gained in academic courses.

The first practicum on sea level rise and public health was completed in 2016. MPH student Christine Gumina was based at the IPP, where she worked under the direction of preceptor Emily E. Steinhilber, Assistant Director of Coastal Resilience Research. (The author served as the student's academic advisor.) Ms. Gumina's multipart project involved carrying out an initial review of public health impacts of sea level rise, focusing on a smaller subset of those impacts and relating the findings to the Hampton Roads area. Ms. Gumina also participated in IPP committee and working group meetings, where she interfaced with officials from local, state, and federal agencies, the uniformed services, research institutions, and other organizations (IPP, 2016).

The following year, a second MPH student practicum on sea level rise and health was successfully completed. This second practicum, under the auspices of the Commonwealth Center for Recurrent Flooding Resiliency at ODU, focused on identifying opportunities for increasing public health resilience to sea level rise and recurrent flooding in Hampton Roads. Plans for additional sea level rise practicums are at an advanced stage as of the time of this writing. Meanwhile, since the two interrelated modules on sea level rise and public health were added to the first-year MPH student curriculum, more than 160 students have covered and been examined on the content. This number will continue to grow in the coming years. All will take this knowledge with them as they assume positions in the public health workforce.

Next Steps

Although the new training initiative on sea level rise and public health is still a work in progress, it has already created a solid foundation for expanded efforts in the near future. Next steps include incorporating additional sea level rise content into second-year elective courses, creating an entire MPH level course on sea level rise and public health, and establishing a broader range of sea level practicum sites. Another near-term step involves further developing the training effort's competencies and learning outcomes. The initial set of competencies that guided the launch of the training effort will be expanded and refined using experience gained to date and drawing on input and feedback from sea level rise experts, local and state health departments, and other agencies and stakeholders. Likewise, metrics and evaluation methods will be refined. Taken together, these next steps will help to ensure the continued effectiveness of the training effort.

Conclusion

Global sea level rise has the potential to directly or indirectly affect the health of vast numbers of coastal communities and inhabitants. Thus, in partnership with other fields working to address the issue of sea level rise, public health agencies and professionals have a pivotal role to play in protecting populations, identifying, reducing and preventing impacts, and fostering resilience. The new training initiative in Coastal Virginia—though still in its early stages—is already beginning to help prepare the next generation of public health professionals to meet the challenge.

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Modeling the Impacts of Sea Level Rise on Storm Surge Inundation in Flood-Prone Urban Areas of Hampton Roads, Virginia

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ABSTRACT

Hampton Roads is a populated area in the United States Mid-Atlantic region that is highly affected by sea level rise (SLR). The transportation infrastructure in the region is increasingly disrupted by storm surge and even minor flooding events. The purpose of this study is to improve our understanding of SLR impacts on storm surge flooding in the region. We develop a hydrodynamic model to study the vulnerability of several critical flood-prone neighborhoods to storm surge flooding under several SLR projections. The hydrodynamic model is validated for tide prediction, and its performance in storm surge simulation is validated with the water level data from Hurricane Irene (2011). The developed model is then applied to three urban flooding hotspots located in Norfolk, Chesapeake, and the Isle of Wight. The extent, intensity, and duration of storm surge inundation under different SLR scenarios are estimated. Furthermore, the difference between the extent of flooding as predicted by the hydrodynamic model and the "bathtub" approach is highlighted.

Keywords: hydrodynamic modeling, storm surge, sea level rise, flooding of transportation infrastructure

Introduction

Nearly 30% of the U.S. population, or 87.4 million people, lived in coastal counties in 2008, showing an increase of 84.3% with respect to 1960 (Wilson & Fischetti, 2010). Recent hurricanes Irma (2017), Harvey (2017), Sandy (2012), and Katrina (2005) have had devastating impacts on highly populated coastal areas in the U.S. Gulf and Atlantic Coasts. High wind speed and storm surge flooding are the main hazards for people and coastal infrastructure. Prior to major storms, the authorities may demand evacuation of residents from areas vulnerable to storm surge. State roads and interstates prove to be the preferred evacuation routes, despite the potential high vulnerability that they may have in respect to flooding (Kleinosky et al., 2007).

Climate change and its consequences, including sea level rise (SLR), threaten the low-lying coastal infrastructure, and hence, accurate estimation of storm surge flooding in the current and future state of the climate is critical for coastal planning and management. SLR provides a path for storm surge and energetic oceanic waves to propagate toward the infrastructure in the upland and cause damage. Furthermore, atmospheric models suggest that climate change can result in an increase in the number of large hurricanes (Bender et al., 2010).

Storm surge flooding may be estimated using different approaches depending on the necessities and the resources available (Murdukhayeva et al., 2013). For instance, the "bathtub" approach has long been used to estimate the extent of storm surge flooding and SLR impacts. Although this approach can provide first-order estimates of storm surge, it can include significant inaccuracies since it is based on static increase in water level. However, the response of storm surge to increase in sea level is nonlinear, such that a certain amount of increase in sea level does not necessarily result in the same amount of increase in storm surge flooding (Atkinson et al., 2013). This is due to the complex physics of the interactions among storm surge, tides, waves, and the overland flow, as well as their interactions with the natural and urbanized landscape. Therefore, a more accurate estimate of storm surge requires an approach that accounts for the dynamicity of storm and tides.

The Hampton Roads region of Virginia is one of the most vulnerable areas in the world to climate change and SLR in terms of population size and values of assets. It is a metropolitan region located at the confluence of the James, Elizabeth, and Nansemond rivers and comprises 10 cities with a total population of 1.7 million. The Port of Virginia located at Hampton Roads is the second largest port on the East Coast of the United States, and Norfolk is home to the largest naval base in the world. The region has the second highest relative SLR rate in the United States (~7 mm/year) only behind New Orleans (Boon et al., 2010). Several factors including crustal warping, sediment compaction, and groundwater withdrawal (Kleinosky et al., 2007), as well as the dynamics of the Gulf Stream (e.g., Ezer et al., 2013), contribute to this high rate of relative SLR. Recurrent flooding of the infrastructure is a common occurrence in the region, and SLR has exacerbated the problem. Research shows that the accelerated rate of minor flooding due to high tides and precipitation in recent years can be attributed to SLR (Ezer & Atkinson, 2014).

Several previous studies have investigated storm surge flooding in the Hampton Roads region. For instance, Li et al. (2013) used the Coastal Modeling System (CMS), a suite of models that simulate storm surge, waves, circulation, sediment transport, and morphological change, to study SLR impacts on Naval Station Norfolk. The domain of the CMS was limited to the naval base, and the boundary conditions to this domain were produced by the ADCIRC model (Westerink et al., 2008). Loftis et al. (2016) used the subgrid modeling approach (Neelz & Pender, 2007) to simulate the precipitation- and storm surge-driven flooding in NASA Langley Research Center. The approach allows for nesting high-resolution LiDAR elevation data in lower-resolution computational grids of the hydrodynamic model. They show that flooding estimation improves by accounting for infiltration using land use data. The hydrodynamic model used in the study is the UnTRIM^2 model (Casulli & Stelling, 2011). Sadler et al. (2017) estimated the most vulnerable transportation infrastructure is in the Hampton Roads cities of Norfolk and Virginia Beach. Applying the “bathtub” approach, results suggested that under the intermediate scenario, by 2100 around 10% of major roads in Virginia Beach and Norfolk were predicted to regularly flood due to tides reaching 2.1 m NAVD88. The percentage increases to over 15% of major roads with a 99% tide (2.6 m) and to over 65% of major roads with the addition of a 100-year storm surge (4.5 m). The study uses the “bathtub” approach to add storm surge estimates to SLR projections. Consequently, earlier flooding studies have either used the “bathtub” approach (e.g., Sadler et al., 2017) or have used hydrodynamic models to focus on a small study area (Li et al., 2013; Loftis et al., 2016).

In this study, a hydrodynamic model is developed to predict hurricane storm surge in high resolution at several flood-prone critical spots in the Hampton Roads region of Virginia. These critical spots are known to experience recurrent and storm surge flooding that causes disruption in the transportation infrastructure. This study expands the earlier investigation by Castrucci and Tahvildari (2017) in which the vulnerability of two critical areas in Norfolk to storm surge flooding was assessed. The effect of various SLR projections on storm surge flooding is considered.

Methodology

The hydrodynamic model of the region is developed based on the Delft3D model. Delft3D is a widely used three-dimensional modeling suite that can simulate coastal, estuarine, and riverine processes. The model has recently been used for storm surge simulations (Vatvani et al., 2012; Hu et al., 2015). The hydrodynamic model is set up with boundary conditions at the bottom (bathymetry and topography), water surface (atmospheric forcing), tidal forcing, and freshwater input at the boundaries. The model then solves the complex interactions between the flow and the landscape over a computational grid and obtains high temporal and spatial resolution information on water surface elevation at grid cell centers and flow velocity at grid cell faces.

The wind field that drives the storm surge is generated using the Holland et al. (2010) parametric model and the pressure and track data for Hurricane Irene (2011) provided by the National Oceanic and Atmospheric Administration (NOAA) National Hurricane Center (Lixion & Cangialosi, 2011). We assess the impacts of three SLR scenarios, namely intermediate-low (IL), intermediate-high (IH), and extreme on storm surge flooding of three flood-prone critical spots. These areas are the West Brambleton Avenue (US 58) and the Hague neighborhood in the City of Norfolk, the James River Bridge that connects Isle of Wight County to the City of Newport News, and the High Rise Bridge on I-64 in the City of Chesapeake. The first spot was selected due to historic issues with recurrent flooding and vicinity to the Norfolk General Hospital, which houses the region's only Level 1 trauma center (Scott Smith [City of Norfolk], personal communication). The last two spots were selected due to known flooding problems and substantial traffic volume (Robert Morgan & Andrew Scott [Virginia Department of Transportation], personal communication). By comparing model output on water levels with high-resolution topographic data obtained from a geographic information system data set, we determine the flooding extent, intensity, and duration at these critical points. Accurate prediction of the time and duration of flooding at these areas will help the decision makers with advanced warnings and rerouting of the general traffic as well as emergency vehicles.

Hydrodynamic Model Setup

In this study, we use the Delft3D-FLOW model to simulate the nonsteady flow processes generated by tidal and meteorological forcing. The model solves the equations for fluid motion and obtains flow variables, namely velocity vectors, pressure, and water surface elevations over a computational grid.

Grid Generation

The grid size is selected such that the results are obtained at high spatial resolution while keeping the computational time reasonable. It is noted that, in a grid with a variety of cell sizes, the simulation time step is governed by the smallest cell. Therefore, an efficient way to run the simulations using structured grids is to define multiple models with different domain extents that have nearly uniform grid cell sizes. In this approach, known as model nesting, the model that covers a larger geographical area will have a lower grid resolution (Level 1) and produces the boundary condition for a nested model (Level 2) that has a computational grid covering an area within the larger grid of the model at Level 1. The nesting can continue to higher levels (e.g., Levels 3, 4, etc.) in a similar manner. An advantage of model nesting approach is that it allows for utilizing high-resolution data (e.g., meteorological, topographic, or bathymetric data) at higher levels of nesting where high-resolution output is desired whereas low-resolution data are used at the models in lower levels of nesting. This approach will result in considerable reduction in computational time. In this study, we decided to develop the hydrodynamic models in three levels of nesting (Levels 1–3). This approach allows us to use high-resolution LiDAR data (0.76 m horizontal resolution) at several critical flood-prone spots in Level 3 models and keep the computational time reasonable with available resources.

The computational grid of the Level 1 model is shown in Figure 1. The grid is equidistant, such that the distances between a cell center and adjacent cell centers are equal. The cell size in this grid is 125 × 200 m^2. Figure 2 shows the computational grid of the Level 2 model as well as grids of local Level 3 models. The grids of Level 2 and Level 3 models are curvilinear, and their cell sizes vary 30–90 × 30–90 m^2 and 2.5–3.5 × 2.5–3.5 m^2, respectively. The yellow lines in Figure 2 show the boundaries of the Level 2 model, and red areas show the domain of high-resolution Level 3 models, which are constructed around the critical spots. The high grid resolution in Level 3 models enables us to utilize

FIGURE 1

(a) Delft3D model domain at Level 1 of nesting and (b) the computational grid of the Level 1 model in the Hague neighborhood in Norfolk.

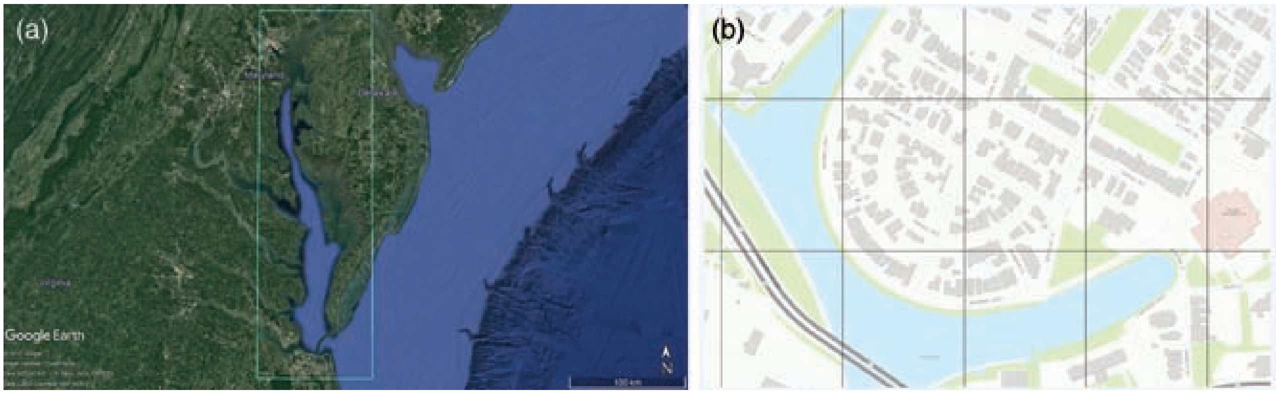
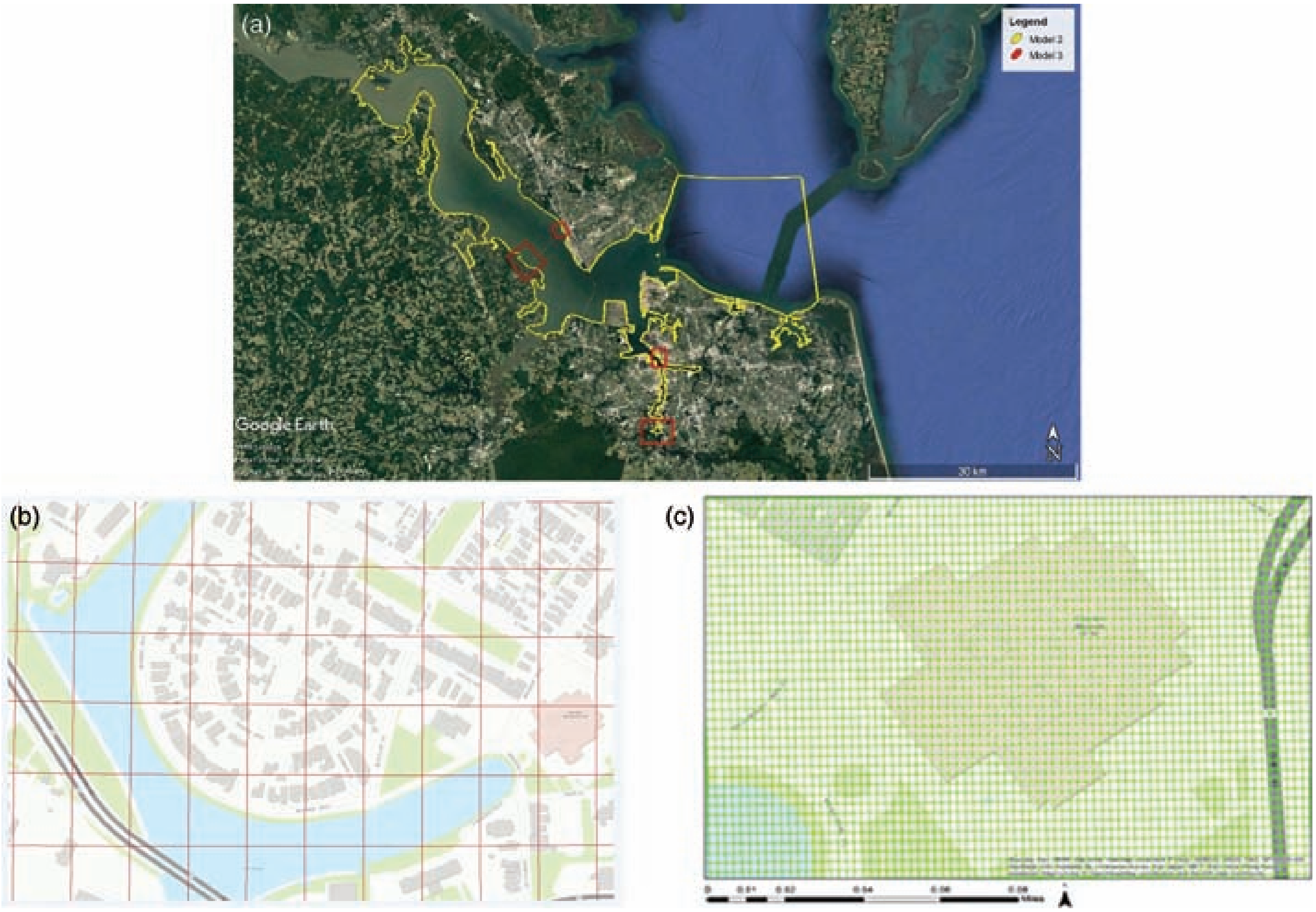


FIGURE 2

(a) Level 2 (specified in yellow) and Level 3 (specified in red) model domains, (b) the computational grid of the Level 2 model, and (c) Level 3 models in the Hague neighborhood in Norfolk.



high-resolution LiDAR data and develop street level flood maps.

Boundary Conditions

The hydrodynamic storm surge model requires topography, bathymetry, tide, wind, and river discharge data to perform the numerical simulations.

Topography and Bathymetry Data. The accuracy of the predictions of hydrodynamic models depends on the resolution of the available data (Sebastian et al., 2014). High-resolution LiDAR topographic data for this project are not available for the entire Hampton Roads region, but it completely covers the cities of Norfolk, Hampton, Virginia Beach, and Chesapeake. The topographic data were extracted from the digital elevation model of this data set, which has a 0.76 m horizontal resolution and was utilized in the simulations that used the Level 3 model. In Level 1 and Level 2 models, which have larger domains, we used the freely available highest-resolution bathymetric and topographic data from NOAA. Table 1 summarizes the sources of the topographic/bathymetric data used in the

TABLE 1

The bathymetric and topographic data sources and resolution in the nested model.

Data	Source	Resolution/Nesting Level
Topography	NOAA–Coastal Relief Model	90 m/first level
Topography	NOAA–Virginia Beach Raster	10–30 m/second level
Topography	USGS–Hampton Roads LiDAR	0.76 m/third level
Bathymetry	NOAA–Coastal Relief Model	90 m/first level
Bathymetry	NOAA–Virginia Beach Raster	10–30 m/second and third level

study as well as the spatial resolution of each data set. The elevation data from different sources did not have the same datum and coordinate system, and as such, they were converted to NAVD 88 using VDatum. Although the bathymetry and topography had the same resolution in Level 1 and Level 2 models, their resolution differed in Model 3 where the topography and bathymetry had 0.76 m and 10–30 m resolution, respectively.

Tides. High tides contribute to the flooding significantly, and they should be accounted for in the storm surge model. The Delft3D model is forced by amplitudes and phases of nine primary tidal constituents (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, and M_4) at the open boundaries of the Level 1 model. The amplitudes and the phases of these harmonics were interpolated using the values from the TPXO global tide model (Egbert & Erofeeva, 2002), which has a 1/30° resolution at the U.S. East Coast. The points where the tidal information is extracted are selected such that they are close to the coastline, otherwise the tidal propagation in shallow water may not be adequately reproduced due to relatively low topography and bathymetry resolution in the Level 1 model.

Wind Profile. The most important boundary condition in hurricane surge simulation is the wind and pressure fields. According to the data from the NOAA tide gauge at Sewells Point, VA, Hurricanes Irene (2011) and Sandy (2012) caused the largest storm surge among the hurricanes that affected the Hampton Roads region in the past decade. The storm surge that resulted from these two hurricanes in Hampton Roads (based on measurements at the Sewells Point tide gauge) are nearly the same. For this research we decided to use the characteristics of Hurricane Irene to set up the wind field. Because of the low resolution of wind and pressure data from satellites, the hurricane profile was created using the Holland et al. (2010) model. The model generates the wind profile using the maximum wind velocity, minimum pressure, and storm diameter. The storm path, maximum wind velocity, and minimum pressure were provided by the NOAA National Hurricane Center (Lixion & Cangialosi, 2011), whereas the storm diameter was estimated according to the Gross et al. (2004) model. The output values from the Holland et al. (2010) model were inserted in a meteo mesh, which shaped as a spider web can host variable grid sizes that increase resolution as they approach the center of the network. The spider web grid was generated to be large enough to accommodate changes in storm size, which varies with maximum velocity and central pressure, which experienced changes along Hurricane Irene's path. The main characteristic of the spider web domain is related to its nonstationary position, which changes during the simulation according to the hurricane path. The wind field is interpolated to the computational grid.

River Discharge. The discharge of the James River is used as a boundary condition in the western open boundary of the Level 2 model. The river discharge is recorded every quarter of an hour by a United States Geological Survey (USGS) gauge located near Richmond, Virginia.

Results

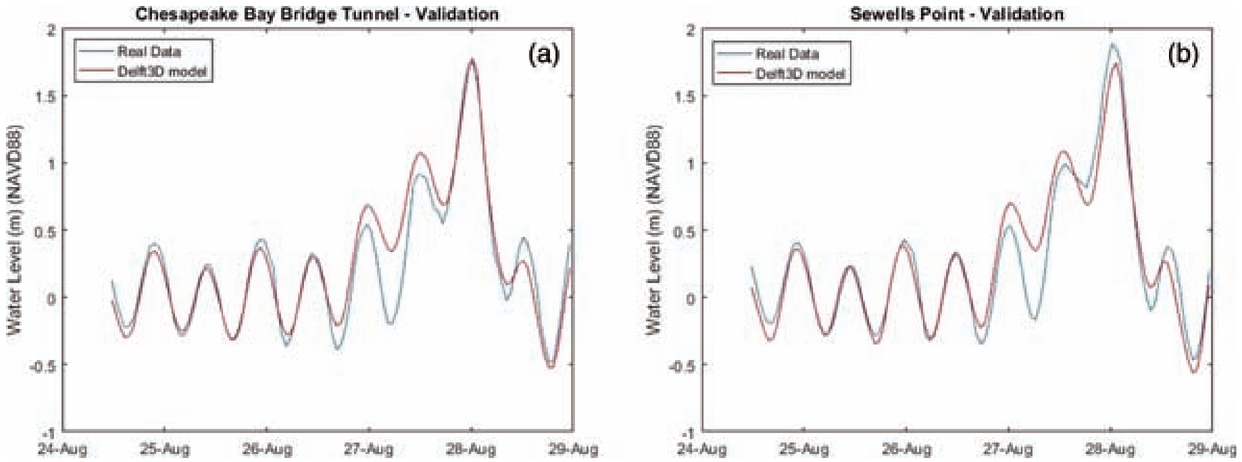
Model Validation

Prior to applying the storm surge model to future SLR scenarios, we validate the model with the observed storm surge from Hurricane Irene (2011). The validated storm surge model then uses the Hurricane Irene parameters to predict storm surge levels and flooding duration due to Irene-like storms in future sea level conditions.

The model parameters are kept constant over the three levels of nesting. Sea water density is 1,025 kg/m^3, background atmospheric pressure is 1,030 mbar, the bottom roughness is represented by the Manning coefficient, which is assumed to be 0.03 in the Level 1 model and 0.02 in both Level 2 and Level 3 models. These values were obtained through tide calibration. Horizontal eddy viscosity is kept the same as the default value of 1 m^2/s. All the boundary conditions in the model, such as bathymetry and initial water level, have been specified at the corners of the grid cells, and the threshold depth for wetting and drying is specified to be 0.1 m. The vertical datum is NAVD88. We used the data from two NOAA tide gauges located at the Chesapeake Bay Bridge Tunnel (CBBT) and the Sewells Point to validate the performance of the Delft3D model. The CBBT data were used to validate the Level 1 model. The domain extent and grid resolution of the Level 1 model were selected such that the storm track through the Hampton Roads area is captured adequately while ensuring that the grid has a high enough resolution to capture the storm and tide propagation into the Chesapeake Bay. As seen in Figure 3(a), Level 1 model results for Hurricane Irene and the tidal elevations prior to the storm compare well with the buoy data. The root mean square error (RMSE) is 0.156 m. The only notable discrepancy occurs

FIGURE 3

Comparison between hydrodynamic model results for water level and measurements at (a) CBBT and (b) Sewells Point tide gauges during Hurricane Irene (2011).



at two tidal cycles prior to the storm peak, which can be due to uncertainty in the size of the storm in this time frame; Hurricane Irene's radius was hard to estimate due to larger than normal size of the cyclone and the absence of a particularly intense inner core during August 26–27 (Lixion & Cangialosi, 2011). Therefore, we hypothesize that the assumption that the hurricane radius is constant with time and space may have resulted in this discrepancy. We note that the HWind legacy data for Hurricane Irene is publicly available and using the data may resolve these discrepancies. However, recent research shows that a hydrodynamic + wave model that uses a Holland-type parameterization for atmospheric forcing can provide a more accurate estimation of storm surge than the model, which uses HWind data (Dietrich et al., 2017). The study used the data from Hurricane Isaac (2012) in the Gulf of Mexico, and the results of the study may not be applicable to the present investigation. Nevertheless, the model estimation for water levels at the storm peak compare well with the data. Level 2 model is validated using the Sewells Point tide gauge. As seen in Figure 3(b), the model result for tidal elevation and the storm surge compare well with the data. The RMSE is 0.155 m. The slight discrepancy observed at the peak may be attributed to the inadequacy in representation of the shallow bathymetry in the model. There were no tide gauges in the domains of Level 3 models in 2011; hence, the calibration and validation of these models with tide and storm surge data were not possible. However, a tide gauge was installed on a bridge in the Hague area in 2016, and the data can be used for similar future studies.

Storm Surge Under SLR

Several critical flood-prone locations were considered, and three were selected for this study: the Hague neighborhood located in downtown Norfolk, the James River Bridge connecting the Isle of Wight county to the City of Newport News, and the I-64 Bridge in Chesapeake. These three spots are known to be vulnerable to direct storm surge inundation, and their flooding can significantly disrupt the traffic flow. It is worth noting that there are many spots in the transportation infrastructure in the region that are indirectly vulnerable to storm surge flooding. In these spots, higher water due to storm surge and high tides submerge the outlets and cause the storm water to back up in the drainage system and prevent the storm water infrastructure from functioning properly. This effect will contribute to flooding even in areas that are not directly inundated by storm surge. However, our study is focused on the direct storm surge-induced inundation.

We considered three SLR projections presented in a recent NOAA report by Sweet et al. (2017). This report adds an extreme flooding scenario to estimates proposed in earlier studies. In this study, we use SLR with IL, IH, and extreme rates. Table 2 summarizes these estimates for 2050 and 2100, the two time frames considered in this study. It should be noted that the study can readily be extended to other SLR estimates. The effect of SLR is added to the model by increasing the water level to the desired values at the boundaries of Model 1

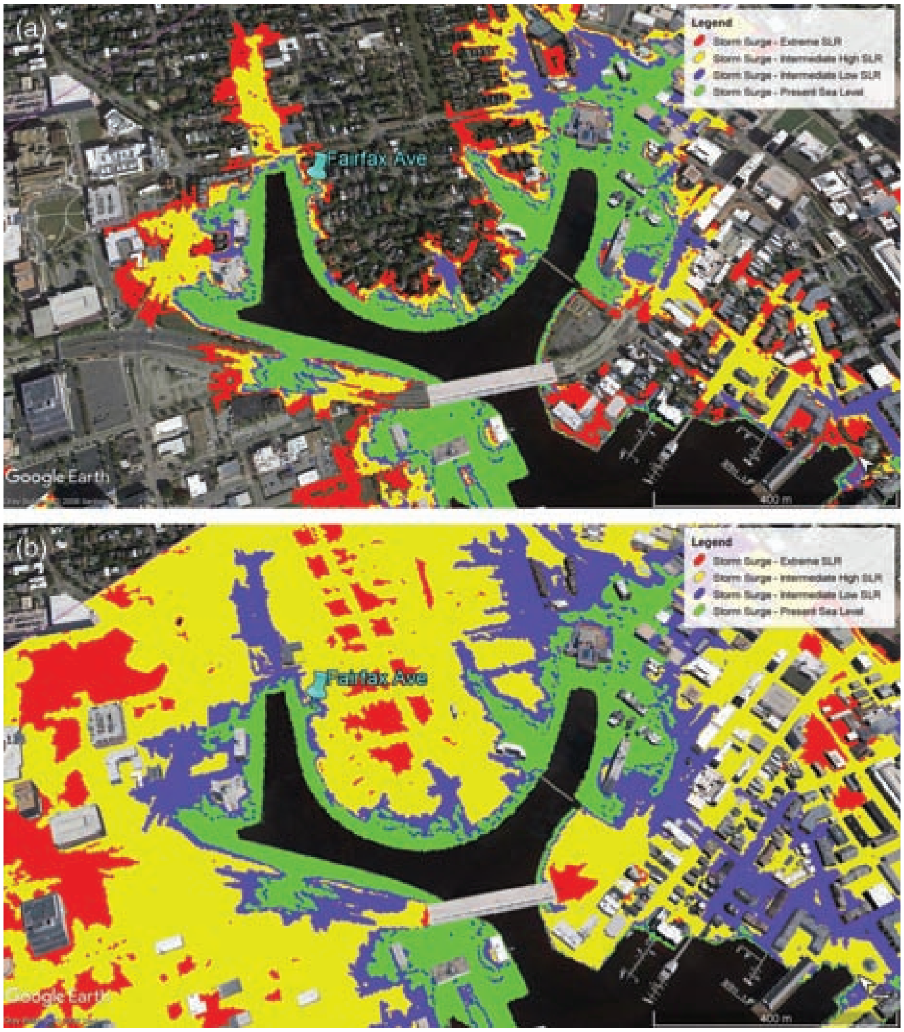
TABLE 2

SLR scenarios used in storm surge simulations. These values are obtained from Sweet et al. (2017).

SLR (m)	2050	2100
IL	0.24	0.5
IH	0.44	1.5
Extreme	0.63	2.5

FIGURE 4

Flood map at the Hague neighborhood for Irene-like hurricanes under IL, IH, and extreme SLR in (a) 2050 and (b) 2100. The blue pin shows the locations where the model outputs flooding level and duration.



and allows enough time for the sea level change to propagate throughout the domain. This will change the boundary conditions for Models 2 and 3 subsequently.

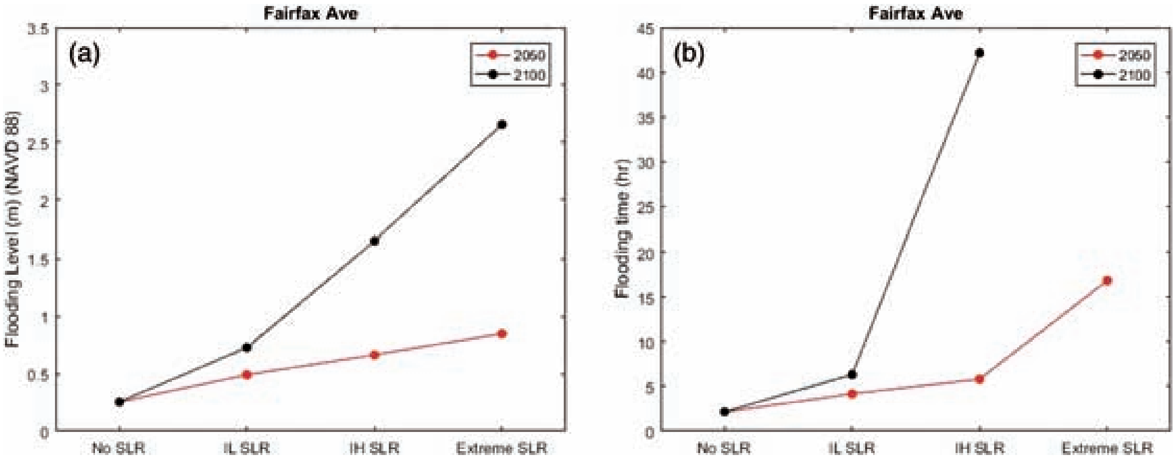
In Figure 4, the extent of storm surge flooding in the Hague area is depicted. The map shows the extent of flooding due to Hurricane Irene (2011) under the present sea level as well as potential hurricanes that could occur in 2050 with the same parameters as Hurricane Irene under SLR projections outlined in Table 2. As expected, flooded areas increase with increase in SLR projection for the year 2050. In the year 2100, the extent of inundation is significantly increased from IL to IH scenario, such that a wide area of the city, well beyond the Hague area, will be inundated. The increase in flooding extent from IH to the extreme SLR scenario is not as pronounced. Note the upland border of the computational grid in Figure 4(b) indicating that areas that are not colored in this figure are outside the grid and not necessarily dry.

In addition to depth of water level over the flooded area, the hydrodynamic modeling approach allows us to estimate the duration of flooding. In estimating the flooding duration, we assumed that a location is flooded once the total water level (storm surge + tide + SLR) is higher than the elevation of the point. It should be noted that the hydrodynamic model does not account for drainage, infiltration, or evaporation, and hence, if the water creates a pond at a low-lying spot after the storm surge has receded, the water level will remain at a constant nonzero value at that location. Therefore, we considered flooding to end once the water level is subsided and reaches a value that is constant with time, even if this value is not zero. It is noted that the 0.10 m threshold for wetting/drying filters out some of the ponds, but in some of the simulations, the depth of the ponds saturated to a value larger than this threshold after the completion of the storm.

Flood level, defined as the maximum water surface elevation during the storm event, and *flood duration,* defined as the time over which the model predicts the existence of water over an area, are the two main outputs of the model. The "observation point," where this information is output at high temporal resolution, is

FIGURE 5

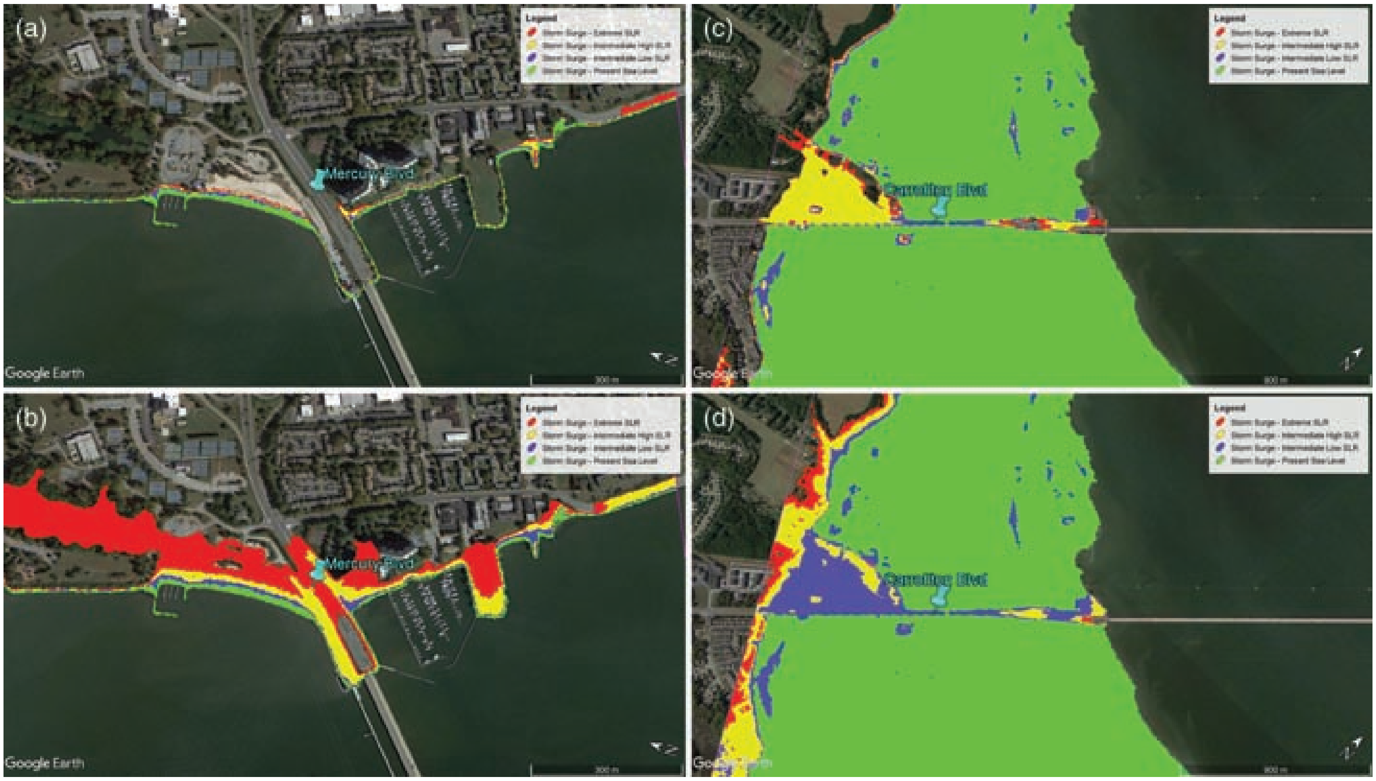
Storm surge flooding intensity (a) and duration (b) at the Hague area in Norfolk, VA, due to Hurricane Irene under present sea level and IL, IH, and extreme scenarios.



shown by a blue pin in Figure 4. In the Hague area, we placed the observation point at the Fairfax Avenue as a representative spot in the area. As seen in Figure 5, flooding level increases linearly with SLR scenarios in 2050. On the other hand, the flooding level in 2100 and flooding time increase nonlinearly with SLR scenarios. It is also noted that the trend in flooding times shows a significant increase from the IL to IH

FIGURE 6

Flood maps for the north (a, b) and south (c, d) sides of the James River Bridge in 2050 and 2100. SLR scenarios include IL, IH, and extreme conditions.



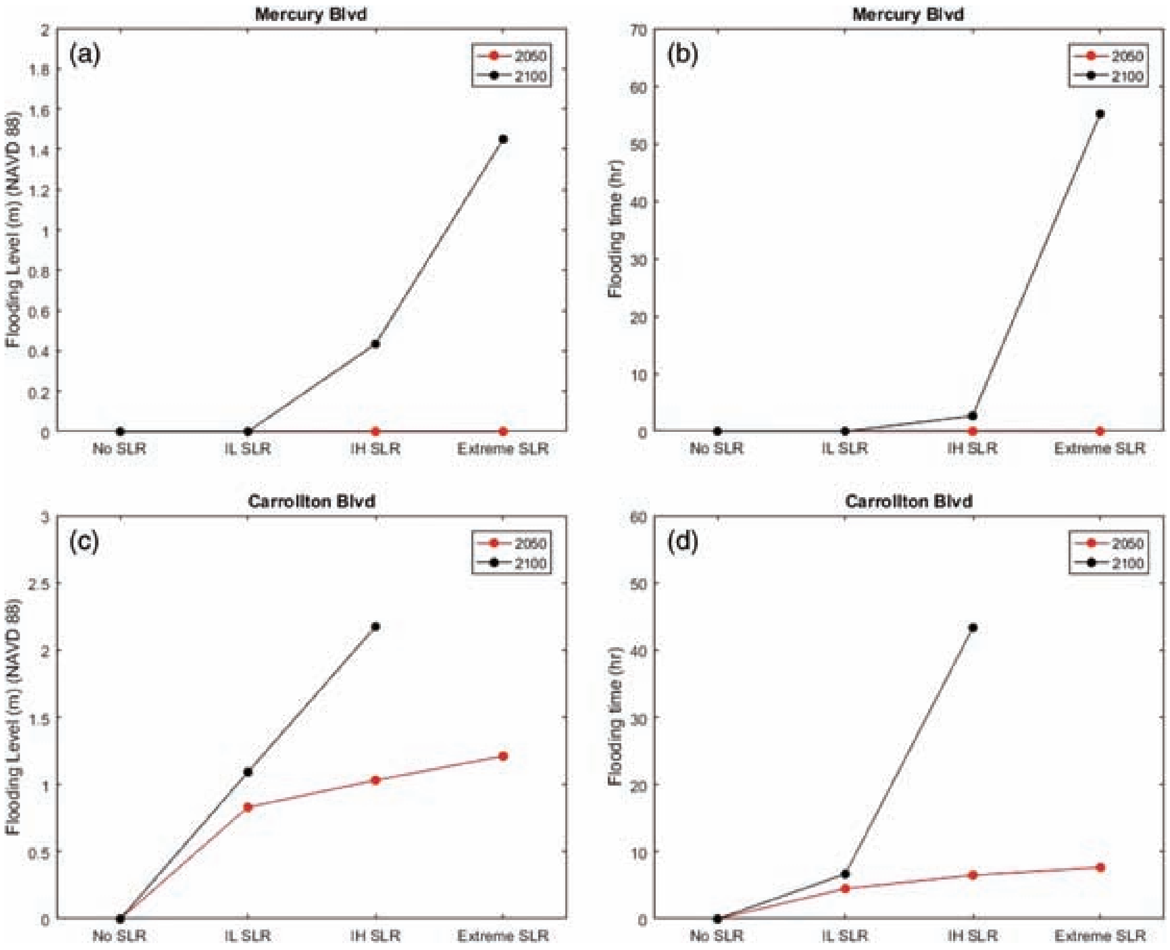
scenario in 2100, whereas the difference between current sea level condition and IH scenario is not as pronounced. The neighborhood is under water in extreme SLR scenarios at 2100 even without storm surge; thus, the flooding time for this scenario is not included in Figure 5(b).

The second critical spot in this study is the bridge over James River, which connects Isle of Wight County to Newport News and has a high traffic volume. Castrucci and Tahvildari (2017) showed that the north side of the bridge is not vulnerable to storm unless IH or extreme SLR conditions are considered. In this study, we extend the analysis to include a spot in the south side of the bridge, which has a significantly lower elevation than the north side, and hence will determine the storm surge and SLR conditions that will disrupt traffic flow through the bridge. Figure 6 shows flood maps at the north (Mercury Blvd.) and south (Carrolton Blvd.) side of the bridge under different SLR scenarios at 2050 and 2100. As seen, the north side does not experience flooding under any SLR projection in 2050, but it is expected to be inundated by storm surge at year 2100 under IH and extreme SLR scenarios. The extent of flooding is significantly larger in the south side compare to the north side, even at present sea level condition. Figure 7 shows the flood duration and intensity at the James River Bridge. As seen, storm surge flooding at this location occurs only in the IH and extreme conditions at 2100. The flooding time in the south side of the bridge increases linearly with SLR projection for 2050 but increases nonlinearly for 2100. The south side of the bridge starts being flooded since the IL SLR scenario of both 2050 and 2100. This spot is expected to be flooded under extreme SLR without storm surge.

The bridge on I-64 in the City of Chesapeake is the third critical spot to be studied as the flooding around this bridge can affect a substantial traffic

FIGURE 7

Storm surge flooding intensity and duration at north (a, b) and south (c, d) sides of the James River Bridge.

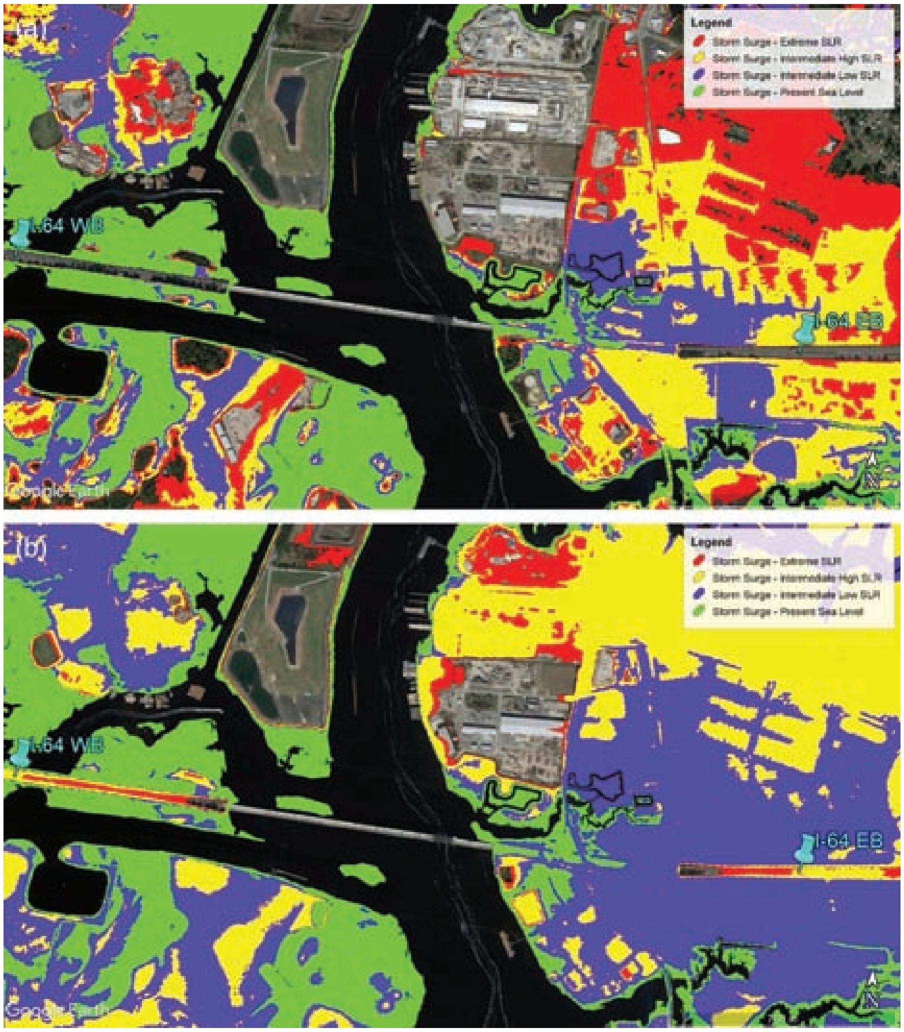


volume. In Figure 8, the extent of storm surge flooding in the east and west sides of the bridge is shown. The storm parameters and SLR projection are the same as those used in the previous simulations. The observation points, which are placed on the road, do not capture any flooding for year 2050, but we note that the east side of the bridge in the vicinity of the river will be flooded even under current sea level. Because of high ground elevation on both sides of the bridge, flooding does not occur at the observation points except in IH and extreme SLR scenarios in 2100 (Figure 9).

To highlight the difference between the hydrodynamic model results and the bathtub approach, we compare the estimates of the two approaches for the IH SLR scenario in the Hague neighborhood of Norfolk. As seen in Figure 10, the bathtub approach overestimates the extent of the flooding, and streets farther from the water front, which will be clear based on the hydrodynamic model results, are expected to be flooded based on the bathtub approach.

FIGURE 8

Flood map at I-64 Bridge in Chesapeake under IL, IH, and extreme SLR in (a) 2050 and (b) 2100.



Summary and Discussion

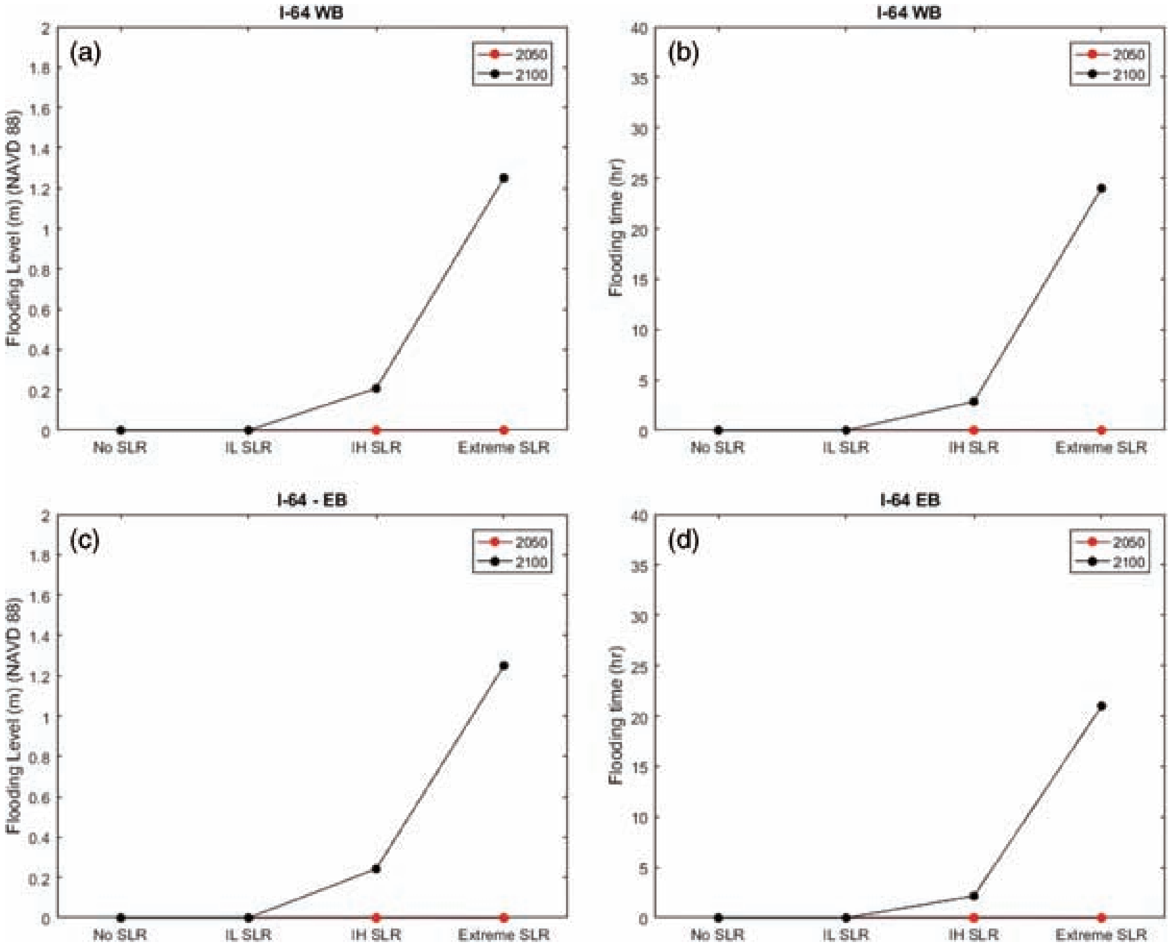
The objective of this research is to improve our understanding of vulnerabilities in the Hampton Roads region of Virginia to storm surge flooding in the face of SLR. In consultation with local and state officials, several critical flood-prone spots were identified. These areas are either in the vicinity of critical emergency facilities or have a substantial traffic flow.

A hydrodynamic model is developed based on the Delft3D modeling suite to simulate storm surge flooding under different SLR conditions. The study focuses on three flood-prone spots representing multiple municipalities in Hampton Roads, namely the cities of Norfolk, Chesapeake, and Newport News and Isle of Wight County. To reduce the computational time, the model was developed at three levels of nesting with spatial resolutions varying from ~200 m to ~2.5 m. The numerical models Level 1, Level 2, and Level 3 used 13, 13, and 59 Intel Xeon E5-2670 v2 2.50 GHz CPUs, respectively. The combined computational time of nested model was between 48 and 72 h, depending on the study site in the Level 3 model.

Three different SLR scenarios, namely IL, IH, and extreme SLR, were selected, and storm surge flood maps were developed for a historic hurricane for the present sea level as well as the projected SLR for 2050 and 2100. The hurricane was defined using the parameters of Hurricane Irene (2011). The first flood-prone areas that are studied are the Hague neighborhood in the City of Norfolk, the James River Bridge connecting

FIGURE 9

Storm surge flooding intensity and duration at west (a, b) and east (c, d) sides of the I-64 Bridge in Chesapeake.



the county of Isle of Wight and the City of Newport News, and the High Rise Bridge over Interstate 64 in the City of Chesapeake. As expected, increase in SLR estimates results in increase in flooding, and the dependency of flooding intensity and duration on SLR are site specific. Tables 3 and 4 summarize the flooding level and duration at these locations, respectively.

We compared the results of the hydrodynamic model for the Hague neighborhood with the widely used bathtub approach for one SLR scenario. The results indicate that the bathtub approach overestimates the extent of the flooding in the selected area; thus, it is critical to use hydrodynamic analysis to estimate SLR impacts on storm surge flooding.

The present study can be improved in several directions. We note that, in a nested modeling approach, all the nested models need to be validated. At the time of our analysis, there was no data available in the domain of models at the third level of nesting. Therefore, although models at the first and second level of nesting were validated with water level data, the information from Level 3 models still requires validation. The City of Norfolk has recently installed a tide gauge in the Hague area, which could be used to validate the Level 3 model and similar hydrodynamic models in the future. The second shortcoming of the study is that the effect of waves is not included. Coupling the spectral wave model SWAN (Booij et al., 1999) with the Delft3D-FLOW model is straightforward in the Delft3D modeling suite and is being conducted in an ongoing study.

Although the present study focuses on three specific spots in the transportation network, the developed model and approach can be applied to other coastal areas vulnerable to storm surge and SLR. The results of this study on the extent, intensity, and duration of flooding under different SLR projections would enable more accurate design and implementation

FIGURE 10

Comparison between the storm surge model estimates for inundation extent under IH SLR in 2050 (yellow) and estimates based on the bathtub approach (red).

of flood mitigation measures such as tide gates, seawalls, or storm water infrastructure and will help the transportation planners and emergency managers with advanced warnings and rerouting of the traffic, thereby increasing the resiliency of the critical infrastructure operations in the region to extreme weather and SLR.

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TABLE 3

Flood intensity in study areas.

Flooding Level (m)	Current Sea Level	2050 Scenarios			2100 Scenarios		
		IL	IH	Extreme	IH	IL	Extreme
Hague (Fairfax Ave.)	0.26	0.50	0.67	0.85	0.73	1.66	2.66
James River Bridge South (Carrollton Ave.)	0	0.83	1.03	1.21	1.09	2.17	Continues flooding
James River Bridge North (Mercury Ave.)	0	0	0	0	0	0.43	1.45
I-64 West	0	0	0	0	0	0	1.08
I-64 East	0	0	0	0	0	0.41	1.38

TABLE 4

Flood duration in study areas.

Flooding Duration (h)	Current Sea Level	2050 Scenarios			2100 Scenarios		
		IL	IH	Extreme	IH	IL	Extreme
Hague (Fairfax Ave.)	2.17	4.17	5.83	16.83	6.33	42.17	Continues flooding
James River Bridge South (Carrollton Ave.)	0	4.5	6.5	7.67	6.67	43.34	Continues flooding
James River Bridge North (Mercury Ave.)	0	0	0	0	0	2.67	55.17
I-64 West	0	0	0	0	0	0	18
I-64 East	0	0	0	0	0	5	32

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COMMENTARY

Institutionalizing Resilience in U.S. Universities: Prospects, Opportunities, and Models

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Introduction

The United States is taking a largely region-specific approach to addressing challenges posed by climate change, in contrast with national and international approaches in most of the rest of the world. In locations such as Hampton Roads, New Orleans, and coastal Connecticut, the impacts of climate change tend to be addressed as they become locally evident rather than as part of a larger anticipatory national plan. Given that regional focus, universities can play a unique role in how the United States responds to the challenges of a changing climate. Universities can be knowledge brokers positioned outside or across political, jurisdictional, and agency boundaries (localities, states, and federal) that often are problematic for regional planning and action and that tend to particularize rather than generalize knowledge. Universities have the capacity to translate that knowledge from local cases to politically and culturally contextualized states to global generalizations.

Another of the central challenges presented by climate change is that the physical processes involved, as well as their multiple consequences, require time scales of decades and centuries to develop and implement effective adaptation and mitigation strategies (Stehr & Vonstorch, 1995). In contrast with political election cycles (of 2 and 4 years) and business depreciation schedules (typically of 5–20 years), universities are among the few U.S. social institutions that intentionally plan for a century and beyond, a time scale sufficient to assess the ongoing impacts of climate change.

At the same time, responses to climate change also require the application of diverse bodies of knowledge and disciplinary skills to engage with a phenomenon that has implications for all aspects of life on this planet. Alone among U.S. public institutions, universities aspire to assemble and synthesize "universal" knowledge across the multiple fields and disciplines that are needed to address those pervasive implications.

Thus, universities may be uniquely positioned to innovate and model the ways in which other U.S. social institutions can internalize long-term responses to a changing physical environment from multidisciplinary and local-to-global perspectives. Universities are just now beginning to incorporate that broader enterprise of resilience—defined, generally, as the ability of physical, ecological, and social systems to absolve, deflect, or resist the disruptive impacts of climate change, as well as to adapt to and recover from those ongoing perturbations—into their core missions of scholarship, teaching, and outreach. Arguably, how they do so may presage the ways in which the United States deals with the consequences of climate change for decades to come.

In what follows, we consider key implications of that prospect, primarily from the perspective of coastal resilience, as climate-induced sea level rise increasingly disrupts the multiple complex systems affected by land-sea interactions.

Generalizable Knowledge

Whereas individual scientists and scholars working on resilience tend to focus on case studies and empirical data that inform the fundamental development of general theories (Wise et al., 2014), universities as institutions have taken a more applied practice-based approach, facilitating planning and evaluation of local projects intended to increase resilience to manifestations of climate change already evident in their regions. Universities with coastal resilience initiatives, for example, are undertaking projects that respond to local priorities for targeted interventions in areas such as risk communication (Covi & Kain, 2016), socioeconomic vulnerability to storm surges (Liu et al., 2016), critical habitat loss (Kirwan & Megonigal, 2013), and fisheries impact (Sumaila et al., 2011).

Academic resilience projects often take existing technologies and methods and apply those to real-world problems resulting from climate change. Those projects also often require working with community stakeholders for planning, design, and implementation, as social and cultural contributors can be just as significant as physical contributors in resilience outcomes (Adger et al., 2013). Thus, whereas science and engineering innovations are a necessary part of resilience, so too are the translation of innovation to practice and the social science of stakeholder and community engagement. Much of what is generalizable as resilience research will be developed in those latter two areas.

The authority that universities can bring to resilience efforts depends in large part on their reputations for the objective analysis and evaluation of generalizable knowledge. The increasing pace of climate change will place a premium on having an openly available literature that provides worldwide access to evidence-based, state-of-the-art technologies, strategies, and methods for mitigating and adapting to climate change as those are developed and validated. In building that resilience literature, universities have the unique role of verifying the globally applicable "science" of resilience by supporting a transparent peer review process.

Academic Trajectory

Schools of public health may be an existing academic model for the path that resilience might take as it is institutionalized in universities. In the 19th century, prior to the establishment of university-based schools, public health in the United States largely had comprised local efforts to improve sanitation practices and infrastructure in response to periodic epidemics of infectious diseases such as yellow fever and cholera. Those interventions often were as politically controversial in the 19th century as adaptation and mitigation for climate change are in the United States in the 21st century. Schools of public health emerged in the United States in the early 20th century through a combination of a growing demand for public health workers as well as for national standards for their training, the increasing focus of medical training on biological rather than social aspects of health, the prioritization of academic theory building over outcomes-based applications in traditional social science disciplines, and the need for community- and population-based perspectives on health (Duffy, 1992).

Like public health in the last century, public resilience is emerging as a discipline from the earth sciences, social sciences, systems engineering, and law and policy. Also like public health, this emerging academic domain is based largely on local and regional efforts to develop interventions focused on prevention (informed by quantitative analytics and stakeholder engagement) that are designed to optimize the application of current best practices and technologies for enhancing community resilience. Although resilience, as also public health, may be the site for methodological and theoretical innovations, the ultimate metric will be measurable improvements in quality of life. Building a portfolio of evidence-based interventions and a workforce to implement those will resonate more loudly at the institutional level than will building an academic resilience theory, even though the latter will advance the former.

Funding and Sustainability

For the moment, resilience remains an area in which reactions to events like Hurricanes Katrina and Sandy drive the U.S. research agenda because their aftermaths set funding priorities as well as local and state agendas for their public research universities. Consequently, universities located in regions facing early threats from climate change are those with the more mature resilience initiatives. At some point, though, the field will mature when long-term preparation and prevention outweigh reactions to immediate catastrophes in how funding becomes available for resilience research and applications.

Still, funding for academic resilience programs will remain multifaceted with significant support likely coming from local and state sources. To date, most academic resilience centers in the United States are funded primarily by institutions, philanthropic donations, and state governments. Virginia and Connecticut, for example, have established legislatively funded university-based resilience centers to provide scientific and technical assistance to localities (Virginia Chapter 440 of the 2016 Acts of Assembly, Connecticut Special Act 13-9, 2013). Ten universities in Florida have leveraged institutional and other funds to establish the Florida Climate Institute. At the same time, apart from NOAA and USGS regional centers focused on climate science in general, there is no academic network of federally funded resilience centers of excellence such as the National Institutes of Health designates and funds cancer, diabetes, and other centers of excellence for health or as the National Science Foundation funds engineering research centers—nor is this likely to change in the foreseeable future due to the partisan nature of climate change as a topic in public discourse. The lack of centralized federal designation and funding in the United States has the advantages of each university developing resilience emphases that are more closely tailored to regional issues, of resilience being more likely to spread across multiple departments and colleges rather than being isolated in a stand-alone center or institute that is in turn focused on satisfying the uniform requirements of the federal agency that funds it, and of university resilience efforts developing sustainable internal funding models.

The most sustainable model for resilience in a university setting will likely be through tuition for certificates and degrees in emerging resilience-related skills and competencies supplemented by research grants, which is the traditional disciplinary-specific academic business model. This sustainability strategy likely will lead university-based resilience initiatives to develop workforce training programs faster than a path via dedicated research centers and also to constitute resilience as an academic school like public health that can control its own academic degree programs rather than persist as an interdisciplinary collaboration dependent on the good will of other schools and colleges within the university.

Universities as Public Conveners

Although it often is said that social institutions in the United States have become politicized, universities nonetheless retain a greater ability than others for scientific authority as well as for public trust (Pew Research Center, 2016). In addition, universities are not constrained by the arbitrary and confusing geography of political boundaries, and so often can address regional issues and interests that otherwise are fragmented by multiple political subdivisions. That greater geographic reach is matched by greater chronological reach, as universities have a capacity for longer-term planning and perspectives on issues like climate change that have much shorter-term political horizons. Universities are proving to be useful platforms for regional dialogues about resilience that require conversations across political jurisdictions, levels and agencies of government (local, state, and federal), and different time horizons. The need for that functionality is likely to increase over time as planning for resilient adaptations to widening effects of climate change requires greater coordination.

Old Dominion University, for example, convened a 2-year intergovernmental pilot project (IPP) to create a framework for intergovernmental planning for sea level rise and recurrent flooding in a region composed of 17 localities and 24 federal facilities (Steinhilber et al., 2016). More than 300 unique participants representing 11 federal agencies and six state agencies along with municipalities, nonprofits, private sector partners, and other stakeholders took part. A primary lesson of the IPP was the extent of the jurisdictional and procedural complexities involved in assembling working groups across such a diverse but necessary collection of organizations, let alone reaching consensus about specific recommendations for the region and then implementing those.

Economic Development

If climate change has the magnitude of societal impacts that the science predicts, then resilience will become a pervasive knowledge-based activity across many if not all economic sectors. Universities will be key players in training and credentialing that workforce, which is why certificate and degree programs are likely to become the primary business model for growing and sustaining resilience as part of the academic enterprise. Universities also can become central in building regional economic clusters based on resilience innovations and applications (Filer, 2017). For example, water technology clusters are emerging in New Orleans, Miami, and Virginia's Hampton Roads with the engagement of local research universities because of the high vulnerability of those regions to sea level rise. Milwaukee is developing a cluster focused on water quality, and Nevada is developing one on water conservation, both with key university involvement.

Resilience, though, can benefit all economic sectors and clusters by slowing the growth of maintenance costs due to climate change and reducing the risks that climate change imposes on investment decisions. Ultimately, resilience as a set of evidence-based practices and technologies will become more effective in helping us deal with the effects of climate change as those practices and technologies become more engrained in everyday economic activities. In the absence of a coordinated federal effort, universities will play a central role in innovating and evaluating resilient practices and technologies that reduce costs and risks across all sectors, in translating them into commercialize-able products and services that are integrated as agglomerative place-based economic clusters, and in training a workforce to fill the jobs that will be created in those clusters.

Conclusion

Although the phenomenon of climate change is global, the experience of U.S. universities' institutional engagement with resilience so far has had a local and regional focus. This suggests that resilience initially will develop in the United States more as a local and regional necessity in other social organizations. Subsequently, national and international standardization of workforce credentials, best practices, and other aspects of resilience must be developed and disseminated, in large part through peer-reviewed validation of generalizable knowledge generated by universities. In the meantime, though, resilience as an emerging American practice will grow through the more diverse contexts of region-specific conditions and priorities. During that growth, universities must play a unique role in facilitating the diversity of those community- and population-based experiments in resilience in their local natural laboratories while also carrying out the academic function of generalizing resilience as a body of knowledge and theory. As a result, resilience should become more embedded within U.S. universities than other trending academic initiatives and, in turn, will embed universities more firmly in their local communities and regional economies.

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