SURGING WATERS

SCIENCE EMPOWERING COMMUNITIES IN THE FACE OF FLOODING

A REPORT FROM AGU

AGU100 ADVANCING EARTH AND SPACE SCIENCE

EXECUTIVE SUMMARY

Surging Waters: Science Empowering Communities in the Face of Flooding **is a report produced by AGU, a global not-for-profit scientific society dedicated to advancing the Earth and space sciences for the benefit of humanity. The report is reviewed by leading experts in these fields.**

From devastating monsoons to sea level rise, extreme weather is taking its toll across the globe. *Surging Waters* looks at flooding in the United States and demonstrates how science is supporting flood management, as well as furthering the solutions needed to mitigate flood impacts on people and property in the future.

The report's authors highlight three types of flooding—flooding due to hurricanes, floods in the central U.S., and coastal flooding—through local stories. In 2017, Houston, Texas, was hit by Hurricane Harvey, the second most damaging weather disaster in U.S. history, and is still recovering. The city of De Soto, MO, is emblematic of many areas in the Midwest that have been plagued by recurrent flash flooding. The Hampton Roads area of coastal Virginia has fallen victim to sinking land and rising seas.

Through these stories and others, and compelling flood data presented for regions across the United States, the report shows how scientific research and data collection are essential to finding modern-day and future solutions to mitigate flooding. Robust funding for science-related federal agencies drives the advancement of science and provides support that is critical for the most vulnerable communities and individuals.

Surging Waters recommends actions that community members and leaders, scientists, federal agencies, and policy makers can take to build a strong foundation to empower communities to make decisions for a more resilient and sustainable future.

Communities can use this report to inform and guide conversations with stakeholders on local, regional, and national levels. Lawmakers need to hear that people care about flooding issues and support the scientists working toward solutions. It is essential that science, with support from policy makers, continues to inspire readiness, cultivate collaboration, and empower communities.

To ready our nation for future challenges presented by flooding and other extreme weather impacts, Surging Waters ends with the following recommendations:

- **Empower communities** to make resilient and sustainable decisions about their future
- **Empower scientists** to conduct robust scientific research and data collection
- **Prioritize partnerships** among scientists who study both the physical world and human behavior and between scientists and communities

Full recommendations are presented at the end of the report. In brief, we recommend the following:

CONGRESS CAN

- Fund relevant science-based federal agencies
- Invest in cross-cutting science centers and programs
- Support evidence-based policy
- Emphasize future planning

SCIENCE AGENCIES AND CENTERS CAN

- Prioritize partnerships and collaboration
- Engage with communities
- Pursue critical areas of research and planning

SCIENTISTS CAN

- Engage with communities
- Promote interdisciplinary research and collaboration

COMMUNITIES CAN

- Leverage existing resources

INDIVIDUALS CAN

- Stay informed
- Create a plan
- Be an advocate for science

> Together, we can rise above the floodwaters.

FEDERAL AGENCY ABBREVIATIONS

The federal agencies listed below are mentioned in the body of the report.

EPA: Environmental Protection Agency

- EPA is an independent federal agency.
- EPA's mission is "…to protect human health and the environment."

epa.gov/aboutepa/our-mission-and-what-we-do

FEMA: Federal Emergency Management Agency

- FEMA is a part of the Department of Homeland Security.
- FEMA's mission is "Helping people before, during, and after disasters."

fema.gov/about-agency

NASA: National Aeronautics and Space Administration

- NASA's administrator reports directly to the White House.
- NASA's mission is to "Drive advances in science, technology, aeronautics, and space exploration to enhance knowledge, education, innovation, economic vitality and stewardship of Earth."

nasa.gov/careers/our-mission-and-values

NHC: National Hurricane Center

- NHC is a part of the National Centers for Environmental Prediction (NCEP), which is a part of NWS.
- NHC's mission is "to save lives, mitigate property loss, and improve economic efficiency by issuing the best watches, warnings, forecasts, and analyses of hazardous tropical weather and by increasing understanding of these hazards."

nhc.noaa.gov/aboutintro.shtml

NIEHS: National Institute of Environmental Health Sciences

- NIEHS is a part of the National Institutes of Health (NIH), which is a part of the Department of Health and Human Services.
- NIEHS's mission is "…to discover how the environment affects people in order to promote healthier lives."

niehs.nih.gov/about/strategicplan/index.cfm

NOAA: National Oceanic and Atmospheric Administration

- NOAA is a part of the Department of Commerce.
- NOAA's mission is

1. To understand and predict changes in climate, weather, oceans and coasts;
2. To share that knowledge and information with others; and
3. To conserve and manage coastal and marine ecosystems and resources.

noaa.gov/our-mission-and-vision

NSF: National Science Foundation

- NSF is an independent federal agency, guided by the National Science Board.
- NSF's mission is "…to promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense.…"

nsf.gov/about/glance.jsp

NSSL: National Severe Storms Laboratory

- NSSL is a part of the Oceanic and Atmospheric Research (OAR) office, which is a part of NOAA.
- NSSL's mission is "…to enhance NOAA's capabilities to provide accurate and timely forecasts and warnings of hazardous weather events."

nssl.noaa.gov/about/

NWS: National Weather Service

- NWS is an office under NOAA.
- NWS's mission is to provide "…weather, water, and climate data, forecasts and warnings for the protection of life and property and enhancement of the national economy."

nws.noaa.gov/mission.php

USACE: U.S. Army Corps of Engineers

- USACE is a part of the Department of the Army, which is a part of the Department of Defense.
- USACE's mission is to "Deliver vital public and military engineering services; partnering in peace and war to strengthen our Nation's security, energize the economy and reduce risks from disasters."

usace.army.mil/About/Mission-and-Vision/

USGS: U.S. Geological Survey

- USGS is a part of the Department of the Interior.
- USGS's mission is to provide "…reliable scientific information to describe and understand the Earth; minimize loss of life and property from natural disasters; manage water, biological, energy, and mineral resources; and enhance and protect our quality of life."

usgs.gov/about/about-us/who-we-are

OTHER ABBREVIATIONS AND ACRONYMS

- **3DEP:** 3D Elevation Program
- **AGU:** American Geophysical Union
- **CBO:** Congressional Budget Office
- **CCFR:** Citizens' Committee for Flood Relief
- **CCRFR:** Commonwealth Center for Recurrent Flooding Resiliency
- **CoSMoS:** Coastal Storm Monitoring System model
- **FJWC:** Faith and Justice Worker Center
- **FLASH:** Flood Locations and Simulated Hydrographs
- **GEER:** Geotechnical Extreme Events Reconnaissance Association
- **GOES:** Geostationary Operational Environmental Satellite
- **GPS:** Global Positioning System
- **HFIP:** Hurricane Forecast Improvement Program
- **Lidar:** Light detection and ranging
- **MRMS:** Multi-Radar/Multi-Sensor System
- **NGGPS:** Next Generation Global Prediction System
- **PPE:** Personal protective equipment
- **SLOSH:** Sea, Lake, and Overland Surges from Hurricanes model
- **StEER:** Structural Extreme Events Reconnaissance Network
- **VIMS:** Virginia Institute of Marine Science

INTRODUCTION

Flooding affects us all. At local, state, and national levels, it is a problem we must address. This issue was prominently on display throughout the first half of 2019. In just the week of the writing of this introduction, three notable floods occurred: Tropical Storm Barry threatened New Orleans, La., less than a week after the city was caught by surprise in a 5- to 7-inch deluge.[1] Days earlier, Washington, D.C., received over 3 inches of rain in a single hour, causing a waterfall to erupt in one Metro station and water to seep into the White House basement.[2] That same evening in central Nebraska, up to 9 inches of rain fell overnight, filling homes and businesses with over a foot of water for the second time in 5 months.[3]

The full ramifications from this year's flooding events are unclear at the time of this report's publication, but we can begin to put numbers on some specific economic, national security, and health impacts. For example, the March 2019 Missouri River floods cost Iowa farmers alone at least $2 billion and put up to 1 million drinking water wells in 10 states at risk of contamination with E. coli and other pathogens.[4,5] The U.S. Army Corps of Engineers (USACE) estimates that $1 billion is needed to repair levees in the Missouri River basin,[6] and the Air Force asked Congress for $350 million to help clean up the damage to Nebraska's Offutt Air Force Base, where 60 buildings filled with river water up to 8 feet high.[7,8]

THE NUMBERS REFLECT WHAT AMERICANS ALREADY KNOW: FLOODS ARE AFFECTING OUR WAY OF LIFE, AND THE FLOOD-AND-REBUILD STATUS QUO IS NO LONGER GOOD ENOUGH.

Scientists project that as the climate changes, hurricane winds and rain will intensify and heavy rainstorms and "high tide" floods related to sea level rise will become more frequent. As the exception increasingly becomes the rule, we must find new ways of adapting and preparing.

Flooding is a complex problem that will require a complex solution. A key, and often unseen, role will be played by the scientists and engineers who seek to measure, predict, manage, and mitigate floods.

The chapters of this report highlight three types of flooding: flooding caused by hurricanes, floods in the central U.S., and coastal flooding. Each chapter introduces an affected community and a scientist, or team of scientists, who partnered with the community to find solutions. The first story highlights a scientist helping residents of Houston, Texas, recover from Hurricane Harvey, the second most damaging weather disaster on record in the United States.[10] Second is the story of a team of scientists and engineers working with residents of De Soto, Mo., to understand which part of their town is at risk of recurring, deadly flash floods. Finally, there is Hampton Roads, an area of coastal Virginia, and the scientist-activist team educating its community on how a combination of sinking land and rising seas causes flooding even on sunny days. Following these narratives, the report describes additional examples of how science contributes to solving the challenge of flooding.

These stories and the others detailed in this report offer important lessons for community leaders, scientists, and policy makers at all levels of government. They provide a road map to a future where communities are empowered to break out of the flood-and-rebuild cycle by making informed flood management decisions through access to data and science.

THESE STORIES OF ACTION BY INDIVIDUALS AND COMMUNITIES SHOULD SERVE AS AN INSPIRATION FOR OTHERS WHO MAY BE FACING SIMILAR CIRCUMSTANCES.

An estimated 40 million people live in areas of the country where they have a 25% chance of their home being flooded before they can pay off a 30-year mortgage.[11,12]

TO SUPPORT COMMUNITIES AT RISK, THE UNITED STATES MUST COMMIT TO SUPPORTING THE SCIENCE NECESSARY TO ACHIEVE A NEW PARADIGM OF FLOOD MANAGEMENT AND MITIGATION.

We must continue to support the experimentation and modeling that help us mitigate and adapt to the impacts of extreme weather and the data collection that supports up-to-date risk management through tracking development and climate.

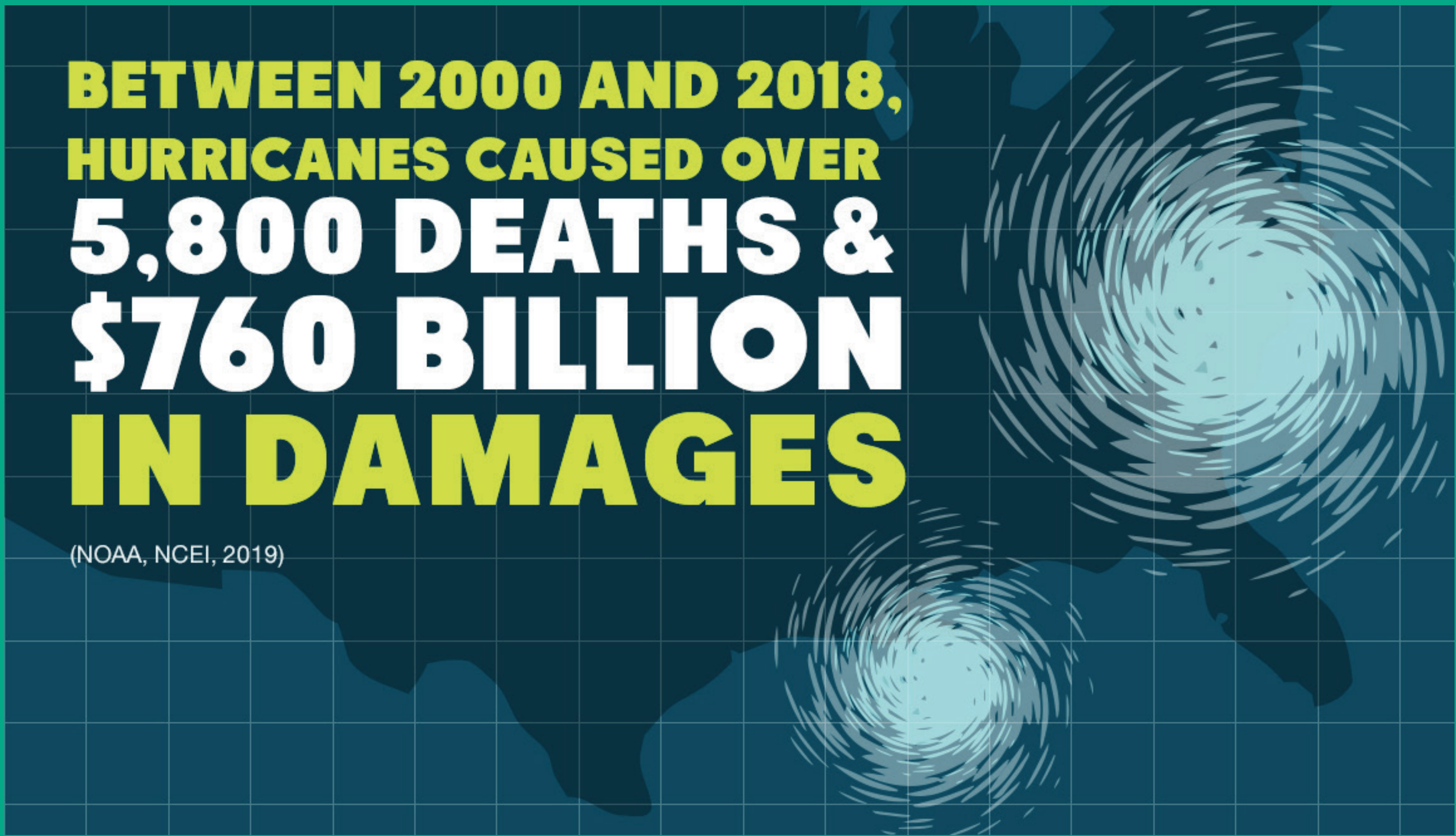
Finally, scientific insights must be coupled with those of multiple stakeholders to develop solutions for this intractable problem. We urge federal and local governments, scientists, flood managers, and everyday citizens to prioritize partnerships that result in listening, learning, and building mutual trust. When knowledge is shared in good faith between scientists and communities, science can be a powerful tool for making informed decisions about the future.

IF KNOWLEDGE IS POWER, THEN SHARED KNOWLEDGE IS EMPOWERMENT.

HURRICANES

AFTER THE STORM, DIFFICULT DECISIONS

In July 2019, nearly 2 years after Hurricane Harvey crashed ashore near Rockport, Texas, Elvia Escobar is still repairing her home. Compared with other areas, her neighborhood escaped much of the flooding caused by the estimated 34 trillion gallons of rain Harvey dumped across Texas and Louisiana.[13] But Escobar stripped off wallpaper and paneling inside her home anyway, exposing the framework and insulation. Her neighbors didn't understand what she was doing. "Unlike the community, I am fully aware of the consequences of having mold in our house," Escobar explains. "So I demolished some of the walls in my house; I made sure it was all sprayed with a solution against mold. Now the house doesn't look very pretty, but at least it's clean from mold."



Escobar is a construction worker who is originally from Mexico, and a volunteer trainer with the Fe y Justicia (Faith and Justice) Worker Center (FJWC) in Houston, Texas. In her role with FJWC, Escobar delivered health and safety trainings to her construction peers. This was when she learned about the immediate and long-term health consequences of flooding. However, many in the construction community still lacked access to this information and basic safety equipment. Following Harvey, FJWC organizers Kendra Baldazo-Tudon and Chris Wager Saldívar helped survey construction day laborers in Houston. Of the 361 surveyed workers entering hurricane-affected sites, 85% had received no training on the risks of mold or how to work safely in contaminated water, 32% lacked access to gloves, and 61% lacked access to a respirator.[14] Without proper training and personal protective equipment (PPE), many of these same workers were already reporting health impacts such as difficulty breathing (27%), skin rashes (28%), recurring headaches (35%), and eye infections (40%).[14]

FJWC strives to educate and advocate for Houston workers. As Harvey approached, they braced for a different kind of impact than most Texans. "It's common knowledge among worker centers that after hurricanes and other natural disasters, labor violations are more frequent," explains Wager Saldívar. The negative health and legal impacts for workers following Hurricanes Katrina and Sandy were well documented,[15,16] and already in the 4 weeks following Harvey's landfall over one quarter (26%) of surveyed day laborers reported wage theft to FJWC, with the total amount of unpaid wages exceeding $20,000.[14] Wager Saldívar says of the weeks following Harvey, "We had a difficult decision to make. Do we put our energy into health and safety or wage theft and other legal issues? Ultimately, we went with health and safety."

FROM HEALTH RESEARCH TO HURRICANE RECOVERY

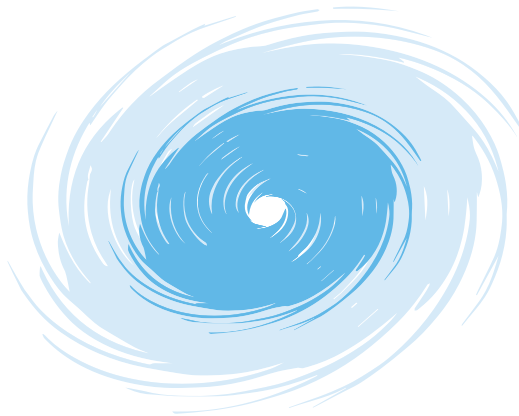
Like Escobar, Houston resident and public health researcher Janelle Rios has not yet completed the repairs to the home she and her husband were in the process of renovating when Harvey hit. Rios has a habit of classifying the various tropical storms and hurricanes that she has weathered during her decades of living in the state as either rain events or wind events. "Harvey," she says, "was a biblical rain event. It was raining so hard for 3 days solid. We just watched the water rise and rise and rise." On the third day, Rios convinced her husband to canoe to their home. They could hear helicopters above as they paddled, and they were dismayed to find that they could row right into their kitchen.

Also like Escobar, Rios was aware of the risks of living in and cleaning up flooded homes and buildings. Rios is a faculty associate at UTHealth School of Public Health and a co–principal investigator at the Texas-Utah Consortium for Hazardous Waste Worker Education and Training (Texas-Utah Consortium), a research and training facility funded by the National Institute of Environmental Health Sciences (NIEHS). Her research focuses on environmental health risks to workers. Working with her colleagues at the Texas-Utah Consortium, Rios began to do what she could for cleanup workers in the Houston area.

Baldazo-Tudon explains that the Texas-Utah Consortium was one of many partners that teamed with FJWC following Harvey to address the need for more safety trainings and PPE for day laborers. These partners collaborated to provide training workshops aimed at educating peer trainers, like Escobar, who could relay the information to their fellow workers on construction sites. Ultimately, 785 peer trainers received health and safety trainings in the 6 months between December 2017 and May 2018, according to the FJWC.

The Texas-Utah Consortium also played a key role in obtaining protective equipment for workers. Rios spearheaded efforts to reallocate funds for the purchase and distribution of 1,000 N95 respirators, which are designed to filter out mold spores and other hazardous particulates that might be present in a building that has been filled with water for several days.[17] She and her colleagues at the Texas-Utah Consortium trained workers on the use of respirators, as well as how to recognize common health risks like heat stress. Rios also distributed informational booklets in English and Spanish and Tyvek suits and leather gloves to protect those who would rebuild the city.

Rios still hasn't moved into her house, but she insists she is one of the lucky ones. She and her family had shelter during the storm; they continue to have a permanent place to live; and they had access to the services they needed both before the storm and in the ongoing recovery period. For Escobar and many other vulnerable Houstonians...



...THE IMPACTS FROM HARVEY ARE STILL UNFOLDING. "MOST PEOPLE DIDN'T THINK IT WAS THAT DANGEROUS TO GO BACK INTO THE HOUSE," SAYS ESCOBAR. "THERE IS STILL NOT A GREAT AWARENESS IN THE COMMUNITY ABOUT THE HEALTH CONSEQUENCES FROM HARVEY."

When asked about the continuing impacts to workers, Baldazo-Tudon and Wager Saldívar say they're still trying to figure this out. "As a nonscientist, you don't really know what to look out for in terms of the long-term effects," explains Wager Saldívar. "We could really use more scientists looking at that." At least one NIEHS-funded study is currently tracking Harvey's long-term health impacts on nearly 200 Texans living in homes flooded during the storm, as part of NIEHS's disaster research response priorities.[18,19] The hope is that Wager Saldívar and Baldazo-Tudon, and all those working to keep flood-impacted individuals healthy, will get answers soon.

SCIENCE SAVES LIVES

With the sole exception of Hurricane Katrina, no weather event on record has ever caused as much damage in the United States as Hurricane Harvey.[10] However, hurricanes themselves are nothing new to the residents of the south central and southeastern United States. Between 2000 and 2018, hurricanes caused more than 5,800 deaths and $760 billion in damages.[10] Fortunately, the efforts of Rios and organizations like the FJWC were also not unique. This is only one example of how scientists and engineers work alongside public safety officials, community leaders, and first responders during all stages of extreme weather events, from preparation to addressing the aftermath.

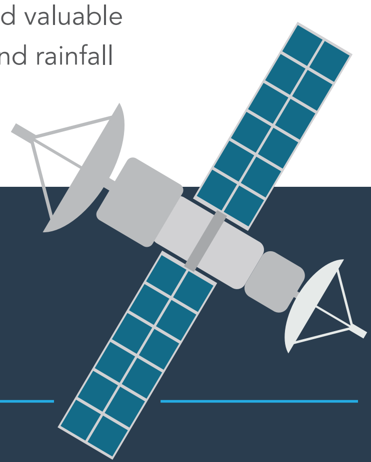
CLIMATE SCIENCE AND THE ECONOMY: THE BOTTOM LINE

The current scientific consensus predicts that hurricane maximum wind speeds and precipitation rates will increase with projected climate change.[9] Change has already started; some studies indicate that human-caused climate change has contributed to the observed increase in North Atlantic hurricane intensity since the 1970s.[9] For Hurricane Harvey, in particular, multiple modeling studies suggest that human-driven climate change increased the likelihood of the observed extreme precipitation accumulations from the storm.[9] One study found that warmer sea surface temperatures, caused by carbon dioxide (CO2) accumulation in the atmosphere, increased the highest amounts of total rainfall by at least 19%, with a best estimate being 38%.[38] A second study found that the 3-day rainfall was 15% more intense than predicted by a warmer atmosphere holding more moisture alone.[39] In both studies, human-driven factors were estimated to increase the likelihood of the observed extreme rainfall during Harvey by 3–3.5 times.[38,39]

The Congressional Budget Office (CBO) estimates that hurricane wind and flooding damage will cost the U.S. economy $54 billion annually under current conditions, an amount greater than the individual gross domestic products of Montana, South Dakota, Wyoming, or Vermont.[40,41] Given climate predictions, however, it is likely that future costs from hurricane damages will exceed the CBO's current estimates.

HURRICANE WIND AND FLOODING DAMAGE WILL COST THE U.S. ECONOMY
$54 BILLION
ANNUALLY UNDER CURRENT CONDITIONS

The day before Harvey made landfall, 23 August 2017, the National Hurricane Center (NHC) issued its first hurricane watch tracking the storm.[20] Meteorologists at NHC and the National Weather Service (NWS) worked around the clock to predict where Harvey would make landfall. In near-real time, they pored over updated imagery from a weather satellite known as GOES-16, a satellite developed and launched by NASA and the National Oceanic and Atmospheric Administration (NOAA). GOES-16 is just one of multiple satellites operated by NASA and NOAA that first spotted the tropical wave off the coast of Africa that later developed into Harvey. Satellites provide forecasters at NWS data to feed into sets of equations, collectively called models, and create forecasts. NOAA's weather prediction models, such as the Global Forecast System, provided valuable predictions of the storm's path and rainfall days in advance.[21]



TECHNOLOGY:

THE EYES ABOVE

The GOES series satellites fly in "geostationary orbit," revolving around the Earth at a speed matching the planet's rotation, which allows the satellites to remain in a fixed position relative to the Earth's surface. Launched in 2016, GOES-16 monitors central and eastern North America, South America, and the Atlantic Ocean from 22,300 miles above the Earth's surface, about 10 times the distance between New York City and Las Vegas.[42] Its counterpart, GOES-17, monitors the North American west coast, Hawaii, and the Pacific Ocean.[42] Both GOES-16 and GOES-17 scan the Earth 5 times faster than their predecessors, as often as every 30 seconds, and at 4 times higher resolution.[42]

In addition to geostationary satellites, the majority (85%) of the information used in weather forecasts comes from polar-orbiting satellites, which circle the Earth 14 times a day, traveling from pole to pole.[43]

During Harvey, satellite images and the related forecasts developed by NWS were distributed in near-real time through the Emergency Managers Weather Information Network, allowing emergency managers and public safety officials to access information rapidly and take action.[20] Almost a decade of social science funded by the National Science Foundation (NSF) and NOAA informed how NWS forecasters shared information with emergency manager partners and their television counterparts.[22]

EFFECTIVE COMMUNICATION WAS ESSENTIAL FOR THE PUBLIC TO UNDERSTAND THE RISK, BELIEVE THE MESSAGE, AND KNOW WHAT ACTION TO TAKE.[22]

Ultimately more than 1 million Texas residents evacuated in advance of Hurricane Harvey.[20]

SCIENTISTS AT THE SCENE

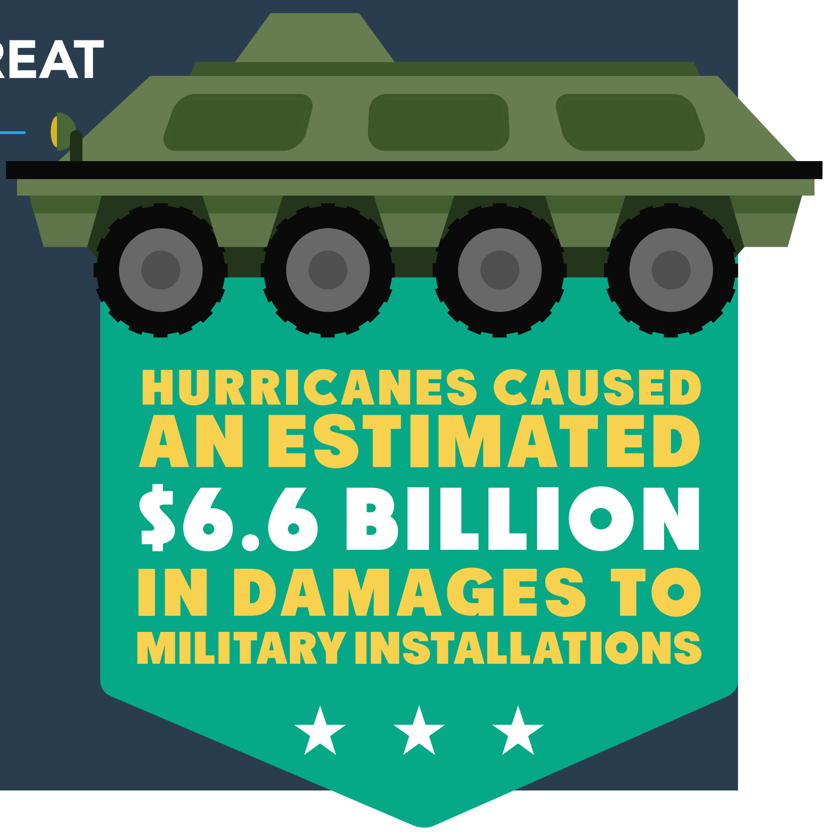
Unlike humans in the path of a storm, buildings cannot evacuate.

Data collected by researchers after disasters can help us understand how to construct buildings, roads, bridges, and other pieces of critical infrastructure so that they can withstand future events. The Geotechnical Extreme Events Reconnaissance (GEER) Association, funded by NSF, which began decades ago as an ad hoc group of engineers and engineering geologists who self-assembled to survey damages and collect perishable data after large earthquakes, now deploys volunteers to other extreme events like hurricanes.[23]

NATIONAL SECURITY:

HURRICANES AS A THREAT

Within just 1 month in 2018, hurricanes caused an estimated $6.6 billion in damages to military installations.[44] In late September 2018, Hurricane Florence damaged Camp Lejeune and other Marine Corps facilities in North Carolina; a preliminary estimate placed the repair costs at $3.6 billion.[44] Just a few weeks later, in October, Hurricane Michael hit Tyndall Air Force Base in Florida. The repairs were estimated to require $3 billion and more than 5 years to complete.[44]



Nina Stark, an associate professor in the Department of Civil and Environmental Engineering at Virginia Tech, was a coleader of GEER's Hurricane Harvey response team. Stark, who studies soil erosion processes, along with members of her team flew to San Antonio a few days after Harvey made landfall. Following the path of the storm, Stark and her team worked with colleagues from local universities like Texas A&M and the University of Texas along with the USACE, municipalities, and local community organizations to record the extent of erosion immediately after the storm, before any natural backfilling or cleanup took place.

By being at the scene so quickly after Harvey had passed through southeastern Texas, Stark observed that erosion around some bridge pilings was deeper than she expected based on current scientific models of erosion processes. Stark suspects that this occurred because current models are based on data collected much longer after storms when new sediment has already begun to fill the holes left by erosion. The resulting research could affect models that predict when bridges will fail, or even the way bridges are designed. Stark emphasizes,

"IT'S REALLY IMPORTANT TO UNDERSTAND THE PROCESSES IN ORDER TO PREDICT WHAT WE HAVE TO PREPARE FOR IN THE FUTURE—TO MAKE SURE THAT EVENTS MAY BE LESS DEVASTATING BECAUSE WE'RE BETTER PREPARED AND MORE RESILIENT."

To that end, GEER leaders recruited Tracy Kijewski-Correa, an associate professor of civil engineering and global affairs at the University of Notre Dame, for the Hurricane Harvey mission. GEER had coordinated many extreme event responses before, but never one that included structural engineers. Surveying the damage after hurricanes like Harvey can help structural engineers learn how to build back communities stronger by making homes better able to withstand hurricane-force winds and storm surges. Kijewski-Correa assembled a team of engineers to survey residential building damage. They deployed in multiple teams, including one team mapping the extent of storm surge inundation, multiple teams walking door to door to assess damage due to wind and storm surge, and one creating 3-D maps of storm damage across entire neighborhoods.[24]

Stark, Kijewski-Correa, and all the participants in these efforts were volunteers, and all the data they collected are freely available.[25,26,27,28,29] Surveys for domestic events like Harvey cost GEER about $19,000 to complete; an engineering firm would charge an estimated $170,000 for the same response.[30] The data generated by these federally funded surveys therefore cost only about 11 cents on the dollar. But the true return on investment is invaluable when considering the lives and homes saved through changes to construction practices informed by the results of the surveys.

AN EYE ON THE FUTURE

Harvey is just one example of how hurricanes devastate communities.

SCIENTISTS ARE WORKING TIRELESSLY PAST THE INITIAL STAGES OF RECOVERY TO IMPROVE FUTURE FORECASTS AND LEARN HOW TO PREPARE AND RECOVER FASTER IN THE FACE OF DISASTER.

The 2017 hurricane season demonstrated the need for structural engineers like Kijewski-Correa to formalize their response to extreme events. She has since received NSF funding to create a coordinated Structural Extreme Events Reconnaissance (StEER) Network. NSF also supported the creation of a central "node," the Natural Hazards Reconnaissance Facility, to organize the response of extreme event reconnaissance between organizations like StEER and GEER. This facility is based at the University of Washington and successfully coordinated responses to Hurricanes Michael and Florence in the 2018 hurricane season, among other events.[31]

Hurricane forecast models are continually improving based on our understanding of the physical processes that drive weather patterns. After Hurricane Sandy in 2012, Congress passed a funding bill providing $15 million for improved computing capacity and research to strengthen hurricane forecasting.[32] With this investment, NOAA scientists developed the Next Generation Global Prediction System (NGGPS) model. Preliminary results are promising; during the 2017 hurricane season, a prototype of NGGPS predicted hurricane paths better than the existing U.S. and European models.[33]

ECONOMY:
VALUE OF WEATHER FORECASTS

Americans surveyed about the economic value of accurate weather forecasts are willing to pay approximately $285 per year per household to ensure that they have this information at their fingertips.[45] This is equivalent to $31.5 billion in benefits to the American public from weather forecasting, and a benefit-to-cost ratio of 6.2:1, given the $5.1 billion annually spent by both the federal government and the private sector on weather forecasts and supporting operations.[45]

AMERICANS ARE WILLING TO PAY

APPROX.
$285 PER YEAR PER HOUSEHOLD

TO HAVE WEATHER FORECASTS AT THEIR FINGERTIPS

The NGGPS model is useful for storm and general weather forecasting, but NOAA also develops models specifically to predict hurricanes through the Hurricane Forecast Improvement Program (HFIP). Between 2008 and 2016, models created through HFIP decreased intensity and hurricane track forecast error by 20%–25% for 1- to 5-day forecasts.[34] A 2004 study estimated the value of a 50% improvement in the 48-hour hurricane forecast to the oil and gas industries alone at $15 million, more than twice the operating budget of the National Hurricane Center[35,36]

NOAA-developed models also support the work of Federal Emergency Management Agency (FEMA) insurance agents seeking to distribute insurance claim funding by type of damage. The 2012 Consumer Option for an Alternative System to Allocate Losses (COASTAL) Act asked NOAA to produce models that could predict after a home is leveled to its foundation whether the damage was caused by wind, wave action, or storm surge.[37] To fulfill this ask, NOAA scientists are working on developing models that can create these hindcasts at the level of an individual house.[33]

SCIENCE CANNOT PROTECT US FROM ALL EXTREME WEATHER IMPACTS, BUT AS WE SAW IN THE CASE OF HURRICANE HARVEY, IT CAN HELP US AVOID CATASTROPHE.

Collectively, the United States needs to ensure that communities across the country facing all varieties of extreme weather—from hurricanes to wildfires to tornadoes and landslides—have the resources and information they need to best prepare and recover in the face of disaster.

SUMMARY

Hurricanes are a costly, deadly problem for our nation. Between 2000 and 2018, hurricanes caused over 5,800 deaths and $760 billion in damages.

Cleaning up after a disaster is a team effort. Science funded by federal agencies and institutes brings together volunteer scientists and engineers from across the country to rapidly respond to disaster situations, collecting data to help us build back better and stronger, and providing evidence-based trainings to keep workers safe.

Knowing when and where a hurricane is going to make landfall, and the predicted intensity of rain and wind, helps keep people safe. The federal agencies NOAA and NASA team up to provide the satellites and modeling capabilities needed to improve lead time for an informed and adequate response by emergency managers.

Disasters like hurricanes are not going away and are predicted to intensify, but scientists, inside and outside federal agencies, working in partnership with affected communities, are advancing their understanding of and ability to predict and respond to this type of extreme weather.

FLOODS

AND OUR CHANGING CLIMATE

Current science shows that Earth's climate, primarily driven by human activity, is changing rapidly compared with the natural variations of the past, and the impacts of the changing climate—including on precipitation, sea levels, and other factors that affect flooding—are already unfolding. For centuries, modern society and all the infrastructure on which we rely—roads, sewers, buildings, bridges, and everything in between—were built with reliance on a relatively stable climate. With climate changes, our infrastructure decisions and other responses to flooding must also change. Moreover, while the impacts of global climate change are already being felt in the United States and are projected to intensify in the future, the severity of future impacts will depend largely on actions taken to reduce greenhouse gas emissions and to adapt to the changes that will occur.

The Fourth National Climate Assessment evaluated the peer-reviewed science of climate change and variability, and the resulting impacts across the United States, relying on a team of more than 300 U.S. federal and nonfederal experts, regional engagement workshops, public input, and expert peer review. The information that follows is drawn from this report.

> Earth's climate is now changing faster than at any point in the history of modern civilization, primarily as a result of human activities.

Between 1901 and 2016, the global average temperature over both land and ocean increased by 1.8°F. Most of this increase (1.2°F) occurred in the final 30 years of this period, demonstrating the acceleration of this global change. This is a more rapid rate increase of global average temperature than seen in any 20- to 30-year period in at least the past 1,700 years.

Of the many physical signs that confirm the observed trends in global average temperature, a steady increase in global sea level and increased precipitation intensity are two that are also linked to flooding. Global sea level rise is caused by two main factors: (1) Ocean water expands as it warms, and (2) land-based ice sheets and glaciers melt at warmer temperatures, adding more water to the ocean. Since 1900, the global mean sea level has risen 7–8 inches, with 3 of those inches occurring since 1993—faster than in any other century for at least the past 2,800 years. As a direct result of sea level rise, the number of minor, or "nuisance," floods occurring in some coastal U.S. cities has already increased fivefold to tenfold since the 1960s.

The frequency and intensity of heavy precipitation events in the United States have also increased between 1901 and 2016. This is expected with a warming atmosphere—warmer air can hold more moisture, and increased evaporation rates driven by warmer temperatures make more precipitable water available. With more moisture in the atmosphere, precipitation events become more intense when the conditions are right for rain or snow. This trend has been observed especially in the central and northeastern United States. Precipitation rates in hurricanes and other storms are also expected to increase.

While flood risk is determined in part by local land use, changes in land cover, and the design of water management infrastructure, it is impossible to ignore the effect of increasing extremes in precipitation. Our water infrastructure, including flood control infrastructure, is not designed to manage the storms of the future. In the face of the changing climate, new methods and more long-term data are needed to calculate flood risk accurately and adequately protect communities.

FLOODS IN THE CENTRAL U.S.

FED UP WITH FLASH FLOODS

De Soto, Mo., is a small town in Jefferson County on the state's eastern border, a 45-mile drive south from St. Louis. It boasts a quaint Main Street, a post office, and a creek that runs through its downtown. And, like so many towns across the Midwest, De Soto has a flooding problem. In the 4 years from 2015 to 2019, De Soto experienced five flood events, two of which were deemed presidential disasters.[46]

When Paula Arbuthnot moved to De Soto from a neighboring town in 2015, she hoped she was leaving the dangers of flash flooding behind. She had narrowly escaped being swept off the road in her car by a flash flood in nearby Hillsboro, Mo. She moved her family to De Soto, and by December, Joachim Creek, a tributary of the Mississippi River, had spilled over its banks and flooded the town. In fact, intense rainfall in the early hours of 26 December 2015 affected towns from southwestern Missouri all the way into central Illinois. Three interstates closed and six lives were lost.

TECHNOLOGY: PREDICTING FLASH FLOODS

Flash flooding is characterized by a rapid rise in water levels in streams and creeks. The short time period between rainfall and onset of flooding, the localized occurrence, and the range of conditions that can result in flash floods make this type of flooding particularly difficult to predict.[70]

At NOAA's National Severe Storms Laboratory (NSSL) in Norman, Okla., research hydrologist Jonathan J. Gourley works to improve flash flood forecasting. The Multi-Radar/Multi-Sensor System (MRMS), which grew out of a technique Gourley helped develop where data from multiple weather radars are combined into one large "mosaic," can estimate rainfall rates and storm movement nationwide every 2 minutes.[71] Prior to MRMS, rainfall estimates were made on an hourly basis.[71] Using MRMS data, the new flash flood prediction system, named Flood Locations and Simulated Hydrographs (FLASH), doubles the accuracy of previous predictions, improves the spatial resolution to allow site-specific instead of county-wide predictions, and runs model simulations that cycle across the United States every 10 minutes.[70,72] In the summer of 2018, NWS forecasters began issuing flash flood warnings based on FLASH predictions.[73]

Susan Liley was also fed up with flooding. While her own home does not flood, she wanted to help others. She offered to help clean out flooded houses and distributed eggs from her chickens to families whose homes had flooded. She washed the clothes of a friend's granddaughter after they were submerged in floodwaters, and it felt like the last straw.

Arbuthnot, a civil engineer, and Liley, a retired secretary at the local high school and grandmother of four, connected online and decided to act. They cofounded the Citizens' Committee for Flood Relief (CCFR), an advocacy group focused on finding solutions to the worsening flooding in De Soto. They created a Facebook page and held monthly meetings at a local church. According to Liley, the group regularly attracts 20–30 people from the community and beyond. When heavy rains are expected in the area, they ask for volunteers to fill sandbags. Residents who experience flooding and those who don't are all concerned about the dangerous conditions in De Soto.

MAPPING AND MONITORING TO INFORM SOLUTIONS

Through their involvement with Higher Ground, an initiative of the nonprofit Anthropocene Alliance and the largest flood "survivor" network in the United States, Arbuthnot and Liley soon connected with AGU's Thriving Earth Exchange, which connects communities with scientists to solve local challenges. Thriving Earth Exchange introduced CCFR to hydrologists Robert Jacobson and Susannah Erwin at the U.S. Geological Survey (USGS), and hydrologist Dan Hanes and civil engineer Amanda Cox at Saint Louis University, all of whom volunteered their time to help the De Soto community.

The scientists suggested at the outset that CCFR lobby to have a streamflow gauging station installed on Joachim Creek, which USGS subsequently installed in 2018. The stream gauge measures the depth of water moving through Joachim Creek every 5 minutes,[47] giving the residents of De Soto near-instantaneous information about their stream levels, improved flood predictions, and the ability to make their own evacuation decisions based on the data.

TECHNOLOGY:
HOW WE USE STREAM GAUGES

Stream gauges are devices used to measure the depth of water flowing in a stream at one point over time, which can then be converted by a mathematical relationship called a "rating curve" into a volume of water. Within the United States, USGS supports a network of 10,330 gauges.[74] This network allows us to understand how much water is on the landscape during wet and dry periods and how the amount changes over time. Current and historical observations are available from USGS: https://waterdata.usgs.gov/nwis/sw. International records of streamflow can be accessed from the Global Runoff Data Centre, operated by the World Meteorological Organization: https://www.bafg.de/GRDC/.

The continental United States contains approximately 2.7 million segments of streams and rivers, stretching for more than 3.5 million miles[75]—enough to flow from the Earth to the Moon and back more than 7 times. Of these, only about 4,000 segments have a stream gauge with a measurement record long enough to generate a flood forecast.[76] NOAA's National Water Model, which debuted in 2015, is helping to close this gap.[76] Using NSF-supported supercomputers at the University of Illinois at Urbana-Champaign, the National Water Model incorporates data from the existing network of USGS gauges to calculate streamflow on all U.S. streams and rivers.[76]

Working with Higher Ground, CCFR was also able to secure a Silver Jackets study called a flood management plan. USACE supports communities in addressing flood risk through the Silver Jackets program.[48] The program brings together experts from federal agencies, including USACE, NWS, and USGS, as well as state, local, and tribal agencies, to coordinate efforts to address flooding risk.[48] The flood management plan assesses an area's vulnerability to flooding and offers options to minimize flood damage, with the goal of breaking a community out of the flood–rebuild cycle.[46]

Thriving Earth Exchange scientists helped review the first and second drafts of the Upper Joachim Creek Floodplain Management Plan, making comments and, most important, translating between USACE and resident priorities. With the support of technical advice and independent verification from Thriving Earth Exchange scientists, Arbuthnot and Liley successfully campaigned for the inclusion of a more detailed analysis in the next draft, using a 2-D hydraulic modeling technique.

FOR A FLOOD-WEARY CITY LIKE DE SOTO, ACCESS TO THESE RESULTS WILL PROVIDE RESIDENTS WITH CLARITY AND THE RELIEF OF KNOWING THEIR TRUE FLOODING RISKS AS THEY WEIGH THEIR OPTIONS.

They have also given Arbuthnot and Liley the information required to lobby local leaders to improve local ordinances. Both the city of DeSoto and Jefferson County governments have implemented new flood development ordinances that go beyond the usual recommendations by FEMA.

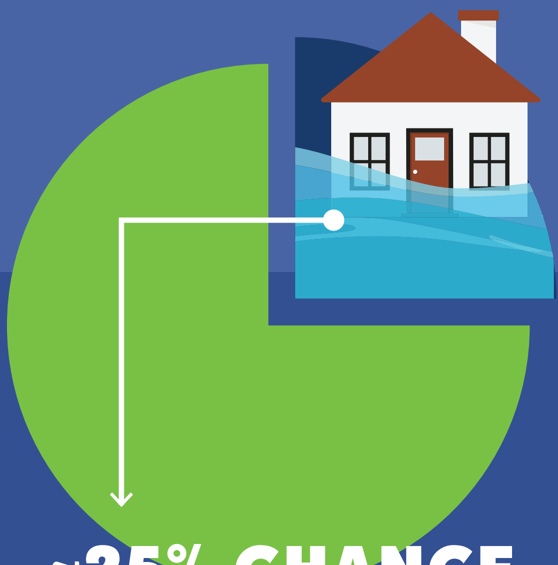
Their goal is to ensure that in the future, flooding will not be the same issue as it has been in the past.

PREDICTING AND MODELING FUTURE FLOODS

De Soto's challenges are a familiar story for cities and towns across the Midwest. This spring, Missouri River communities in South Dakota, Nebraska, Iowa, Missouri, and Kansas all saw major flooding. The floods were caused by more rain than usual falling on deeply frozen ground covered in snow.[10,49] The runoff, unable to be absorbed into the ground, overwhelmed streams and rivers. In March 2019, the upper Missouri River saw 4 times the usual amount of runoff, surpassing the previous record by 51%.[50] The river overflowed its banks and levees; for some communities, this was the sixth major flood event in the past 40 years.[51]

Research confirms what communities already know: The incidence of flooding in the central United States is on the rise.

A study funded by NSF examined data from stream gauges to determine flood rates. They found increasing flood rates between 1962 and 2011 at 34% of the sites included in the study, which were localized in the midwestern states of North Dakota, Iowa, Missouri, Illinois, Indiana, and Ohio.[52]



CLIMATE SCIENCE:

THE 100-YEAR FLOOD DOESN'T COME EVERY HUNDRED YEARS

An important area calculated on any flood hazard map is the 100-year floodplain. Similar to a coin toss, where for every toss you have a 50% chance of landing on heads, areas within the 100-year floodplain have, every year, a 1% chance of flooding. For homeowners who live in a 100-year floodplain, this translates into an approximately 25% chance their home will flood during a 30-year mortgage.[12]

Another reason why the 100-year flood doesn't come every 100 years is that the 100-year floodplain is, in part, determined using historical streamflow data. This calculation assumes that future streamflow will be like past streamflow.[77] In reality, changes to the landscape, built infrastructure, and climate cause changes to streamflow patterns that cannot be predicted using historical data.[77,78]

Climate science shows that the frequency and intensity of heavy precipitation events will increase as the atmosphere warms and holds more moisture.[9] Given the physical connection between precipitation and flooding, and observed correlations between the increasing number of high-intensity rainfall events and floods in the central United States, it seems likely that increases in heavy rainfall will lead to increases in flooding in some areas.[9,52] The overwhelming consensus among water resources engineers and scientists is that new methods and more long-term data are needed to calculate future flood risk accurately.[77,78]

Jacobson and many other scientists have spent their careers working to understand flooding along the Missouri River. They will be the first to tell you that the 2019 flooding will take years to fully understand.

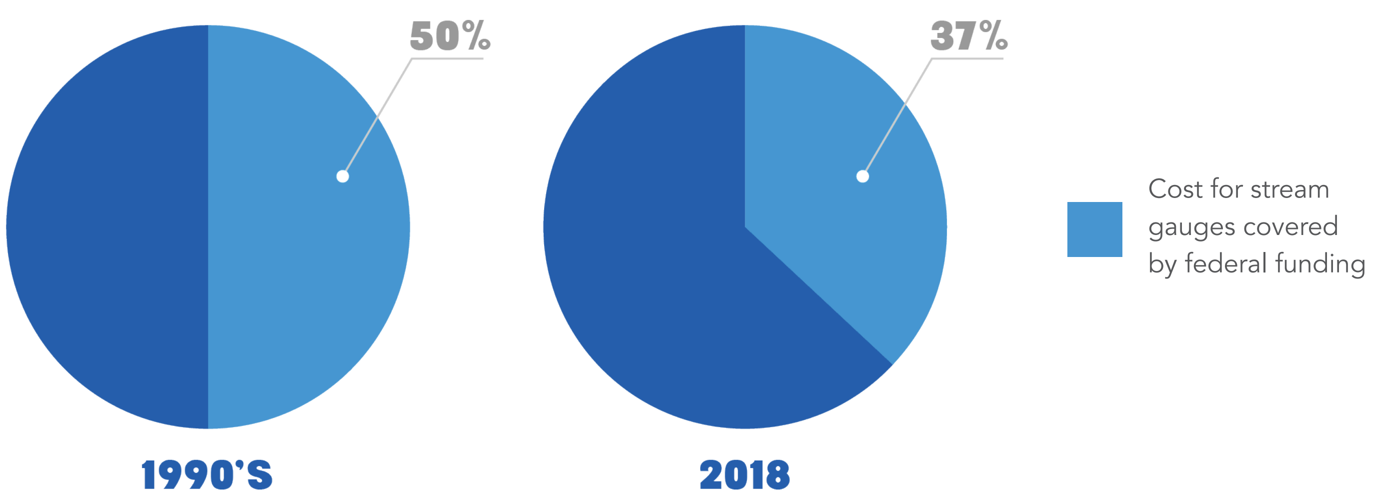
New data and new models are necessary to capture changing precipitation and land characteristics.

Flooding is caused by a combination of factors, which are intensifying due to climate change, including precipitation type, amount, and rate. In addition, rapid development constantly changes the likelihood that precipitation can be absorbed by the ground it falls on.

The Joachim Creek gauge in De Soto is maintained and partially funded by USGS, in cooperation with the city of De Soto and Jefferson County, Missouri. Flood warning systems enabled by streamflow gauging stations provide both tangible and intangible benefits. They allow residents to evacuate and protect their property; they give businesses and utility providers time to prepare, minimizing costs and disruption to customers; and they decrease the stress on an entire community that inevitably results from a rapid emergency evacuation.[53] Importantly, federal funding for stream gauges covers a shrinking portion of the costs (37% in 2018 versus 50% in the 1990s).[54] This creates a possibility that vulnerable communities will not have enough funds to support a stream gauge and understand their flooding risk. While determining an exact monetary value for flood warning systems is challenging, streamflow data collected by gauges—for all their possible uses, including flood management—have a benefit-to-cost ratio of about 4:1.[55]

STREAMFLOW GAUGES CAN HELP PROVIDE SOME IMMEDIATE RELIEF FROM FLOODING BY ALLOWING ADVANCE WARNING.

Knowing a flood is coming is one critical piece of information to communities like De Soto.



Long-term planning requires knowing where flooding is likely to occur, not just today but years into the future.

Developing a flood hazard map is one step toward this understanding and requires both streamflow data collected from gauges and an elevation map.

The USGS 3D Elevation Program (3DEP) has provided 3-D elevation data since 2014 with the support of multiple federal agencies.[56,57] These maps rely on light detection and ranging (lidar) laser technology. Lidar uses an aircraft to pulse laser light that bounces off the Earth's surface and returns to a sensor on the aircraft.[58] Using these measurements, scientists can measure the Earth's surface at a horizontal resolution of approximately 2 feet or less, with a vertical error of about 4 inches.[57,58]

Currently, 3DEP data are available for 53% of the country.[56] These maps provide an estimated $502 million annually in benefits for the support of flood management decisions.[59] A survey of federal, state, local, and tribal governments and private companies identified 602 mission-critical functions that 3DEP maps support, falling into such diverse categories as infrastructure and construction management, agriculture and precision farming, and aviation navigation and safety.[59] Through supporting these functions, 3DEP provides a total potential annual benefit of $13 billion, or a possible 5:1 aggregate return on investment across all its uses.[59]

URBAN FLOODING SPILLS OVER

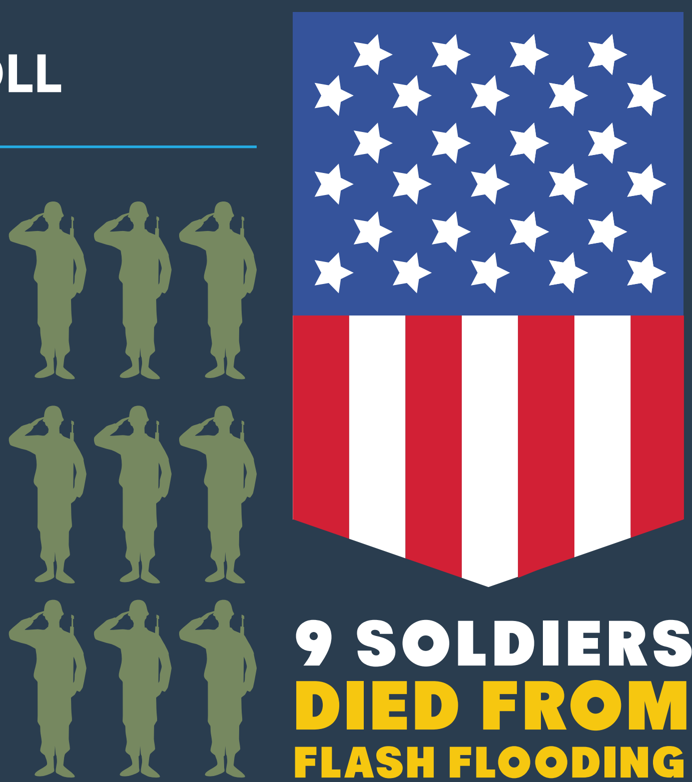
While residents of De Soto can point to Joachim Creek as the primary source of their flooding risk, in other communities across the country a different story is unfolding. For example, in the suburbs of Chicago, parking lots and basements flood without a stream in sight. When the Center for Neighborhood Technology (CNT), a nonprofit that strives to promote urban sustainability, investigated the issue, they found that the floods are being caused by storm water that has nowhere to go because of aging, undersized drainage systems overwhelmed by increased runoff from land development.

Harriet Festing, an advocate for communities dealing with the effects of climate change, led the effort for CNT. Digging into insurance claim data for Cook County, Illinois, which comprises Chicago and some of its suburbs, Festing found that flood insurance claims were no more likely within the mapped 100-year floodplain than outside of it.[60] This finding meant that the prevailing thinking—manage the floodplain and you will manage the floods—did not address the reality of urban flooding in Chicago. Subsequent reports have exposed urban flooding as a national problem.[61,62] With 86% of the U.S. population living in metropolitan and metropolitan-adjacent areas,[61] the implications are enormous.

HEALTH AND SECURITY:
FLOODING TAKES A TOLL

Flash flooding is the second leading cause of death from extreme weather in the United States, behind extreme heat.[33] At the U.S. military post Fort Hood in Texas, nine soldiers died from flash flooding during a training exercise in June 2016.[79] Since then, Fort Hood has installed six USGS stream gauges to help predict flash flooding events.[79,80]

In addition, in a survey of 100 residents of Cook County, Illinois, who experienced flooding in the past 5 years, 84% indicated that flooding caused stress, and 13% of respondents said that flooding contributed to the poor health of someone in their household.[60]



In her current role managing Higher Ground, Festing has also played a role in introducing communities facing urban flooding to scientists through her connections with AGU's Thriving Earth Exchange. This was how Joe Schulenberg, an assistant clinical professor at the University of Illinois at Chicago, met Delia Barajas, director of Ixchel, a grassroots organization advocating for racial equity in education and environmental justice for communities of color in the town of Cicero, a Chicago suburb. Together they sought to provide viable mitigation options for residents of Cicero and the nearby city of Berwyn affected by persistent drainage system backups resulting in basement flooding and sewer backups. These floods are even more life altering in these two towns, where a high cost of living and income inequality often lead to multiple families sharing single-family homes.

Schulenberg and a team of his students expected to provide engineering analysis and design alternatives to address the flooding in Cicero and Berwyn but soon realized the project would not be so simple. Schulenberg and his students found that nearly 70% of a given lot in the two municipalities is occupied by pavement or structures.[63] This lack of open space, combined with a lack of municipal and homeowner funds, made many of the solutions that students suggested, such as constructing a rain garden or a bioswale (a shallow, sloped ditch covered in grass or other plants), to retain flooding from the street, unrealistic to achieve.

Information is another resource limiting Barajas and Schulenberg in their efforts to mitigate the urban flooding in Cicero in particular. Unlike Berwyn, which has a Stormwater Management Plan developed with the help of the Chicago Metropolitan Agency for Planning, Cicero has no readily available plan. Furthermore, while the maps for Berwyn's sewer system are digitized in geographic information system (GIS) software, Cicero's maps remain as scanned drawings from the 1930s. Without updated planning and mapping information, engineers like Schulenberg need to start from nearly scratch when approaching Cicero's flooding problems.

The most challenging aspect for Schulenberg and his students was approaching the issue of urban flooding through an environmental justice lens. "You can do all the studies you want, but if you don't look at it through the lens of racial justice, you're missing the key part," says Barajas. The lack or denial of resources that many lower-income and minority communities face—in terms of access to funding, open space, and information—compounds the effects Cicero and Berwyn residents experience from urban flooding and make them more vulnerable to other environmental threats. For instance, Cicero is downwind of both a major railyard and a wastewater treatment facility, which contribute to air quality issues through soot and noxious odors, respectively.[64,65] Independent water testing has also revealed some instances of lead in Cicero's drinking water, caused by aging water distribution pipes.[66] Ixchel members are spread thin as they work to address flooding and air and water quality in their communities simultaneously. But as more engineers like Schulenberg and his students are willing to engage in analyses and information gathering that recognize how these impacts relate to each other and larger systemic barriers, they are likely to have more help in the future.

NEW SOLUTIONS TO AN OLD PROBLEM

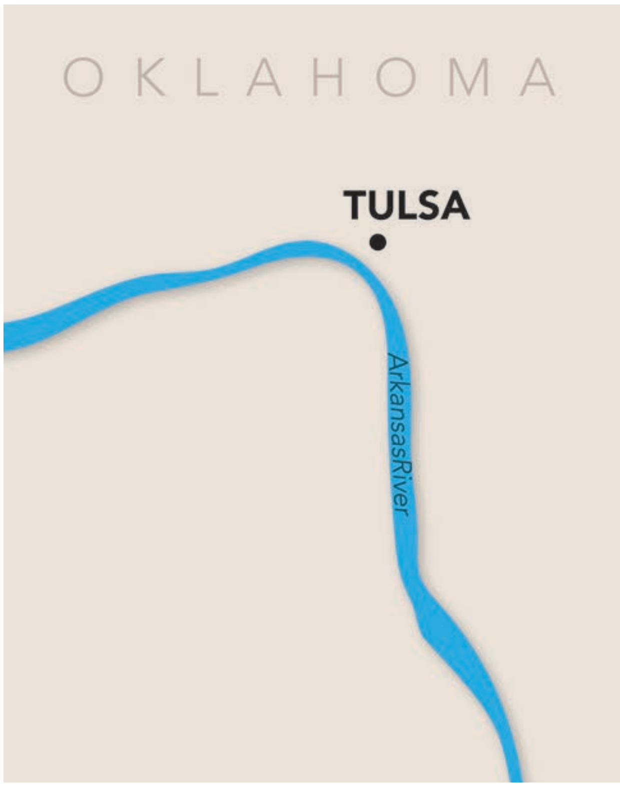
A growing number of communities are seeking new solutions to flooding. Many are opting for so-called "green" infrastructure, which works by allowing storm water to seep into the ground or by slowing the release of water downstream. Examples include rain gardens, permeable pavement, and bioswales. These efforts are based on new understanding of flood mitigation and management and contrast with traditional "gray" infrastructure, such as storm drains in a city road or levees between a town and a river, which both work by diverting water as quickly as possible downstream.

Toledo, Ohio, a city near the western point of Lake Erie, began considering green infrastructure after major flooding in 2006.[67] With funding from the Environmental Protection Agency's (EPA) Great Lakes Restoration Initiative and NOAA, Toledo undertook a study that found that green infrastructure that decreased peak streamflow in nearby Silver Creek by 10% could reduce total economic losses by 46% from a 100-year storm.[67,68] Motivated by this study, Toledo and EPA worked together to install a bioswale.[67]

In Tulsa, Okla., multiple levees and a dam on the Arkansas River built by USACE in the 1940s and 1950s did little to prevent flooding and only provided the community a false sense of security. Seeking new solutions to an old problem, the city established a Department of Stormwater Management in 1984.[69] The city used funds from FEMA to buy out and convert flooded properties to green areas, which are now used for both flood risk reduction and recreation.[69] The city also added stream buffers that provide additional environmental benefits and detention basins for added water storage during storms.[69]

BOTH TOLEDO AND TULSA SHOW HOW CITIES ARE SUCCESSFULLY USING GREEN INFRASTRUCTURE WHEN GRAY INFRASTRUCTURE ALONE DOESN'T SOLVE THE PROBLEM.

The spring 2019 floods along the Missouri River prompted USACE to ask Congress to authorize an updated study of the region, but it remains an open question how policy makers and others in the United States will respond to this disaster. Flood risk management along any river is a complex problem that requires holistic watershed management to avoid passing the floodwaters and associated risk downstream, and high-level modeling informed by long-term, continually updated data sets. Because of the combined efforts of scientists who have dedicated their careers to studying rivers and streams, along with the determination of concerned citizens and organizers across the country who have made their voices heard and demanded better solutions for their communities, progress is being made in tackling the challenges posed by our changing world.



SUMMARY

Floods in the central U.S. takes many forms. From river flooding in rural areas of the country and port cities, to urban flooding in highly populated metropolitan and suburban areas, no state in the country is spared from the costs of floods in the central U.S.

Basic data provided by USGS on streamflow and topography are critical to informing communities about where and how often flooding is expected to occur.

Scientists are continually developing new techniques to predict flooding. Examples include the NSF-funded National Water Model, which allows forecasts for any stream in the nation, and NOAA-developed FLASH, a model and early warning system for flash floods.

We live in a changing world, something already recognized by communities and scientists working on flooding issues. We need more research on new solutions, such as nature-based flood mitigation options, to successfully adapt.

COASTAL FLOODING

NEIGHBORHOODS TURN INTO OCEANS

Cars submerged in water up to their headlights. That's what Virginia Wasserberg and her neighbors saw on the street outside their homes after Hurricane Matthew followed an unexpected track through Virginia Beach, Va., in October 2016.[81,82] The home where she lived with her husband and two young children had lost power, and they realized the extent of the damage only when the Sun came up. Abandoned cars had washed into their yard. Their deck, still laden with furniture, had floated up—a sad, wayward raft prevented from sailing into open waters only by the backyard fence. Inside the house wasn't any better. Nearly 2 feet of water filled the first floor, a mess that would take months for a dedicated contractor to repair.

But this is not a story about extreme storms.

EVEN BEFORE HURRICANE MATTHEW STRUCK, FLOODING WAS A PERSISTENT PROBLEM IN WASSERBERG'S NEIGHBORHOOD.

Soon after she and her family moved to Virginia Beach in 2014, their yard flooded after it had rained the night before. Her son pointed to the waves lapping nearly at their doorstep and said, "It looks like the ocean."

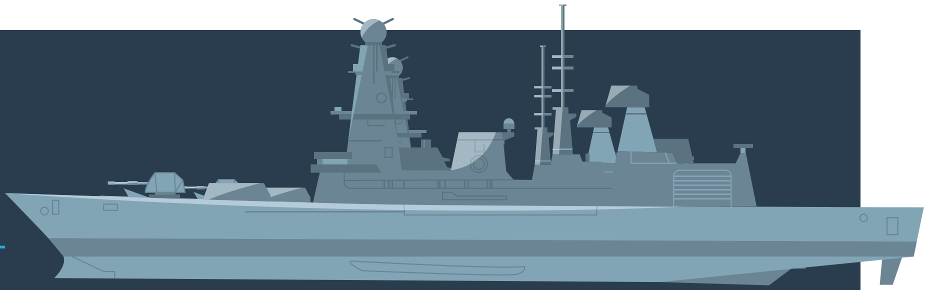
The intersection in front of their house flooded habitually, causing cars, and even school buses, to try to avoid the water by driving through their yard. She and her husband followed the lead of other neighbors and bought metal stakes to help drivers distinguish between yard and road. It didn't work, but it was better than just feeling helpless.

For Wasserberg, a stay-at-home mom who homeschools her children, Hurricane Matthew was the last drop in an already overflowing bucket. In March 2017, when city leaders told homeowners in the neighborhood to document the problem with photos, she created a page on Facebook called Stop the Flooding NOW, which has become a forum for demanding action from local lawmakers.

At the outset, Wasserberg was focused on solutions for her neighborhood, like city funding for tide gates on the tidal creek that her neighborhood's runoff flows into or pump stations that municipal engineers recommended. As the city considered ways to fund these projects, it responded to Wasserberg and her neighbors by cleaning storm drains and dredging ditches and canals in the area. The more Wasserberg learned, however, the more she understood that the problem was not as limited as she had once thought.

"THIS ISN'T JUST A NEIGHBORHOOD PROBLEM; THIS IS A CITYWIDE PROBLEM," SHE SAYS OF HER EPIPHANY. "AND THEN WE EVEN MORE QUICKLY REALIZED IT'S A REGIONAL PROBLEM."

NATIONAL SECURITY:
SEA LEVEL RISE



The Hampton Roads region encompasses the Virginia Beach, Norfolk, and Newport News metropolitan areas and is home to 1.7 million people.[98] Hampton Roads also contains, in the words of former secretary of defense Leon Panetta, "perhaps the greatest concentration of military might in the world."[99] Hampton Roads is home to a total of 38 military and supporting sites and 100,000 military and 40,000 civilian personnel.[100] Significant bases include Naval Station Norfolk, the largest naval complex in the world, which provides support for the entire U.S. Atlantic Fleet, and Joint Base Langley-Eustis.[100] Both bases are no more than 10 feet above mean sea level and already suffer from recurrent flooding, compounded by land subsidence.[80,100,101]

The Air Force rated Joint Base Langley-Eustis as one of the top 10, out of 36 considered priority bases, currently affected by extreme weather, including coastal and inland flooding, extreme heat, and drought.[102] A study by NASA found much higher than average land subsidence rates at Norfolk Naval Shipyard, likely driven by construction during the study period.[101] For the U.S. military in Hampton Roads, flooding and sea level rise in the region pose a dire and immediate threat. As stated by retired Rear Adm. David Titley, who led the Navy's Climate Change Task Force, "I think Norfolk is, in the long term, fighting for its existence, its very existence."[103]

USING SCIENCE TO GIVE OTHERS A VOICE

Michelle Covi, an assistant professor at Old Dominion University and a staff member for the Virginia extension of NOAA's Sea Grant program, played a significant role in this realization. Covi, whose research focuses on climate change and sea level risk perception and risk communication, specializes in framing scientific messages for a variety of audiences. She is currently working with the city of Virginia Beach to engage residents as the city develops a response plan to sea level rise and recurrent flooding.

Not only does she strive to inform residents about the challenges posed by sea level rise, but also she helps to inform city officials on the best ways to incorporate data into flood adaptation decision-making, effectively giving a voice to more Hampton Roads residents. For example, research conducted by Covi and a Ph.D. student in the city of Portsmouth, where, according to Covi, some residents express a high level of distrust of government, found that...

...LOW- TO MODERATE-INCOME HOUSEHOLDS WERE MORE LIKELY TO EXPERIENCE STREET FLOODING THAN HIGHER-INCOME HOUSEHOLDS.[83] THEY WERE ALSO MORE LIKELY TO HAVE A LIMITED ABILITY TO GET OUT OF THEIR NEIGHBORHOODS DURING FLOODING.[83]

Covi and her team provided a set of recommendations to the city of Portsmouth to enhance communication with these households through their preferred communication avenues.[83] These results could also have the potential to inform future flood mitigation and emergency response plans in Portsmouth as a whole.

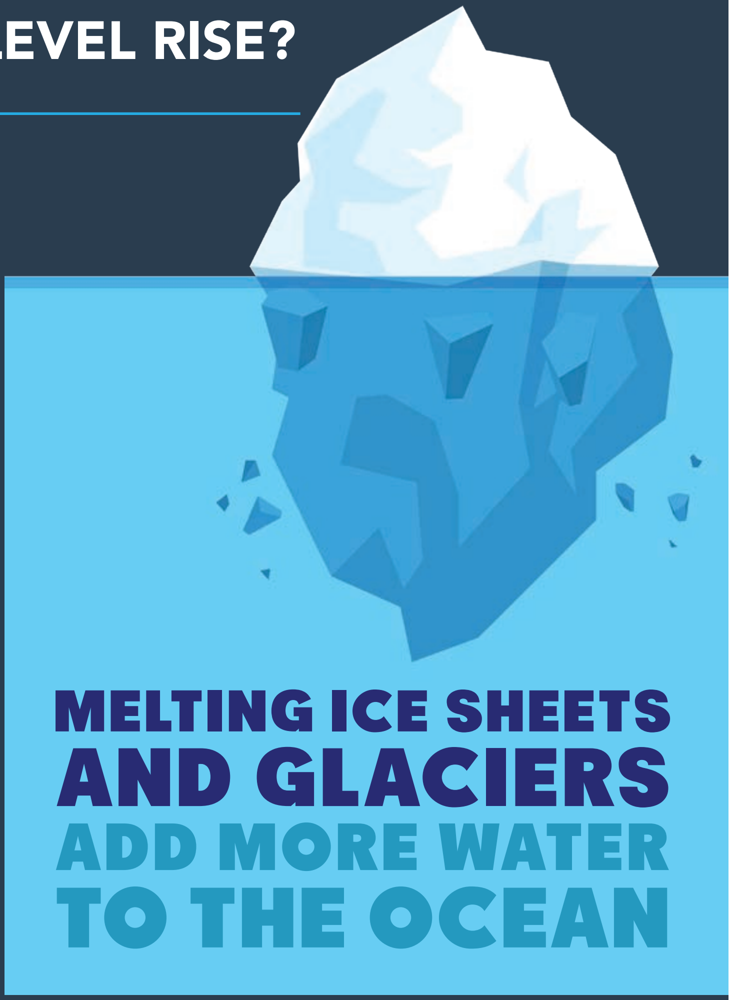
Because of her expertise, Covi was tapped by AGU's Thriving Earth Exchange program as a resource for Wasserberg and Stop the Flooding NOW. She has worked with Wasserberg on what has become a public education project, helping her explain the scientific basis behind Virginia Beach's flooding:

As water is withdrawn from the Potomac Aquifer for drinking water for the region, the land sinks, which is exacerbated by global sea level rise.

CLIMATE SCIENCE:

WHAT IS GLOBAL SEA LEVEL RISE?

Global sea level rise is caused by two main factors, both of which are connected to human-caused climate change: (1) existing ocean water expanding as it increases in temperature, and (2) melting ice sheets and glaciers adding more water to the ocean.[9] Global mean sea level is measured by satellites and through NOAA's global tide gauge network, as an average of the sea level height at multiple locations around the globe.[104] Since 1900, the global mean sea level has risen 7–8 inches, with 3 of these inches occurring since 1993.[9] In specific locations, the sea level may be rising faster or slower compared with the global mean.[105] Human-caused climate change contributed to mean sea level rise during this entire period, contributing to a rate of mean sea level rise that hasn't been seen in at least 2,800 years.[9] As a direct result of sea level rise, the number of minor, or "nuisance," floods occurring in coastal cities has increased fivefold to tenfold since the 1960s.[9]



Wasserberg, in turn, has become both a voice and a resource for her community on flooding and climate science, and Covi credits her with helping to promote real change in local resident populations who may be apprehensive of outside experts. "Virginia engages with a different group than what I would get to come out if I organized a meeting," she says. "She has really been out there talking to people in a different way than I could talk to [them] about this." While Wasserberg is still lobbying city officials for funding for flood mitigation projects, she understands that science education, effective communication, and grassroots activism are also essential for progress to be made on flood mitigation in the region.

Individually, Covi and Wasserberg brought flooding and sea level rise to the attention of their community—as a team, attention turned into knowledge that could improve lives.

UNDERSTANDING RISK REQUIRES A SEA OF DATA

In the same way that communities facing river flooding can begin to understand their risk by measuring the frequency of different water level heights with a stream gauge, coastal communities can quantify their likelihood of flooding using tide gauges. NOAA maintains the National Water Level Observation Network—a network of 210 permanent water level gauges on both coasts and the Great Lakes to observe tide levels and make tide predictions for the nation.[84]

NOAA's tide gauge network is supplemented by local gauges installed by USGS. In response to coastal flooding concerns in Virginia, USGS installed approximately 2 dozen tide gauges in 2015 and 2016, including 10 in Virginia Beach.[85,86] The organization sends data from these gauges directly to NOAA's National Weather Service.

These data help to produce more accurate local forecast and allow emergency managers to make location-based decisions, like determiing evacuation routes.[85] Other groups in the state are also motivated to address the problem of flooding from sea level rise and improve the accuracy of local forecasts. The Commonwealth Center for Recurrent Flooding Resiliency (CCRFR) and the Virginia Institute of Marine Science (VIMS) maintain additional tide gauges in the so-called "Tidewatch" network in the Chesapeake Bay and along Virginia's seaside Eastern Shore. The network makes forecasts in the Hampton Roads region at the scale of individual roads and structures,[87] predicting tide heights and associated flooding 36 hours into the future.[88]

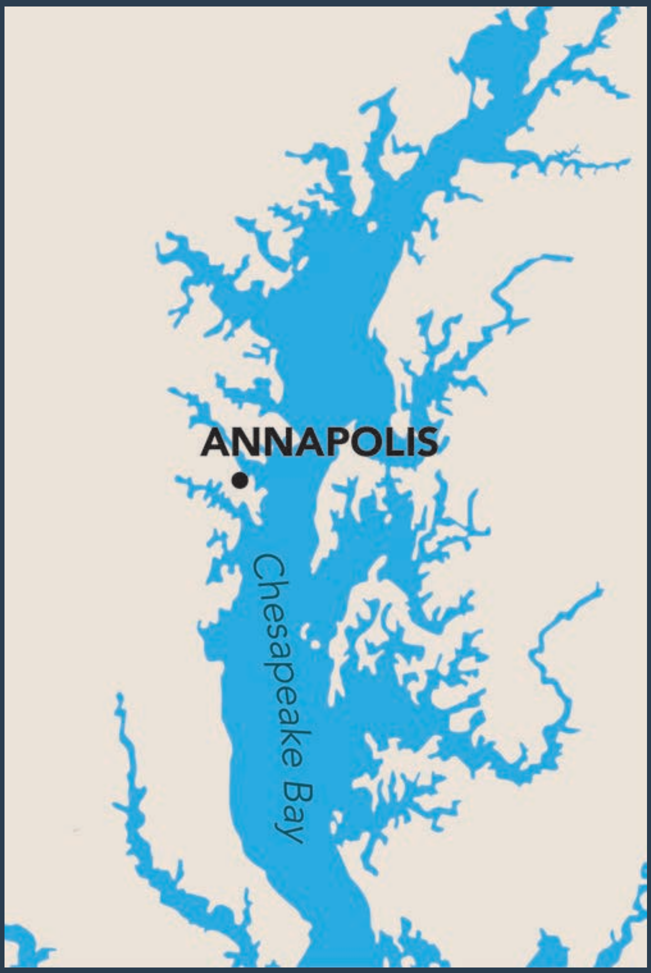
Forecasts of tide and coastal flood height require both elevation data and models to predict how water will flow over the land. Tidewatch forecasts, for example, use topographic maps from USGS and multiple models including NOAA's SLOSH model, which is shorthand for Sea, Lake, and Overland Surges from Hurricanes.[89] In addition to considering variables like water depth and physical features of the shoreline, SLOSH incorporates data about a storm's atmospheric pressure, size, and movement to create a model of how wind and atmospheric pressure affect the height of the storm surge.[90] SLOSH applies all along the East Coast of the United States and the Gulf of Mexico coastline.[90]

ECONOMY:

IMPACT OF "MINOR" FLOODING

A single extreme flooding event can cost several billion dollars, but the probability of such an event is, fortunately, very small. While a single minor flooding event along the coast, also called "sunny day" or "nuisance" flooding, causes less economic damage, the costs add up over time for the frequent, recurring events. In a study of the possible economic losses from extreme and minor flooding events for 11 coastal U.S. cities, five cities—New York, Washington, D.C., Miami, San Francisco, and Seattle—had a larger cumulative cost risk from minor flooding than from extreme flooding events.[106]

Minor floods can also have a significant economic impact on individual residents and businesses. Maryland's capital, Annapolis, is located on the Chesapeake Bay and relies on tourism to its historic downtown. A study of high-tide flooding in a downtown Annapolis parking area found that flooding led to a loss of nearly 3,000 annual visitors to the parking lot and to between \$86,000 and \$172,000 in losses for nearby businesses, or 0.7%–1.4% of their annual revenue.[107,108]



RISING SEAS, PROTECTING CULTURES

On the U.S. West Coast, the Coastal Storm Monitoring System model, or CoSMoS, provides predictions of flooding and wave impacts from current and future storms in combination with sea level rise driven by climate change.[91,92] CoSMoS integrates wind and pressure data from various sources (including the National Weather Service) with data on sea level rise, tides, and stream flooding to predict the impact of storms that are actively occurring. CoSMoS relies on global climate models to project future storms.[93,94]

CoSMoS was originally developed by USGS for the high wave-energy environment along California's coast. In a partnership with the EPA, USGS has also developed a version of CoSMoS to apply to the coastline of the Salish Sea, a complex network of inland waters spanning Washington State and parts of Canada. One of the Salish Sea's main bodies of water is Puget Sound in Washington State. The Skagit River delta at the northern end of Puget Sound has been the homeland of the Swinomish people for thousands of years.

The Swinomish weathered three destructive storms in 4 years. The last, in December 2018, destroyed shoreline structures and left the Swinomish looking to understand how often they could expect storms of this magnitude in the future. The intensification of stream and coastal flooding has not only flooded Swinomish homes, but also threatens their access to important fishing areas and cultural sites as well as their very identity.[95] Tribal elder Larry Campbell told USGS that the tribe's traditional seafood diet is more than nutrition alone. "They're also spiritual foods for us," Campbell explained. "We call it feeding our spirits when we eat these foods."[95] The Swinomish, like other tribes with reservations, face the additional impact of a shrinking land base since reservation boundaries are static and do not shift with rising sea levels.[95]

Out of these concerns grew a unique collaboration between Eric Grossman, a Research Geologist with USGS, and Jamie Donatuto, the environmental scientist employed by the Swinomish tribe. Grossman and his team adapted CoSMoS to predict what land areas and valued habitats within the Swinomish Reservation were at risk from future sea level rise and future major storms and how the frequency of storm disturbances will increase because of sea-level rise and affect planning thresholds and tipping points. However, the Swinomish concerns were about much more than land and resource conservation. As Donatuto describes it, for the Swinomish, "[h]ealth comes from culture, and culture comes from land, water, and air." Donatuto therefore worked with the Swinomish to identify tribal health priorities, which included both conservation of their traditional foods, including clams, crab, and salmon, and reviving intergenerational land-based education. These health priorities allowed the Swinomish to take the CoSMoS results and prioritize areas for protection. It also led to an informal curriculum that emphasized elders teaching tribal youth about land stewardship The combined values and science-based decision-making used by the Swinomish are not new.

As more scientists like Grossman and Donatuto take the time to understand the priorities of the communities they are working with, we can expect to see more collaborative, sustainable, and effective solutions to the climate challenges facing our nation.

TECHNOLOGY:
DIGITAL COAST

Since 2007, NOAA has supported coastal managers on the Atlantic, Pacific, and Great Lakes coasts through its freely available Digital Coast products.[109] Digital Coast serves as a central repository of vetted coastal information and products generated by many sources and provides users with more than 70 terabytes of data and 50 tools, like the popular Sea Level Rise Viewer, which helps users easily visualize data.[109,110] These tools make data accessible and more easily digestible for the state and local coastal managers responsible for strategic planning decisions.

Digital Coast also serves a wide range of users. For example, the Department of Defense used it in its initial assessment of military bases and their risk of inundation from sea level rise.[110] Within 2 years of its creation, the digital data clearinghouse already had proved its worth; the net economic benefits surpassed its net costs.[110] By 2028, the net benefit of Digital Coast is expected to reach $117 million, representing a 411% return on investment.[110]

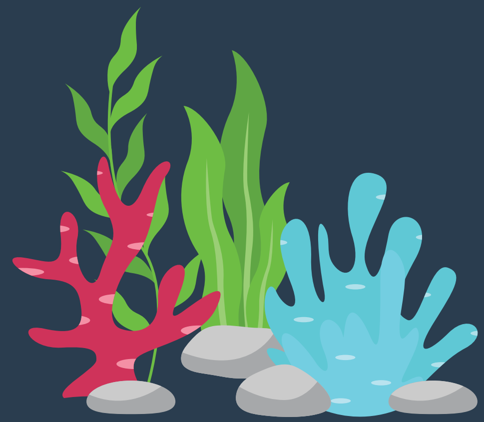
POLICY PLAYS A PART

In Virginia Beach, some political change is starting to take root. The city hired an engineering firm to complete a rainfall study for the region. On the basis of analysis of 70 years of historical rainfall, the engineers found that rainfall intensity increased by about 5% per decade in the Virginia Beach area, as well as similar increases in rainfall intensity along the entire northeastern U.S. coastline.[96] Therefore, they recommended that Virginia Beach increase by 20% the rainfall value used in the design of infrastructure intended to last for the next 40 years, a typical design lifetime.[96]

The report also contributed to the Virginia Beach City Council incorporating scientific predictions of flooding into their zoning and development decisions. Recently, the City Council's decision to deny a developer's request to rezone flood-prone land for a housing development was upheld in court,[97] affirming the lawmakers' legal right to consider climate data and pursue evidence-based policies around flooding. Victories like this demonstrate how a coordinated effort between scientists, everyday citizens, and elected officials to empower a community through data and science can lead to positive change.

TECHNOLOGY OF A DIFFERENT KIND:

NATURE-BASED COASTAL FLOODING MITIGATION



CORAL REEFS PROVIDE NATURAL PROTECTION

The Eglin and MacDill Air Force bases in Florida are experiencing the effects of coastal flooding and erosion. In 2019, the Air Force ranked Eglin and MacDill in the top 10 of bases at risk of extreme weather impacts like inland or coastal flooding, extreme heat, or drought.[102] Eglin was ranked second and MacDill, eighth.[102] In partnership with local community groups, both bases turned to oyster reefs to mitigate coastal erosion.[80] These bases are not alone in turning to "nature-based" coastal flooding mitigation—interest is growing along with research that shows that nature-based mitigation methods, such as the presence of marshes and reefs, provide valuable shoreline protection from flooding damage.[111,112]

During Hurricane Irene, approximately 76% of seawalls—made of concrete and other hard materials—on North Carolina's Outer Banks were damaged, while no damage occurred to the shorelines with marshes within 15.5 miles of the hurricane's landfall.[111] Coral reefs provide another form of natural protection. A recent quantification of the benefits from all coral reefs in the states of Hawaii and Florida, and the territories of Guam, American Samoa, Puerto Rico, and the Virgin Islands, and the Commonwealth of the Northern Mariana Islands, found that coral reefs provide an annual value of $1.8 billion in avoided flood damages.[112] They also prevent 18,000 people from experiencing flooding each year.[112]

Wasserberg is still active in advocating for the residents of Virginia Beach but has moved out of her neighborhood because the investment—financial and emotional—was too great. The family could not sustain another flood like the one in 2016, and, at the same time, another flood seemed inevitable. On the Stop the Flooding NOW Facebook page last fall, Wasserberg shared her story and urged fellow Virginia Beach residents to cast a ballot in the upcoming election.

"FLOODING IS MORE THAN A HOUSE FILLED WITH WATER," SHE WROTE. "IT'S A MUCKED AND GUTTED HOME STRIPPED OF ITS BEAUTY, A FAMILY DISTRESSED AND DISPLACED WITH MOUNTAINS OF STRESS ON THEIR BACKS, A LIFETIME WASHED AWAY IN A MOMENT."

She thanked her community and then ended on a positive note: "We flood and we VOTE!"

SUMMARY

High-tide, "sunny day," or "nuisance" flooding is a problem on the east, west, and Great Lakes coasts of the United States.

Federal agencies like NOAA and USGS work to collect the data required for the best predictions of future coastal conditions.

The issue of adaptation is as much a social issue as it is a technical one—it will require scientists and communities coming together to understand priorities and possible solutions.

We are beginning to see science as a basis for flood policy across the country, a promising sign for our nation's future.

RECOMMENDATIONS

Addressing the complex challenges posed by flooding and extreme weather nationwide will take multiple partners working in collaboration at multiple levels. Science and scientists are a key element of these solutions, but they need support from federal and local governments, and in turn they must be relevant to, accessible to, and engaged with communities.

None of the information and tools provided by the scientists in our example communities would have been nearly as effective without the knowledge of local leaders about their priorities, culture, and existing response capacity. This type of community-based science can only happen through strong mutual trust, communication, and relationship building between scientists and communities. It is a long-term investment that will require commitment and patience from both sides. AGU's Thriving Earth Exchange program provides a library of resources to get started.

To ready our nation for future challenges presented by flooding and other extreme weather impacts, we propose specific recommendations for policy makers, scientists, community leaders, and individuals that will

- Empower communities to make informed decisions about their future;
- Empower scientists to conduct robust scientific research and data collection about flooding and its related issues; and
- Prioritize partnerships that foster collaboration, knowledge sharing, and better communication among scientists who study both the physical world and human behavior, and between scientists and communities.

> Together, we can rise above the floodwaters.

CONGRESS CAN

Fund relevant science-based federal agencies.

- Fully fund agencies and programs that provide immediate flooding relief, with an understanding that a long-term sustainable solution requires coordination and cooperation of various stakeholders.
- Support robust and steadily increasing funding for science-based agencies to carry out long-term, watershed-based data collection and research of the mechanisms behind flooding and flood mitigation options. Such funding should match National Academy of Sciences recommendations of at least 4% real growth every year.

Invest in cross-cutting science centers and programs, including:

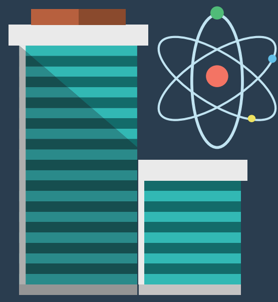
- Place-based science research centers to address region-specific flooding concerns. Examples at the federal level include the USGS's eight regional Climate Adaptation Science Centers, 28 regional Water Science Centers, and 54 Water Resources Research Institutes, and NOAA's Office of Water Prediction Collaborative Centers. An example at the state level that could be replicated by federal funding is the Iowa Flood Center.
- Programs that incentivize long-term relationship building and two-way communication of problems and solutions between scientists and their communities. Examples at the federal level include NOAA's National Sea Grant College Program and USDA's National Institute of Food and Agriculture Cooperative Extension Services.

Support evidence-based policy.

- Support legislation that protects the use and the role of science in decision-making by ensuring that science can be conducted and inform policy freely, openly, and without undue political interference.

Emphasize future planning.

- Develop government policies to manage flooding and impact of inundation that account for a changing world and incorporate the best science around climate, human health, and development predictions.



SCIENCE AGENCIES AND CENTERS CAN

Prioritize partnerships and collaboration.

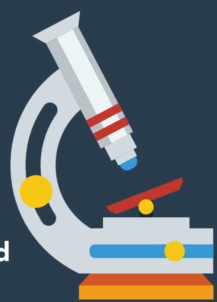
- Engage in deeper communication and collaboration across traditional organizational and disciplinary boundaries (such as microbiology, social sciences, and human health).
- Create unified centers of multidisciplinary collaboration between groups conducting flooding science, leading to a national network of climate, health, and water centers.

Engage with communities.

- Increase communication of the measures and steps communities can take to prepare for flood events and gain access to flood mitigation and recovery funding.
- Establish science community boundary programs that emphasize and incentivize two-way communication of problems and solutions and connect communities to key technical and government resources.

Pursue critical areas of research and planning.

- Focus research on weather and climate modeling, water quantity modeling, land use change modeling, remote sensing, human/agricultural health, social–economic perspectives of flood risk, and determination of best practices for risk communication, especially long-term risks.
- Incorporate into any policies the best climate science and development predictions.



SCIENTISTS CAN

Engage with communities.

- Start talking with and, more important, listening to communities in your area. Find out what their priorities are and what you can contribute to help them.
- Volunteer for existing programs providing scientific support to communities facing floods and other environmental issues. Opportunities to volunteer include AGU's Thriving Earth Exchange or any of the NSF-funded Extreme Event Reconnaissance networks.

Promote interdisciplinary research and collaboration.

- Seek out and share scientific findings with others working on managing floods and flooding risk, especially those outside of your discipline.
- Emphasize collaboration between physical and social scientists to advance best practices for keeping people safe.

COMMUNITIES CAN

Leverage existing resources.

- Seek out and use existing governmental support structures for managing floods. In the United States, for example, determine whether your state has a Silver Jackets program.
- Take advantage of existing programs providing scientific support to communities facing floods and other environmental issues, such as AGU's Thriving Earth Exchange.
- Develop or join organizations connecting flood-impacted communities with each other, such as Higher Ground.

INDIVIDUALS CAN

Stay informed.

- Learn about the flood risks in your neighborhood through FEMA's Flood Map Service Center.
- Learn about the types of disaster assistance available through FEMA and how to apply.
- Pay attention to and follow warnings contained in forecasts and mobile alerts from your local weather stations and the National Weather Service.

Create a plan.

- If your community is at risk of flooding, plan now for an emergency. You can find suggestions at www.ready.gov/floods.
- Incorporate your community into your plan. Do you or any of your neighbors need support evacuating? What are the local emergency organizations, and what services do they provide?

Be an advocate for science.

- Communicate with policy makers at all levels of government about the need to invest in science and science-based policy.

ACKNOWLEDGMENTS

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EDITOR: Stephanie Berrong, Line Edit Communications

We extend our sincerest thanks to the scientists and professionals who lent their time and expertise to this report through many phone calls, meetings, and emails. These conversations shaped our understanding of what is required to advance flooding science and shape evidence-based policies. Furthermore, the stories, contacts, data, and publications they shared added depth and diversity to the report narrative. These individuals are listed below, alphabetized by last name:

Paula Arbuthnot; Co-founder, Citizens' Committee for Flood Relief

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Susannah Erwin, PhD; Research Hydrologist, Columbia Environmental Research Center, US Geological Survey

Harriet Festing; Co-founder, Anthropocene Alliance

Jenn Fogel-Bublick, JD; Spokesperson, Smarter Safer Coalition

Jim Fox; Director, National Environmental Modeling and Analysis Center, UNC Asheville

Kevin Fries, PhD; Data Scientist, One Concern

David Frost, PhD; Elizabeth & Bill Higginbotham Professor, Geosystems Engineering, Georgia Institute of Technology

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We would also like to thank the scientists and engineers who served on our advisory panel. In this role, they provided critical feedback on the scientific accuracy of the report and guidance on the relevant science to include. These individuals are listed below, alphabetized by last name:

Ana Barros, PhD; Professor, Dept. of Civil and Environmental Engineering, Duke University

Bill Brown; Director, Flood Science Center, Association of State Floodplain Managers

Jennifer Collins, PhD; Professor, School of Geosciences, University of South Florida

Dave Fowler, CFM; Senior Project Manager, Flood Science Center, Association of State Floodplain Managers

Gerry Galloway, PhD; Research Professor, Civil and Environmental Engineering, University of Maryland

Jonathan (JJ) Gourley, PhD; Research Hydrologist, National Severe Storm Laboratory, NOAA

Denise Hills; Director, Energy Investigations Program, Geological Survey of Alabama

Antarpreet Jutla, PhD; Associate Professor, Dept. of Environmental Engineering Sciences, University of Florida

Witold Krajewski, PhD; Director, Iowa Flood Center

Coraggio Maglio, CFM; Research Civil Engineer, Engineering Research and Development Center, Coastal and Hydraulics Laboratory, USACE

Julie Vano, PhD; Project Scientist, Hydrometeorological Applications Program, National Center for Atmospheric Research

Donald J. Wuebbles, PhD; The Harry E. Preble Professor of Atmospheric Sciences, Department of Atmospheric Sciences, University of Illinois [reviewer for "Floods and Our Changing Climate"]

REFERENCES

1. Cappucci, M. (2019), A water double whammy: Barry's rain and storm surge could inundate New Orleans, *Washington Post*, https://www.omaha.com/news/nebraska/wood-river-advised-to-evacuate-flooding-reaches-gibbon-as-streams/article_25652fe3-6555-595e-bdbd-f0f330c8b729.html.
2. AbdelHameid, D. (2019), Today's rainfall broke a 148-year record, DCist, https://dcist.com/story/19/07/08/todays-rainfall-broke-a-148-year-record/. (Accessed 11 July 2019)
3. Cole, K. (2019), Wood River advised to evacuate, flooding reaches Gibbon as streams overflow in central Nebraska, *Omaha World-Herald*, 11 July, https://www.omaha.com/news/nebraska/wood-river-advised-to-evacuate-flooding-reaches-gibbon-as-streams/article_25652fe3-6555-595e-bdbd-f0f330c8b729.html.
4. Eller, D. (2019), Iowa highways closed by flooding could take months to reopen, *Des Moines Register*, https://www.desmoinesregister.com/story/money/agriculture/2019/04/11/iowa-nebraska-flooding-closed-roads-dot-road-conditions-council-bluffs-omaha-interstate-29-traffic/3435668002/. (Accessed 15 May 2019)
5. National Groundwater Association (2019), The National Ground Water Association reports thousands of wells potentially affected by midwestern flooding, *2019 Press Releases*, 25 Mar., https://www.ngwa.org/publications-and-news/Newsroom/2019-press-releases/ngwa-reports-thousands-of-wells-potentially-affected-by-midwestern-flooding. (Accessed 12 July 2019)
6. U.S. Army Corps of Engineers (2019), Weekly Missouri Basin flood response update for key stakeholders–8/1, *News Releases*, 1 Aug., https://www.nwd.usace.army.mil/Media/News-Releases/Article/1923686/weekly-missouri-basin-flood-response-update-for-key-stakeholders-81/. (Accessed 12 August 2019)
7. Liewer, S. (2019), Air Force seeks $4.9 billion in emergency funds for storm-ravaged Offutt, Tyndall, *Omaha World-Herald*, 28 Mar., https://www.omaha.com/news/military/air-force-seeks-billion-in-emergency-funds-for-storm-ravaged/article_0f70d1ea-1206-5291-9d19-1a981b45608a.html. (Accessed 15 May 2019)
8. Liewer, S. (2019), Work to raise Offutt's levees was just weeks away from starting. The devastating floods came first, *Omaha World-Herald*, 23 Mar., https://www.omaha.com/news/military/offutt/work-to-raise-offutt-s-levees-was-just-weeks-away/article_7279d7e0-9c51-59fc-b88b-c010fb7b453c.html. (Accessed 17 June 2019)
9. U.S. Global Change Research Program (2018), *Fourth National Climate Assessment, vol. 2, Impacts, Risks, and Adaptation in the United States*, Washington, D.C., https://nca2018.globalchange.gov. (Accessed 19 June 2019)
10. National Oceanic and Atmospheric Administration (NOAA) (2019), U.S. billion-dollar weather and climate disasters, Natl. Cent. for Environ. Inf., Asheville, N.C., https://www.ncdc.noaa.gov/billions/. (Accessed 23 July 2019)
11. Wing, O. E. J., et al. (2018), Estimates of present and future flood risk in the conterminous United States, *Environ. Res. Lett.*, 13, 034023, https://doi.org/10.1088/1748-9326/aaac65.
12. U.S. Geological Survey (USGS). Floods and recurrence intervals, *Water Science School*, https://www.usgs.gov/special-topic/water-science-school/science/floods-and-recurrence-intervals?qt-science_center_objects=0#qt-science_center_objects. (Accessed 23 July 2019)
13. Begley, D. (2017), Harvey will make history books for nation's wettest storm, *Houston Chronicle*, 16 Sept., https://www.houstonchronicle.com/news/article/Harvey-will-make-the-history-books-for-nation-s-12201641.php. (Accessed 26 April 2019)
14. Theodore, N. (2017), After the storm: Houston's day labor markets in the aftermath of Hurricane Harvey, 20 pp., Great Cities Inst., Univ. of Ill. at Chicago, https://greatcities.uic.edu/wp-content/uploads/2017/11/After-the-Storm_Theodore_2017.pdf.
15. Cordero-Guzman, H., E. Pantaleon, and M. Chavez (2013), Day labor, worker centers & disaster relief work in the aftermath of Hurricane Sandy, 32 pp., Sch. of Public Affairs, Baruch Coll., City Univ. of N. Y., New York, https://www.gc.cuny.edu/CUNY_GC/media/365-Images/Aftermath-of-Hurricane-Sandy-Report-FINAL-11-4-13.pdf.
16. Delp, L., L. Podolsky, and T. Aguilar (2009), Risk amid recovery: Occupational health and safety of Latino day laborers in the aftermath of the Gulf Coast hurricanes, *Organ. Environ.*, 22, 479–490, https://doi.org/10.1177/1086026609347193.
17. National Institute of Environmental Health Sciences (NIEHS) (2018), Providing training and tools for Hurricane Harvey recovery, Research Triangle Park, N.C., https://www.niehs.nih.gov/research/supported/success/2018/rios/index.cfm. (Accessed 30 April 2019)
18. National Institute of Environmental Health Sciences (NIEHS) (2019), Environmental health outcomes: Research among Hurricane Harvey survivors, https://tools.niehs.nih.gov/portfolio/index.cfm/portfolio/grantDetail/grant_number/R21ES029616. (Accessed 12 August 2019)
19. Chiu, M. (2019), Researchers share Harvey health impact findings at symposium, Baylor Coll. of Medicine, Houston, Texas, https://www.bcm.edu/news/environmental-health/harvey-health-impacts-findings-symposium. (Accessed 12 August 2019)
20. Murphy, J. (2018), August/September 2017 Hurricane Harvey, Natl. Weather Serv., Natl. Oceanic and Atmos. Admin., Silver Spring, Md., https://www.weather.gov/media/publications/assessments/harvey6-18.pdf.
21. Zhang, F., et al. (2019), Improving Harvey forecasts with next-generation weather satellites: Advanced hurricane analysis and prediction with assimilation of GOES-R all-sky radiances, *Bull. Am. Meteorol. Soc.*, 100, 1,217–1,222, https://doi.org/10.1175/BAMS-D-18-0149.1.
22. Morrow, B. H., and J. K. Lazo (2015), Effective tropical cyclone forecast and warning communication: Recent social science contributions, *Trop. Cyclone Res. Rev., 4*, 38–48, https://doi.org/10.6057/2015TCRR01.05.
23. Geotechnical Extreme Events Reconnaissance (GEER) Association. About GEER, http://www.geerassociation.org/about-geer. (Accessed 13 May 2019)
24. O'Shaughnessy, B. (2017), Shelter and the storm, https://www.nd.edu/stories/harvey/. (Accessed 29 April 2019)
25. Structural Extreme Events Reconnaissance (StEER) Network (2018), Official StEER products, https://www.steer.network/products. (Accessed 12 July 2019)
26. Geotechnical Extreme Events Reconnaissance (GEER) Association. Reconnaissance reports, http://www.geerassociation.org/reconnaissance-reports. (Accessed 12 July 2019)
27. Stark, N., et al. (2018), GEER Hurricane Harvey reconnaissance—initial data collection, doi:10.17603/DS2XD4C.
28. Roueche, D. B., et al. (2018), Collection of perishable data on wind- and surge-induced residential building damage during Hurricane Harvey (TX), doi:10.17603/DS2DX22.
29. Kijewski-Correa, T., et al. (2018), Hurricane Harvey (Texas) supplement—Collaborative research: Geotechnical Extreme Events Reconnaissance (GEER) Association: Turning disaster into knowledge, doi:10.17603/DS2Q38J.
30. Frost, D., personal communication, 2019.
31. RAPID Facility (2019), NHERI RAPID Facility deploys, DesignSafe-CI, https://www.designsafe-ci.org/community/news/2019/february/nheri-rapid-facility-deploys/. (Accessed 13 May 2019)

32. National Oceanic and Atmospheric Administration (NOAA) (2018), Next Generation Global Prediction System (NGGPS), Natl. Weather Serv., Silver Spring, Md., https://www.weather.gov/sti/stimodeling_nggps. (Accessed 30 April 2019)

33. Cikanek, H., et al. (2019), 2018 NOAA Science Report, 128 pp., NOAA Res. Counc., Silver Spring, Md.

34. Marks, F. (2016), Using observations to improve HWRF forecast guidance, http://www.imetsociety.org/wp-content/pdf/docs/tropmet2016/Plenary_20.pdf.

35. Considine, T. J., et al. (2004), The value of hurricane forecasts to oil and gas producers in the Gulf of Mexico, *J. Appl. Meteorol. Climatol.*, 43, 12, https://doi.org/10.1175/1520-0450(2004)043<1270:TVOHFT>2.0.CO;2.

36. Rappaport, E. N., et al. (2009), Advances and challenges at the National Hurricane Center, *Weather Forecasting*, 24, 395–419, https://doi.org/10.1175/2008WAF2222128.1.

37. National Oceanic and Atmospheric Administration (NOAA) (2019), COASTAL Act, Natl. Weather Serv., Silver Spring, Md., https://www.weather.gov/sti/coastalact. (Accessed 13 May 2019)

38. Risser, M. D., and M. R. Wehner (2017), Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation during Hurricane Harvey, *Geophys. Res. Lett.*, 44, 12,457–12,464, https://doi.org/10.1002/2017GL075888.

39. van Oldenborgh, G. J., et al. (2017), Attribution of extreme rainfall from Hurricane Harvey, August 2017, *Environ. Res. Lett.*, 12, 124009, https://doi.org/10.1088/1748-9326/aa9ef2.

40. Congressional Budget Office (2019), Expected costs of damage from hurricane winds and storm-related flooding, 48 pp., Washington, D.C.

41. Siebenack, T., and C. Wang (2019), Gross domestic product by state, fourth quarter and annual 2018, Bur. of Econ. Anal., U.S. Dep. of Commer., Washington, D.C., https://www.cbo.gov/publication/55019.

42. National Oceanic and Atmospheric Administration (NOAA) and NASA. Geostationary Operational Environmental Satellites–R Series, https://www.goes-r.gov/. (Accessed 12 July 2019)

43. National Oceanic and Atmospheric Administration (NOAA) (2017), JPSS-1: New satellite, even better data, *Natl. Cent. for Environ. Inf. (NCEI) News*, http://www.ncei.noaa.gov/news/jpss-1-new-satellite-even-better-data. (Accessed 19 June 2019)

44. U.S. Government Accountability Office (2019), Substantial efforts needed to achieve greater progress on high-risk areas, GAO-19-157SP, 293 pp., Washington, D.C.

45. Lazo, J. K., and D. Waldman (2011), Valuing improved hurricane forecasts, *Econ. Lett., 111*, 43–46, https://doi.org/10.1016/j.econlet.2010.12.012.

46. Upper Joachim Creek Floodplain Management Planning Partners (2019), Draft Upper Joachim Creek Floodplain Management Plan, U.S. Army Corps of Eng.

47. U.S. Geological Survey (USGS) (2019), USGS current conditions for USGS 07019500 Joachim Creek at De Soto, Mo., Natl. Water Inf. Syst.: Web Interface, https://waterdata.usgs.gov/mo/nwis/uv/?site_no=07019500&PARAmeter_cd=00065,63160,00060. (Accessed 19 June 2019)

48. U.S. Army Corps of Engineers. About the Silver Jackets Program, Silver Jackets, https://silverjackets.nfrmp.us/About-the-Silver-Jackets-Program.cfm (Accessed 18 May 2019) https://silverjackets.nfrmp.us/About-the-Silver-Jackets-Program.cfm. (Accessed 18 May 2019)

49. Hassan, A. (2019), Why is there flooding in Nebraska, South Dakota, Iowa and Wisconsin?, *New York Times*, https://www.nytimes.com/2019/03/18/us/nebraska-flooding-facts.html. (Accessed 19 June 2019)

50. Davis, T. J. (2019), Runoff into the Missouri River west of Iowa in March demolished a 67-year-old record, says Army Corps of Engineers, Des Moines Register, https://www.desmoinesregister.com/story/weather/2019/04/03/iowa-floods-sioux-city-record-runoffs-upper-missouri-river-basin-us-army-corps-engineers/3354017002/. (Accessed 15 May 2019)

51. Jacobson, R. B., G. Lindner, and C. Bitner (2015), The role of floodplain restoration in mitigating flood risk, lower Missouri River, USA, in *Geomorphic Approaches to Integrated Floodplain Management of Lowland Fluvial Systems in North America and Europe*, edited by P. F. Hudson and H. Middelkoop, pp. 203–243, Springer, New York, https://doi.org/10.1007/978-1-4939-2380-9_9.

52. Mallakpour, I., and G. Villarini (2015), The changing nature of flooding across the central United States, *Nat. Clim. Change*, 5, 250–254, https://doi.org/10.1038/nclimate2516.

53. Carsell, K. M., N. D. Pingel, and D. T. Ford (2004), Quantifying the benefit of a flood warning system, *Nat. Hazards Rev.*, 5, 131–140, https://doi.org/10.1061/(ASCE)1527-6988(2004)5:3(131).

54. Normand, A. E. (2019), U.S. Geological Survey (USGS) Streamgaging Network: Overview and issues for Congress, Congr. Res. Serv., Washington, D.C.

55. Gardener, J., M. Doyle, and L. Patterson (2017), Estimating the value of public water data, Duke Univ., Durham, N.C.

56. U.S. Geological Survey (USGS), What is 3DEP? 3D Elevation Program (3DEP), https://www.usgs.gov/core-science-systems/ngp/3dep/what-is-3dep. (Accessed 16 May 2019)

57. Carswell, W. J., and V. Lukas (2018), The 3D Elevation Program—Flood risk management, U.S. Geol. Surv., Reston, Va., https://www.usgs.gov/news/3d-elevation-program-flood-risk-management.

58. National Oceanic and Atmospheric Administration (NOAA), What is LIDAR?, Ocean Facts, https://oceanservice.noaa.gov/facts/lidar.html. (Accessed 16 May 2019)

59. Dewberry (2012), National enhanced elevation assessment, U.S. Geol. Surv., Reston, Va.

60. Center for Neighborhood Technology (2014), The prevalence and cost of urban flooding—A case study of Cook, County, IL, 32 pp., http://www.cnt.org/sites/default/files/publications/CNT_PrevalenceAndCostOfUrbanFlooding2014.pdf.

61. National Academies of Sciences, Engineering, and Medicine (2019), *Framing the Challenge of Urban Flooding in the United States*, Natl. Acad. Press, Washington, D.C., https://doi.org/10.17226/25381.

62. Center for Disaster Resilience, University of Maryland, and Center for Texas Beaches and Shore, Texas A&M University, Galveston Campus (2019), The growing threat of urban flooding: A national challenge, http://www.tamug.edu/newsroom/2018articles/UrbanFloodingReport.pdf.

63. Schulenberg, J., personal communication, 2019.

64. Rizzo, M., et al. (2014), Cicero Rail Yard Study (CIRYS) Final Report, 159 pp., U.S. Environ. Prot. Agency, Washington, D.C.

65. Lotus, J. (2017), Water Reclamation District, EPA will address Stickney odor complaints, *Cook County Chronicle*, https://chronicleillinois.com/news/cook-county-news/water-reclamation-district-epa-will-address-stickney-odor-complaints/. (Accessed 12 August 2019)

66. Hawthorne, M. (2018), Flint researchers find alarming levels of lead in Cicero, Berwyn tap water, suggesting thousands of older homes at risk, Chicago Tribune, https://www.chicagotribune.com/news/ct-met-cicero-berwyn-lead-water-testing-20180809-story.html. (Accessed 12 August 2019)

67. Allen, T., L. Cary-Kothera, and K. Fahey (2015), Study explores green infrastructure's economic benefits for two Great Lakes cities, Clear Waters, 2 pp., https://coast.noaa.gov/data/docs/digitalcoast/clear-waters.pdf.

68. Eastern Research Group Inc. (2014), Economic assessment of green infrastructure strategies for climate change adaptation: Pilot studies in the Great Lakes Region, NOAA Coastal Serv. Cent., Silver Spring, Md.

69. Naturally Resilient Communities. Mingo Creek, Tulsa, Oklahoma. Explore Solutions & Case Studies, http://nrcsolutions.org/tulsa-oklahoma/. (Accessed 18 May 2019)

70. National Oceanic and Atmospheric Administration (NOAA), FLASH—Flooded Locations and Simulated Hydrographs Project, Natl. Severe Storms Lab., Norman, Okla., https://blog.nssl.noaa.gov/flash/. (Accessed 16 May 2019)

71. Young Landis, B. (2019), Streaming flash flood forecasts into the hands of emergency managers, Thriving Earth Exchange, https://thrivingearthexchange.org/tex-stories/streaming-flash-flood-forecasts-hands-emergency-managers/.

72. National Oceanic and Atmospheric Administration (NOAA), NSSL Research: Flooding, Natl. Severe Storms Lab., Norman, Okla., https://www.nssl.noaa.gov/research/flood/. (Accessed 24 July 2019)

73. Gourley, J. J. (2018), FLASH system transitioned to the National Weather Service, revolutionizes tools used for flash flood forecasting, FLASH—Flooded Locations and Simulated Hydrographs Project.

74. Eberts, S. M., et al. (2019), Monitoring the pulse of our nation's rivers and streams: The U.S. Geological Survey Streamgaging Network.

75. U.S. Environmental Protection Agency (2013), Rivers & Streams, EPA's web archive, https://archive.epa.gov/water/archive/web/html/index-17.html. (Accessed 23 May 2019)

76. Dubrow, A. (2016), Flood forecasting gets major upgrade, *Natl. Sci. Found. Res. News*, https://www.nsf.gov/discoveries/disc_summ.jsp?cntn_id=189556. (Accessed 18 May 2019)

77. Villarini, G., et al. (2018), Floods and nonstationarity: A review, *CWTS 2018-01*, 88 pp., U.S. Army Corps of Eng., Washington, D.C., https://sites.tufts.edu/richardvogel/files/2019/04/2018_floodsAndNonstationarity.pdf.

78. Milly, P. C. D., et al. (2008), Stationarity is dead: Whither water management?, *Science, 319*, 573–574, https://doi.org/10.1126/science.1151915.

79. Bryant, D. A. (2018), Fort Hood working to ensure safety after floodwater deaths, *Killeen Daily Herald*, http://kdhnews.com/military/fort-hood-working-to-ensure-safety-after-floodwater-deaths/article_7514c7b0-6068-11e8-9a30-7f3eaaf7f627.html. (Accessed 10 May 2019)

80. U.S. Department of Defense (2019), Report on effects of a changing climate to the Department of Defense, 22 pp., https://media.defense.gov/2019/Jan/29/2002084200/-1/-1/1/CLIMATE-CHANGE-REPORT-2019.PDF.

81. Hankerson, M. (2017), Virginia Beach residents who were flooded during Hurricane Matthew will host flood insurance workshop, *Virginian-Pilot*, https://pilotonline.com/news/local/environment/article_05b99000-2d9d-5783-a03a-0f3282b5d3ae.html. (Accessed 22 May 2019)

82. Hampton Roads Planning District Commission. Hurricane Michael overview, Chesapeake, Va.

83. Council, D., et al. (2018), The new normal of flooding in Portsmouth, Virginia: Perspectives, experiences, and adaptive responses of residents and business owners in low-to-moderate-income communities, 25 pp., https://raft.ien.virginia.edu/system/files/The%20New%20Normal%20of%20Flooding%20in%20Portsmouth.pdf.

84. National Oceanic and Atmospheric Administration (NOAA) (2018), How does NOAA monitor water levels around the nation?, *Ocean Facts*, https://oceanservice.noaa.gov/facts/nwlon.html. (Accessed 24 May 2019)

85. U.S. Geological Survey (2016), New tide gauges installed along Virginia Beach's coastline, https://www.usgs.gov/news/new-tide-gauges-installed-along-virginia-beach-s-coastline. (Accessed 24 May 2019)

86. Mayfield, D. (2016), The push is on to improve tide forecasts across Hampton Roads, *Virginian-Pilot*, https://pilotonline.com/news/local/environment/article_8be430b8-e686-5e0e-af8b-10428f34406a.html. (Accessed 24 May 2019)

87. Commonwealth Center for Recurrent Flooding Resiliency (2017), Water level predictions—Tidewatch, *Projects*, https://www.floodingresiliency.org/projects/water-level-predictions/tidewatch/. (Accessed 24 May 2019)

88. Virginia Institute of Marine Science (2018), A deeper dive—Forecasting tidal flooding, *YouTube*, https://www.youtube.com/watch?time_continue=111&v=gYIDVbUlH0k. (Accessed 24 May 2019)

89. Malmquist, D. (2012), Tidewatch forecasts go public, Va. Inst. of Mar. Sci., Gloucester Point, https://www.vims.edu/newsandevents/topstories/archives/2012/tidewatch_forecasts.php. (Accessed 24 May 2019)

90. National Oceanic and Atmospheric Administration (NOAA). Sea, Lake, and Overland Surges from Hurricanes (SLOSH), Natl. Hurricane Cent., Miami, Fla., and Cent. Pac. Hurricane Cent., Honolulu, Hawaii, https://www.nhc.noaa.gov/surge/slosh.php. (Accessed 24 May 2019)

91. Deltares and U.S. Geological Survey. CoSMoS Southern California, Southern California Coastal Hazards, http://cosmos.deltares.nl/SoCalCoastalHazards/index.html#results?scenario=forecasts. (Accessed 15 July 2019)

92. Herdman, L., et al. (2016), Integrating fluvial and oceanic drivers in operational flooding forecasts for San Francisco Bay, *Geophys. Res. Abstr.*, 18, EPSC2016-18125.

93. U.S. Geological Survey. PS-CoSMoS: Puget Sound Coastal Storm Modeling System, Pac. Coastal and Mar. Sci. Cent., Santa Cruz, Calif., https://www.usgs.gov/centers/pcmsc/science/ps-cosmos-puget-sound-coastal-storm-modeling-system?qt-science_center_objects=0#qt-science_center_objects. (Accessed 24 May 2019)

94. Barnard, P. L., et al. (2019), Dynamic flood modeling essential to assess the coastal impacts of climate change, *Sci. Rep.*, 9, 4309, https://doi.org/10.1038/s41598-019-40742-z.

95. U.S. Geological Survey (2017), Water is life for the Swinomish Indian tribal community, https://www.usgs.gov/news/water-life-swinomish-indian-tribal-community. (Accessed 24 May 2019)

96. Dewberry (2018), Analysis of historical and future heavy rainfall, 97 pp., Dep. of Public Works, https://www.hrpdcva.gov/uploads/docs/5A_Attachment_AnalysisofHistoricalandFutureHeavyPrecipitation_Finalrev_20180326.pdf.

97. Coutu, P. (2019), Judge rules Virginia Beach council can factor in sea level rise when deciding on new developments, *Virginian-Pilot*, https://pilotonline.com/news/government/local/article_f05e1e32-66e1-11e9-b07a-ff3214644d86.html. (Accessed 28 May 2019)

98. U.S. Census Bureau (2017), American Community Survey demographic and housing estimates, Washington, D.C.

99. U.S. Department of Defense. Secretary of Defense speech: Hampton Roads Chamber of Commerce, https://archive.defense.gov/Speeches/Speech.aspx?SpeechID=1729. (Accessed 22 May 2019)

100. Connolly, M. (2015), Hampton Roads, Virginia, and the military's battle against sea level rise, 9 pp., Cent. for Clim. and Security, Washington, D.C., https://climateandsecurity.files.wordpress.com/2015/10/hampton-roads-virginia-and-military-battle-against-sea-level-rise.pdf.

101. Greicius, T. (2017), NASA finds Virginia metro area is sinking unevenly, http://www.nasa.gov/feature/jpl/nasa-finds-va-metro-area-is-sinking-unevenly. (Accessed 22 May 2019)

102. Conger, J. (2018), Hurricane Florence's impacts on military installations and missions in the Southeast, Cent. for Clim. and Security, Washington, D.C., https://climateandsecurity.org/2018/09/19/hurricane-florences-impacts-on-military-installations-and-missions-in-the-southeast/.

103. U.S. Senate Committee on Homeland Security and Governmental Affairs (2019), The cost of inaction: Failure to address financial costs of climate change will hurt taxpayers, Gov. Account. Off., Washington, D.C., https://www.hsgac.senate.gov/imo/media/doc/Climate%20Change%20Adaptation%20Report%20v12%20Final_COVER_FINAL.pdf.

104. National Oceanic and Atmospheric Administration (NOAA) (2019), Is sea level rising?, https://oceanservice.noaa.gov/facts/sealevel.html. (Accessed 19 June 2019)

105. Valle-Levinson, A., A. Dutton, and J. B. Martin (2017), Spatial and temporal variability of sea level rise hot spots over the eastern United States, *Geophys. Res. Lett.*, 44, 7,876–7,882, https://doi.org/10.1002/2017GL073926.

106. Moftakhari, H. R., et al. (2017), Cumulative hazard: The case of nuisance flooding, *Earth's Future*, 5, 214–223, https://doi.org/10.1002/2016EF000494.

107. Frank, T. (2019), Sea-level rise: Annapolis parking lot foreshadows future flood losses, *ClimateWire*, https://www.eenews.net/stories/1060128369. (Accessed 23 May 2019)

108. Hino, M., et al. (2019), High-tide flooding disrupts local economic activity, *Sci. Adv.. 5, eaau2736*, https://doi.org/10.1126/sciadv.aau2736.

109. National Oceanic and Atmospheric Administration (NOAA), About Digital Coast, Off. for Coastal Manage., Charleston, S.C., https://coast.noaa.gov/digitalcoast/about/. (Accessed 22 May 2019)

110. National Oceanic and Atmospheric Administration (NOAA) (2015), Projected benefits and costs of the Digital Coast, 56 pp., Off. for Coastal Manage., Charleston, S.C., https://coast.noaa.gov/data/docs/digitalcoast/benefits-costs.pdf.

111. Gittman, R. K., et al. (2014), Marshes with and without sills protect estuarine shorelines from erosion better than bulkheads during a Category 1 hurricane, *Ocean Coastal Manage.*, 102, 94–102, https://doi.org/10.1016/j.ocecoaman.2014.09.016.

112. Storlazzi, C. D., et al. (2019), Rigorously valuing the role of U.S. coral reefs in coastal hazard risk reduction, *USGS Open File Rep. 2019-1027*, vi + 42 pp., https://doi.org/10.3133/ofr20191027.

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