Testimony of

Hanadi Rifai

Director, Hurricane Resilience Research Institute (HuRRI)

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Chairwoman Fletcher, Ranking Member Roger Marshall and Members of the Subcommittee, I appreciate the opportunity to testify before you here today. My name is Hanadi Rifai; I am John and Rebecca Moores Professor of Environmental Engineering and Director of the Hurricane Resilience Research Institute (HuRRI) at the University of Houston.

I have organized my testimony into three sections highlighting the past, the present and the future of my hurricane and coastal research. I use this framework to summarize the lessons learned and identify the improvements needed to current research efforts and the knowledge gaps that remain. I conclude my testimony with a call-to-action and make the case for increased funding for research as a low risk but incredibly high rewards investment strategy towards coastal resilience and empowerment of coastal communities like Houston to be better prepared for high winds, storm surge, and heavy rain.

The Past

My research journey with hurricanes and severe storms dates back to Hurricane Katrina in 2005, at the time, Houston felt New Orleans's pain profoundly. A group of us (faculty) from Houston and Louisiana met to discuss what could be done and that was the seed that germinated the Severe Storm, Prediction, Education, and Evacuation from Disaster (SSPEED) Center. It was difficult then to secure research funding for the Center and it remains difficult now to do the same. Centers such as SSPEED and HuRRI are very critical for our nation's safety, security and resiliency. In SSPEED and HuRRI, our work has been interdisciplinary, fundamental, transformational, and responsive to societal needs before, during and after hurricanes and severe storms. While SSPEED has focused mainly on the Houston-Galveston region, HuRRI is aimed at our entire 3rd coast, the Gulf of Mexico and its coastal communities and their challenges.

My work with SSPEED focused on Houston's industrial infrastructure and its vulnerability to natural hazards. This focus stemmed from my significant involvement in the U. S. Environmental Protection Agency's (EPA) Galveston Bay National Estuary Program (GBNEP) that culminated in a novel and unique non-point source study for the Galveston Bay region[1] and in the development of the Galveston Bay Plan[2]. I currently serve on the Galveston Bay Council, a coordinating body of the Galveston Bay Estuary Program (GBEP) created and appointed in 1995 by the Texas Natural Resource Conservation Commission (TNRCC now known as the Texas Commission on Environmental Quality or TCEQ). The Council is charged with providing a forum for stakeholder involvement and ensuring stakeholder commitment towards implementation of the Galveston Bay Plan. I represent Major Universities on the Council.

Houston's industries are concentrated along the 50-mile Houston Ship Channel (HSC), stretching from the Gulf of Mexico to Houston and Harris County, Texas. The Channel is home to more than 200 chemical and petrochemical facilities (Figure 1). Along with the Port of Houston that moves almost 300 million tons of cargo annually and is one of the largest ports in the world, the HSC is credited with fostering the growth and prosperity of the entire State of Texas. With this economic opportunity and prosperity, however, comes vulnerability. The industries along the channel produce, store, and transport chemicals and petrochemicals and in times of natural hazards, their processing units and storage and transportation facilities, including the Port of Houston, are vulnerable to storm surge, wind, rainfall and high channel flows. There are upwards of 4,100 storage tanks in the HSC region of various types and shapes containing a variety of chemicals and petrochemicals at any given time (Figures 2 and 3). These tanks can experience failure due to uplift pressures, for example, that would transport an impacted tank with the flowing water thereby increasing the potential for breaching it and spilling its contents.

Our research in SSPEED developed the first of its kind predictive model that quantified economic losses in the HSC that would be incurred due to varying storm surge heights at the individual facility level and for the entire Channel region. With this Facility Economic Damage and Environmental Release Planning or FEDERAP model, we predicted catastrophic losses exceeding 70 billion dollars for 25 ft surge[3] in the HSC and Port of Houston. It is important to note that FEDERAP integrates a storm surge predictive model (ADCIRC+SWAN)[4] with an in-stream water and sediment quality model (EFDC)[5] to generate scenarios of inundation and storm surge using Hurricane Ike as a model hurricane with varying strengths and landfall locations. The generated scenarios are overlain on ground-based topography and satellite imagery and merged with a detailed Hurricane Vulnerability GeoDataBase (HVGDB) that includes economic productivity data and environmental vulnerabilities in addition to infrastructure at risk for each scenario for each facility (see for example Figure 4). More recently, we developed probabilities of failure for each storage tank at each facility for Hurricane Harvey and demonstrated the utility of this modeling by comparing the projected probabilities to the actual failures that occurred during Harvey (Figure 5).

Such detailed information and integrated models did not exist at the time when we first developed them in my research team but they are instrumental tools and resources for enhancing resiliency in our region and other industrialized regions along the Gulf Coast that are so critical for our nation's economy. Such models and tools need to be further developed and enhanced and broadened to include other infrastructure and services and to model a future with potentially more frequent, stronger, slower storm systems, and rising sea levels.

Other related and critical research that we undertook in the SSPEED Center involved a close look at the environmental impacts associated with surge protection and building gates and barriers across parts of the Galveston Bay System. The Bay is an incredibly productive and critical resource for our region and one of the few estuaries around the country that still has its oysters and a vibrant fisheries and coastal tourism economy. The Bay is heavily dependent on freshwater inflows and a healthy interaction with the Gulf of Mexico that creates a delicate balance for its productive ecosystems. Construction of barriers, dikes, and the like to mitigate storm surge needs to be carefully evaluated and studied to ensure that this delicate balance is not disrupted or harmed. We have developed relatively short-term and long-term models of bay water quality looking at temperatures and salinities when such mitigation measures are implemented that can be used to inform surge protection systems design and implementation. Much more effort is needed, however, to further develop these models into robust predictive platforms that can further elucidate and incorporate the changes in sediment regimes, flood flows in the San Jacinto and Trinity Rivers and their relative timing, drought cycles, climate change, and sea level rise.

The present

As we embarked on our recovery journey in Houston after Harvey, the affinity we felt with Louisiana in 2005 expanded to include the entire Gulf Coast because of the severity of the 2017 hurricane season and its disastrous outcomes that were felt from Texas to Florida. This fueled our resolve to create another broader research entity to serve as a gateway to resiliency of the entire Gulf Coast and a framework to transfer and exchange ideas and lessons learned among its diverse coastal communities.

HuRRI is a collaborative Institute encompassing six founding member universities that include: the University of Houston, Texas Tech University, The University of Texas Tyler, Louisiana State University, the University of Miami, and the University of Florida. In forming HuRRI in 2017 after Hurricane Harvey, we aimed to catalyze innovation in six dimensions of resilience: Mitigation, Assessment, Prediction, Protection, Education and Recovery or MAPPER dimensions. The main goal of the Institute is to change the paradigm from *wait-and-pay* to *anticipate-and-accommodate* to save lives and reduce damage and costs associated with natural disasters. HuRRI goes beyond the physical impacts of wind, surge and rain to infrastructure and their mitigation and takes a close look at cascading consequences and compounding disasters, environmental hazards, and human health post disasters, among other areas of research. At present, and with seed grant funding from the founding members of the Institute, HuRRI faculty are undertaking 12 collaborative research projects that span hurricane and flood modeling, sensor development, resilient power systems, mental and physical health during hurricanes, and public policies associated with hurricanes and severe storms (see Table 1 for a complete list).

In my own research program and with a National Science Foundation (NSF) RAPID grant (RAPID grants support research that has a severe urgency) and seed-grant funding from the Cullen College of Engineering at UH, I was able to mobilize my research team immediately after Harvey and begin to assess the environmental damages and the chemical and biological hazards that may have been released during Harvey from environmental and industrial infrastructure. Water and wastewater facilities, septic tanks, landfills, storm water networks, hazardous waste and Superfund sites, referred to collectively as environmental infrastructure, are all potential hazards to community health in extreme events because of releases, spills and leaks, and failures in their systems. Inundation of wastewater systems, for instance, releases of untreated wastewater and sludge into communities or inundation with floodwaters; all introduce a new ecosystem for pathogenic fungal and bacterial growth, and foster vector-borne diseases especially in low-income neighborhoods. Examples include antibiotic resistant staph infections, flesh-eating bacteria, and diarrheal disease, as well as West Nile, dengue, chikungunya, and zika that are spread by mosquitoes. Contaminated water can spread the organisms causing typhoid and cholera; tetanus, gas gangrene, allergies, asthma and immunological reactions; all are concerns that have affected communities in recent disasters.

We sampled water and sediment quality multiple times over a 1-year period in an effort to assess the resiliency of our waterways, natural water systems, and Galveston Bay. The results[6] were an astounding call-to-action; it was evident that our waterways had become Rivers of Brown (see Figure 6) carrying with them a chemical and biological mix of pollutants onto land, homes, and into waterways and sensitive ecological systems. As time went by, waterways within watersheds that have little to no anthropogenic activities recovered relatively quickly within a day or two after the storm, whereas other natural water systems that are urbanized and with a relatively significant anthropogenic footprint within them had varying degrees of recovery that in some cases persisted beyond six months after Harvey. Buffalo Bayou, for example that had received discharged flood flows from the Addicks and Barker reservoirs in addition to the storm flows from its watersheds, was among the most impacted. In addition to depressed oxygen levels for an extended period of time and significant erosion of its banks, Buffalo Bayou waters became unnaturally acidic due to the water released from the reservoirs (Figures 7 and 8).The long-term impact of these stresses and shocks to Buffalo Bayou are largely unknown.

Similarly, the overall impact on Galveston Bay is yet to be fully quantified and understood. In addition to near zero salinities for an extended period of time, the system experienced extensive sediment deposition and sediment grain-size shifts (silt percentages in the sediment grain size distribution profile increased up to 4-fold at some locations) and extensive pollutant loads containing organics, metals and pathogenic organisms. We saw in our data after Harvey effects down at the microbial level in the system where the microorganisms in Bay sediment reflected the flood flows and the pollutant loads within them. For example, Cyanobacteria, a toxic organism commonly found in freshwater lakes were found at considerably higher levels near the mouth of the San Jacinto River (SJR) than other sampled locations. The source of Cyanobacteria, while not confirmed, could be from the freshwater that was released from Lake Houston into the San Jacinto River during Hurricane Harvey. The impact that the shift in microbial communities within the Galveston Bay system in response to Harvey will have in the long-term on the Bay has yet to be assessed but more research is needed to understand the role that microbial communities play as sentinels of bay and ecosystem health and community exposure to pollutants post disaster.

While the full impact of Hurricane Harvey remains unknown, what is clearly apparent, however, is that much research is needed on how to soften the impact from environmental and industrial infrastructure failures. This knowledge gap has never been greater or more glaring to us as we observed the uneven distribution of these impacts amongst Houston's communities. The NSF RAPID funding allowed us to develop relatively simple geospatial flood prediction models and mapped databases of environmental infrastructure facilities that included wastewater, landfills, superfund sites, and hazardous waste sites and their locations relative to communities and the 100-year and 500-year flood zones in addition to detailed information about spills and leaks from this infrastructure and industrial facilities during Harvey. Figure 9, for example, illustrates our geospatial model prediction compared to an actual aerial image taken for the same wastewater plant after Harvey. Such models are very valuable especially for decision makers since they rely on relatively simple data inputs and can be overlaid on mapped infrastructure and population data as we did in our research to understand the full impact of flooding, and the relationships and interactions between infrastructure and people, a dimension of resilience that is oft ignored but deserves further research and study.

Using the aforementioned geospatial model and associated databases, we determined that while flooding was universally inclusive, human health effects were not equivalently borne by our communities. Houston has a relatively high proportion of concentrated-disadvantage communities that are spread in a north-east-south moon-shaped ring around its central core. Concentrated-disadvantage is defined in our work using 5 measures of disadvantage (Figure 10): (i) % female head of household, (ii) % below poverty line, (iii) % on public assistance, (iv) % unemployed, and (v) % below 18 years of age. In evaluating the distribution of environmental facilities and industrial hazards and the spills, leaks, and releases during Hurricane Harvey, we found a disturbing pattern of their prevalence in areas with a higher percentage of concentrated-disadvantage populations (Figures 11 and 12). This pattern also manifested itself in vector borne diseases as we evaluated the positive responses to Arbovirus (group of viruses transmitted by mosquitoes, in this case the data in the figure are for West Nile) within our communities (Figure 13). In addition, and in an effort to define resiliency of environmental infrastructure, we found many causes for concern, numerous facilities were located within floodplains, others had a history of flooding and significant down-time after severe events, and yet other facilities that are intended to manage solid and hazardous waste had failures and became themselves sources of pollution during Harvey.

Of note is our work with the San Jacinto River waste pits site that was designated a Superfund site after our investigation into the presence and levels of polychlorinated dibenzo-dioxins (PCDDs), polychlorinated dibenzo-furans (PCDFs), and polychlorinated biphenyls (PCBs) in the Houston Ship Channel, the San Jacinto River and Galveston Bay that began in 2002 and continues to the present with numerous sampling campaigns throughout this time period. A remedial cap emplaced over the waste pits experienced failure during Harvey. My research team has collected sediment and tissue samples after Harvey to assess the potential impact from releases that may have occurred due to cap failure. The study is currently underway.

The Future

Harvey is not a typical storm for Houston by any stretch of the imagination and its departure from prior severe storms and hurricanes can be observed by comparing Harvey rainfall depths with those from the most recent extreme events in Houston as shown in Figure 14. What the climate experts are telling us, however, is that storms like Harvey are the *new normal* and that in the future, hurricanes and severe storms will be more frequent, more intense, linger around longer, and move slower. These factors, when taken together do not portend a bright future for our region. Houston, until Harvey, was still implementing Tropical Storm Allison Recovery Projects. We have had multiple severe storms and one hurricane in the 15 year period since Allison and before Harvey. *Confronting this recent rise in disaster losses locally is a defining challenge for Houston as we aim to be both resilient and smart. The good news is that there are scientific and engineering foundations that can reduce the human, economic, environmental, and infrastructure losses from extreme events, however, investments in research must be made to build our society's capacity to reduce and/or manage risks and create resilient and prosperous communities that are well prepared and socially just.*

My analogy and justification for increased research funding for hurricanes and coastal resilience stems from observing the benefits derived from directing funding towards research from penalties after the Deep Water Horizon disaster. Obviously, we cannot penalize Mother Nature for hurricanes and severe storms; on the contrary, we need to respect her power and accommodate it and this can only be accomplished with research and funding for research on how to best achieve hurricane and coastal resilience. There is much to be learned on how to harden the physical infrastructure and how to soften environmental impacts. Much research is needed to understand the ramifications of transitioning to the new NOAA Atlas 14 storm on flooding, infrastructure and communities. An even greater need is to understand future climate projections, sea level rise, and their impacts on our region. We need to evaluate and define the risk level that we as a community are willing to accept and what is the cost that we have to bear to achieve protection that is commensurate with our chosen risk level.

Research should guide our decision making into mitigation and remedies: do we elevate homes and where and how much? Should we expand buyouts and how does that affect community integrity and viability? Do we build tunnels beneath Houston to convey the water to the Gulf of Mexico or expand conveyance within our existing bayous and creeks and what impacts would that have on water quality and human health? Do we build more detention capacity or more reservoirs and where and how and what benefits would be derived? Better yet, we need to research nature-based solutions and what risk reduction they can afford us. We also need to keep an open mind and research and debate holistically the possibility of recharging our depleted aquifers with floodwaters. We need to research ways to reduce vulnerabilities in our infrastructure and systems whether they are water systems, storm sewers, sanitary, solid waste, power, health services, and public health systems and so on.

We also need to research and develop strategies for rapid response during and after extreme events to protect people and ecosystems especially human health. We need to research the best strategies to engage communities and empower them with a culture of preparedness and resilience. We need to address disparities that still exist in disaster outcomes in different communities. As academic institutions, our educational mission cannot be understated. Funding would be needed to integrate knowledge and training and research methodologies and findings into existing and new curricula across disciplines to create a well-trained hazard and disaster mitigation workforce.

Importantly, we need to leverage the power of data, data analytics, machine learning, artificial intelligence, and emerging and enabling technologies such as drones, swarms, Underwater Unmanned Vehicles (UUVs) and Unmanned Aerial Vehicles (UAVs), new water and wind resistant materials and construction technologies, barrier technologies, and sensors and flood warning systems that can go a long way towards addressing vexing challenges with hurricanes and severe storms that prevent human access due to dangerous conditions. We need to continue developing and expanding the suite of predictive models for our region across the board in flooding, storm surge, pollution, mitigation, economic impacts, and transmission of infectious disease, among others. We also need to leverage our human capital and collective mental capacities and rely on citizen science, social media, and the myriad of motivated volunteer corps to engage in being part of the solution. But funding is needed to undertake this research and more.

There are many steps that coastal communities like Houston have taken and should take to prepare for hurricane impacts such as high winds, heavy rains or storm surge. We have made significant advances in coordinated declarations of disaster, disaster response and evacuations, yet many of our evacuation routes remain subject to flooding. It is the right time to begin to *anticipate and accommodate* extreme events and focus on recovery and resiliency. We need to expand our flood warning and flood alert systems in every neighborhood, and provide adequate sheltering options and capacities. We have to research supply chains to ensure supplies of food, water, energy, and basic necessities. We need to research resilient approaches to address the mountains of solid waste and discarded building materials after floods that are a significant hazard to human and ecosystem health because of their components. We need to build redundancies in our hazard mitigation planning to alleviate potential catastrophes such as the Arkema Plant toxic release during Harvey. We need to integrate hazard mitigation planning into every aspect of our society and future development plans and policies. It goes without saying that we need to build surge protection systems and address infrastructure resiliency to high winds and flooding. However, while we continue to emphasize resiliency in our economy, critical infrastructure, our built and natural environment, we must expand our focus to include people especially concentrated-disadvantage communities, their health and well-being.

One of the most important steps we should take, and admittedly, I am somewhat biased in my passion towards research, science, engineering and technology, is to provide continuous and sustained support for research and research centers such as SSPEED and HuRRI; they have missions and visions that transcend day-to-day living and are forward-thinking and forward-looking engines of innovation and creativity. Research on hurricanes and coastal resilience plays a very significant role for our community locally and for other similarly challenged communities nationally and globally. Research centers such as SSPEED and HuRRI focus attention on important societal questions and needs, are nonpartisan, and can respond quickly to the continually changing landscape of our society and train the next generation of natural hazard mitigation workforce. They have access to incredible resources that can be brought to bear on hurricanes and coastal resiliency. In HuRRI, for instance, we have a great resource in the NSF funded National Center for Airborne Laser and Mapping (NCALM) that can mobilize at any time to provide on-demand research-grade accurate LIDAR data (Light Detection and Ranging, a remote sensing method that uses light in the form of a pulsed laser to generate three-dimensional information about the surface characteristics of the Earth), and data on impacts after a hurricane or severe storm as well as detailed data on landscape and topography change over time. We can integrate these data into our predictive models and continuously update model predictions and the uncertainties inherent in them and provide near-real time predictive capabilities. Research Centers such as SSPEED and HuRRI, in addition to their research-focused missions, provide a forum for engagement, debate, and discussion that is, otherwise, not readily available or accessible for communities, decision-makers, policy developers, stakeholders, and other entities.

In conclusion, I greatly appreciate the effort of this committee to support hurricane and coastal resilience research that keeps Houston and America safe, secure, and globally competitive and assure its constituencies a high quality of life, health and prosperity.

I will be glad to answer any questions you may have.

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Table 1. List of research projects underway in HuRRI

1. Identification and assessment of chemical hazards during hurricanes and flooding
2. Towards data-driven hurricane modeling using Unmanned Aerial Vehicles (UAV)-deployed subsurface sensors
3. Hurricane Harvey: experiences, recovery and future policies
4. Wireless carbon nanofiber aggregate sensor system for real-time water level monitoring and flood warning
5. HuRRI-Composites: Resilient coastal communities using advanced construction materials and systems
6. Hurricane evacuation harnessing connected and automated vehicles
7. Understanding hurricane response resilience across mental and physical health: consideration of individual-level and community-level factors
8. Complex dynamics modeling and mitigation of power transmission system under extreme hurricanes and storm surges
9. The aftermath of hurricanes: pathways to resilience and recovery among college students
10. An integrated framework for grid resiliency in disaster recovery through smart control of residential and community level distributed energy resources
11. Predictive tools for large precipitating storms in coastal Texas and Louisiana
12. A comprehensive analysis and assessment of portable fuel cell-solar hybrid power system to provide energy resilience

Supporting Figures

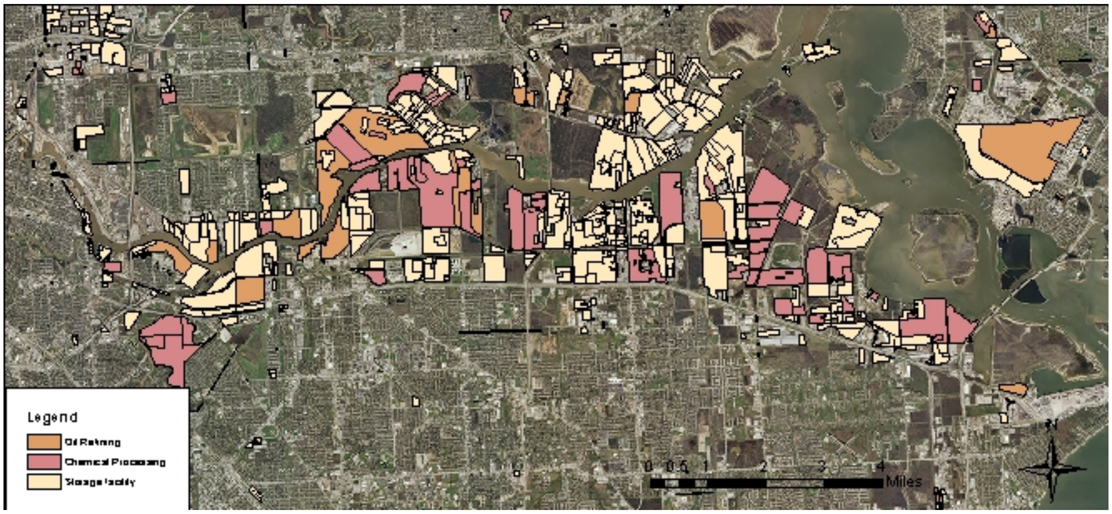

Figure 1. Illustration of Houston Ship Channel facilities categorized by type (oil refining in orange, chemical processing in magenta and storage in light yellow)

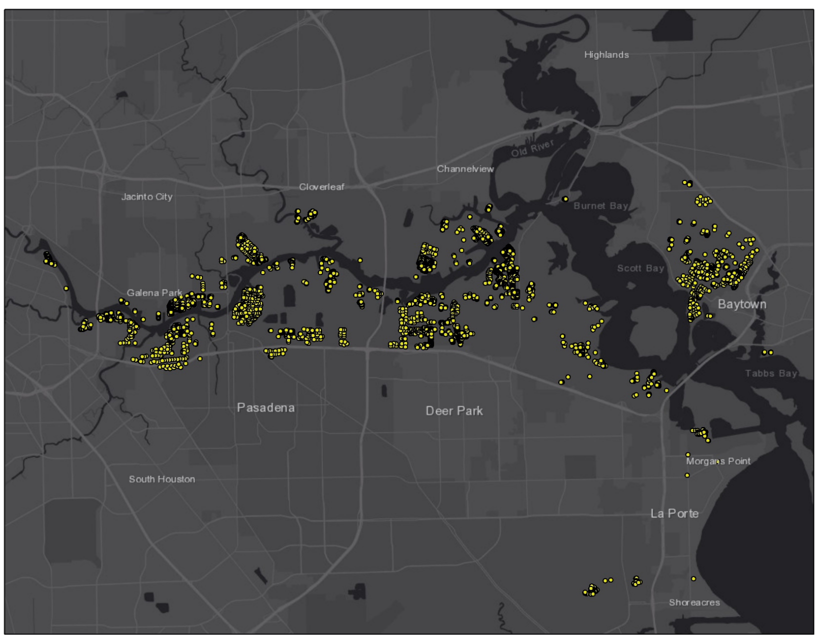

Figure 2. Schematic illustrating the more than 4,100 chemical and petrochemical storage tanks in the Houston Ship Channel region

(a) (http://www.inspection-for-industry.com/images/fix-roof.jpg)

(b) (http://i00.i.aliimg.com/img/pb/541/642/407/407642541_924.jpg)

(c) (http://www.cmpea.fr/wp-content/uploads/2013/12/Equateur.jpg)

Figure 3. Examples of tank types modeled in FEDERAP (a) Floating-top vertical tank (b) Fixed-top vertical tank (c) Horizontal tank (FEDERAP - Facility Economic Damage and Environmental Release Planning Model)

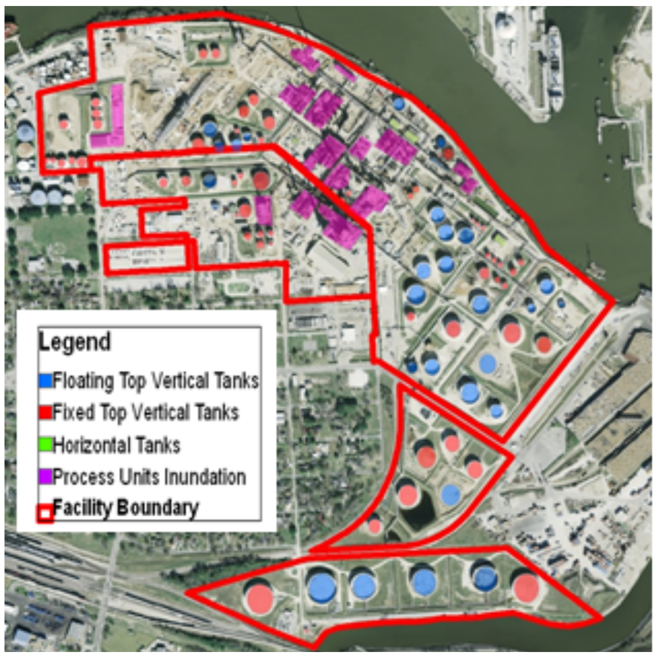

Figure 4. Aerial view of a facility in the Houston Ship Channel illustrating vulnerable infrastructure (the red lines show the boundaries of the different land parcels within the facility)

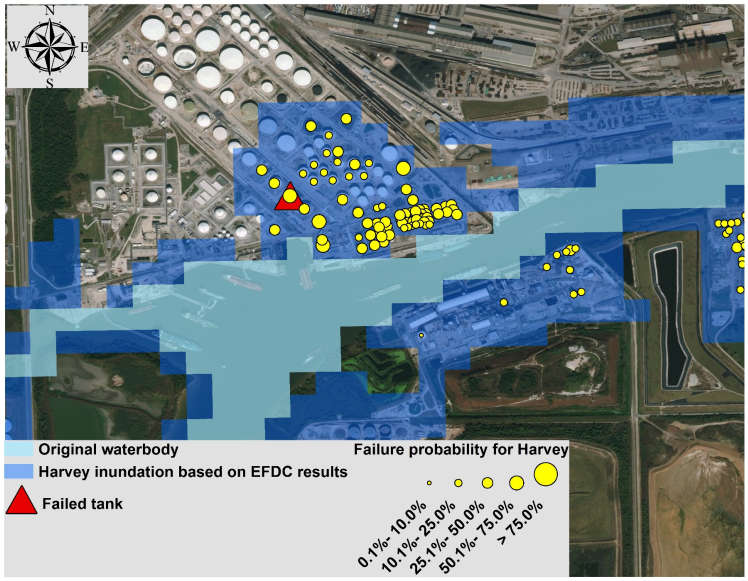

Figure 5. An aerial view that illustrates the modeled-probability of storage tank failure during Harvey at an industrial facility. The red triangle shows the tank that actually failed and had a significant release during Harvey

Figure 6. Satellite imagery showing Rivers of Brown before, during, and after Hurricane Harvey in the Houston area and Galveston Bay (the dates from left to right are August 22nd, September 1st and September 11 in 2017; Harvey made landfall in Texas on August 25, 2017)

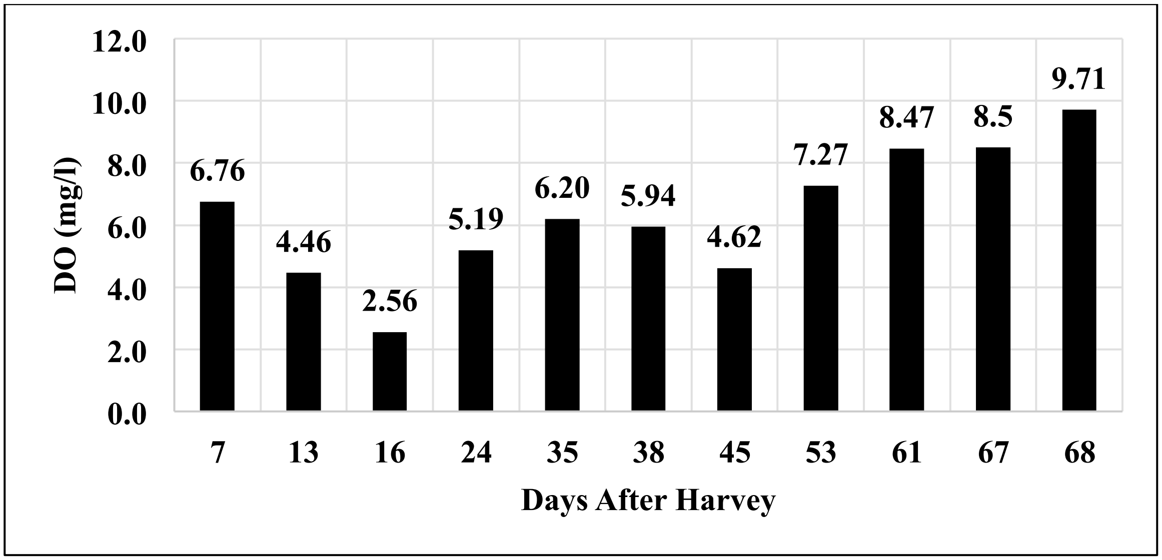

Figure 7. Dissolved oxygen levels in Buffalo Bayou downstream of the Barker Reservoir between 1 week and more than 2 months after Harvey. Depressed oxygen levels as shown on day 16 are outside the historical range for dissolved oxygen measurements in Buffalo Bayou and in general, are not considered supportive of biota and other living forms in the bayou

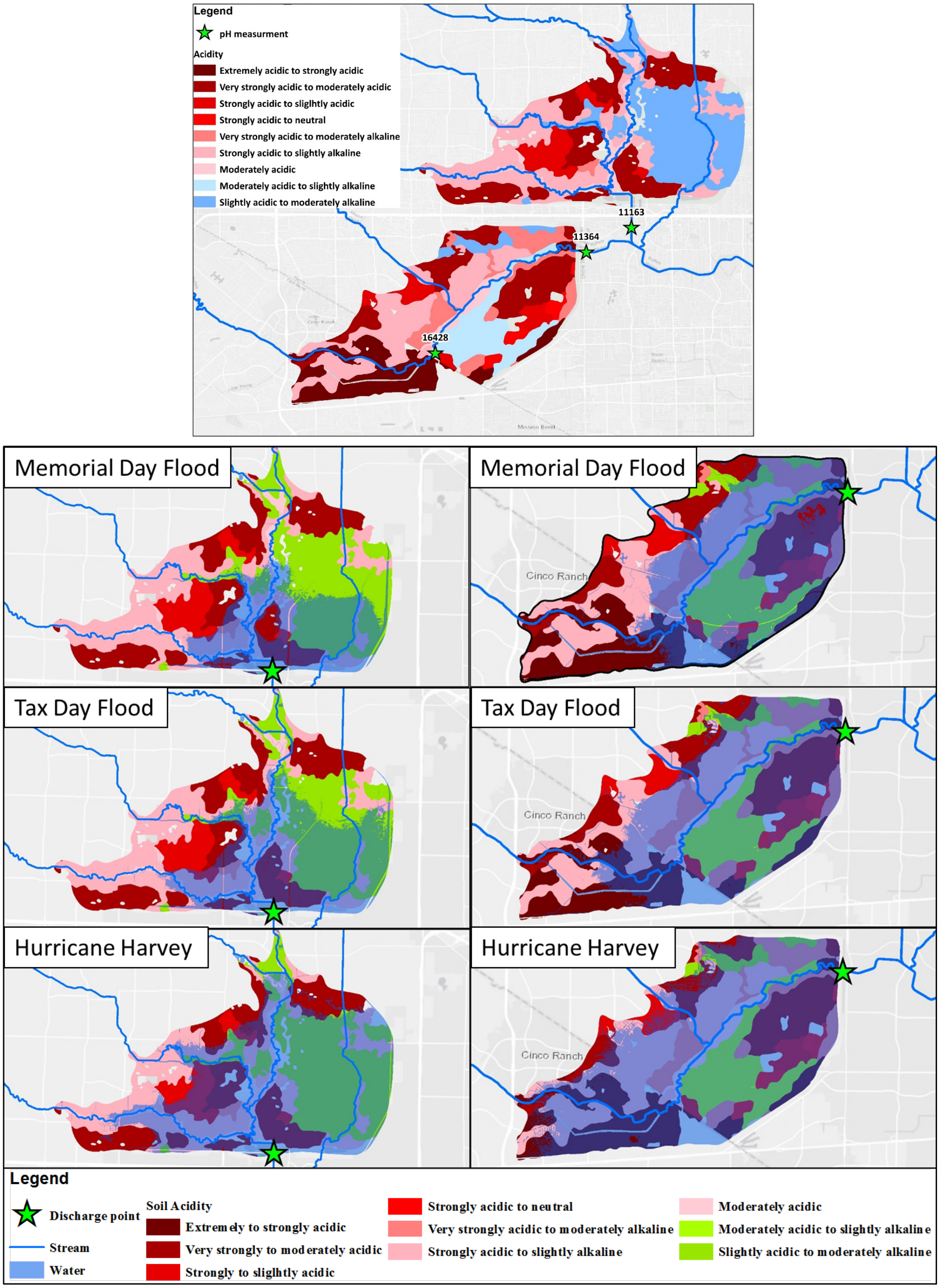

Figure 8. The soils of the Addicks and Barker Reservoirs are naturally acidic. With their historic flood levels experienced during Harvey, water within the reservoirs became unnaturally acidic (Barker reservoir is shown on the left and Addicks on the right)

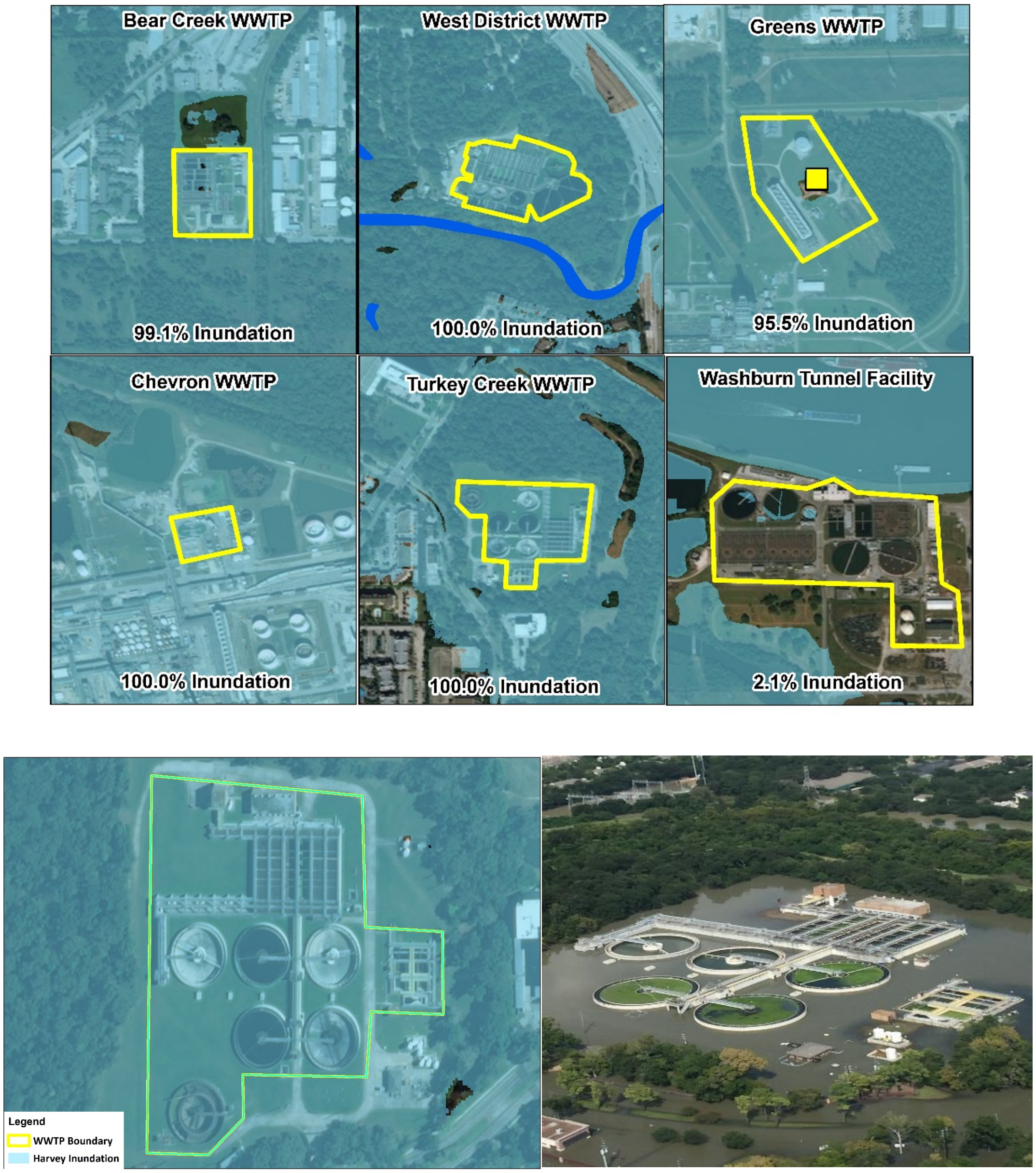

Figure 9. Illustrations of the modeled extent of flooding from geospatial modeling of wastewater treatment plants after Harvey (select facilities shown in the top figures). The bottom images compare the modeled flooding during Harvey on the left to an actual photograph taken during Harvey on the right for the Turkey Creek wastewater treatment plant

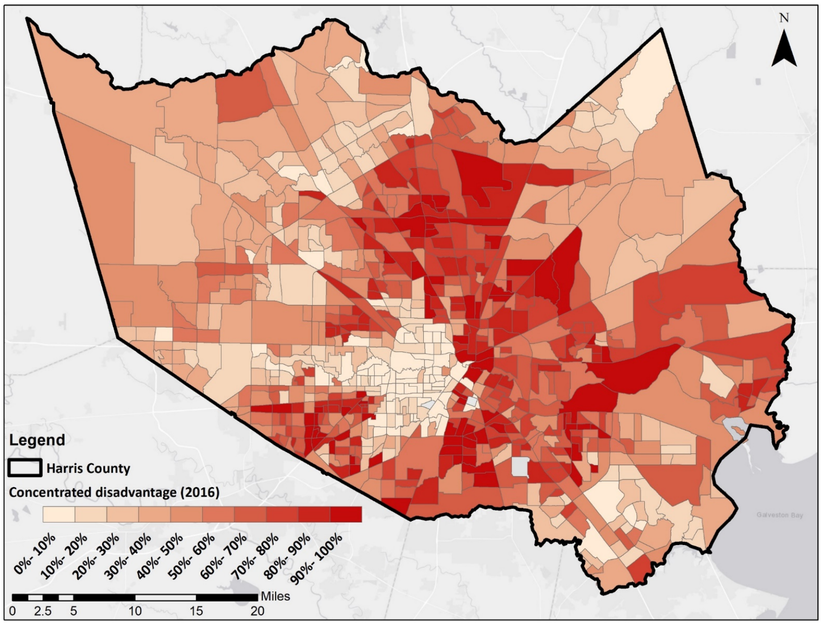

Figure 10. Concentrated-disadvantage communities in Houston form a north-east-south moon-shaped ring around the City's core (Concentrated-disadvantage is defined using 5 measures of disadvantage: (i) % female head of household, (ii) % below poverty line, (iii) % on public assistance, (iv) % unemployed, and (v) % below 18 years of age)

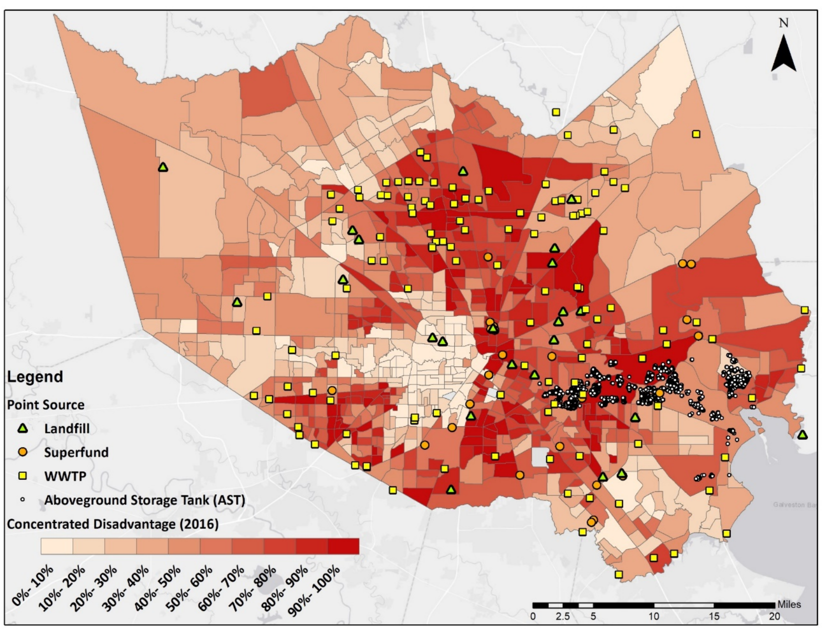

Figure 11. Concentrated-disadvantage communities in Houston bear the brunt of potential failures in environmental and industrial infrastructure associated with extreme events (WWTP – waste water treatment plant)

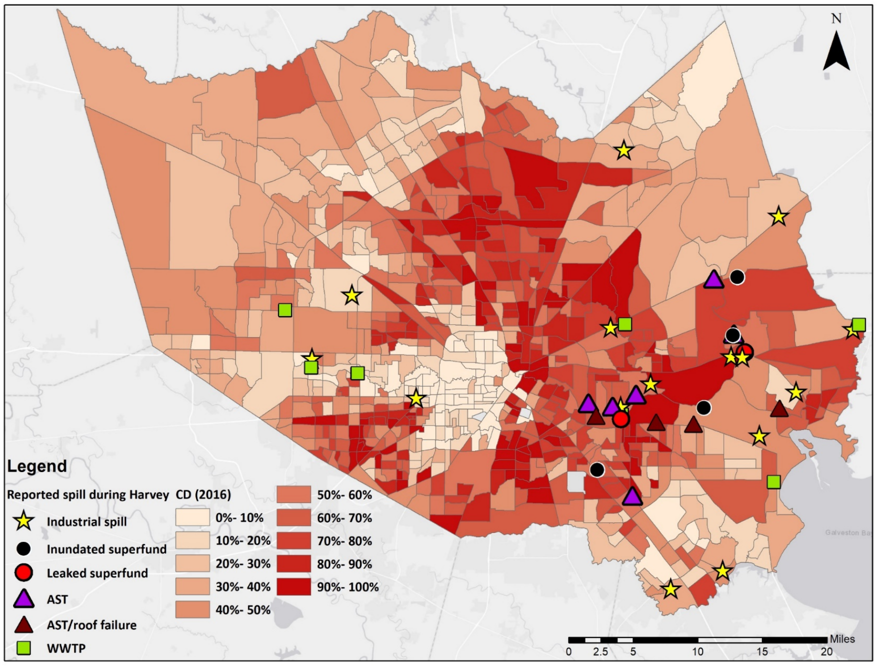

Figure 12. Actual spills and leaks reported during Harvey were almost all located within areas with significant concentrated-disadvantage populations (AST – above ground storage tank, WWTP – waste water treatment plant)

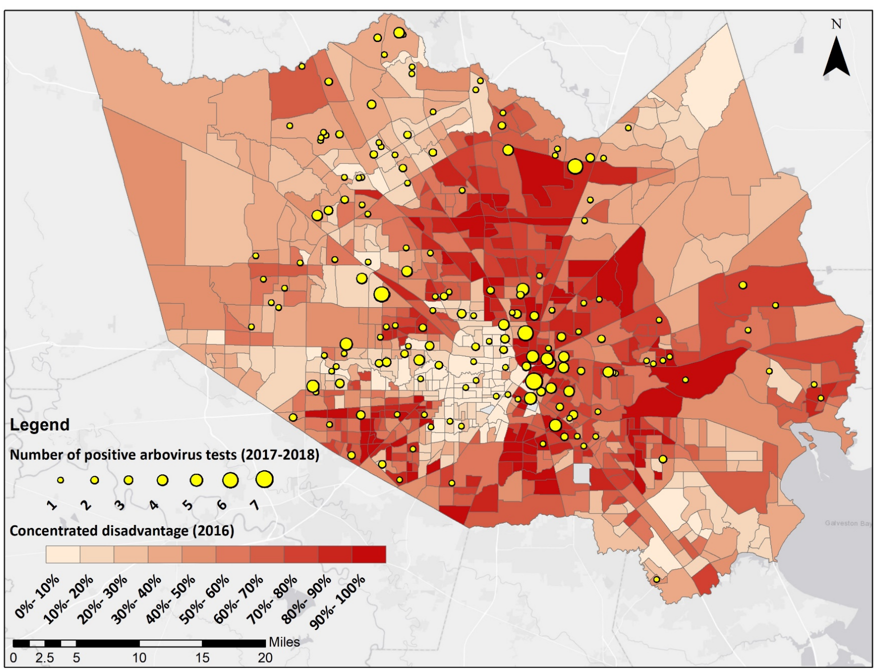

Figure 13. Mosquitoes with positive Arbovirus (group of viruses transmitted by mosquitoes, in this case the illustration shows West Nile) within areas with significant concentrated-disadvantage populations (Arbovirus data from Harris County Public Health)

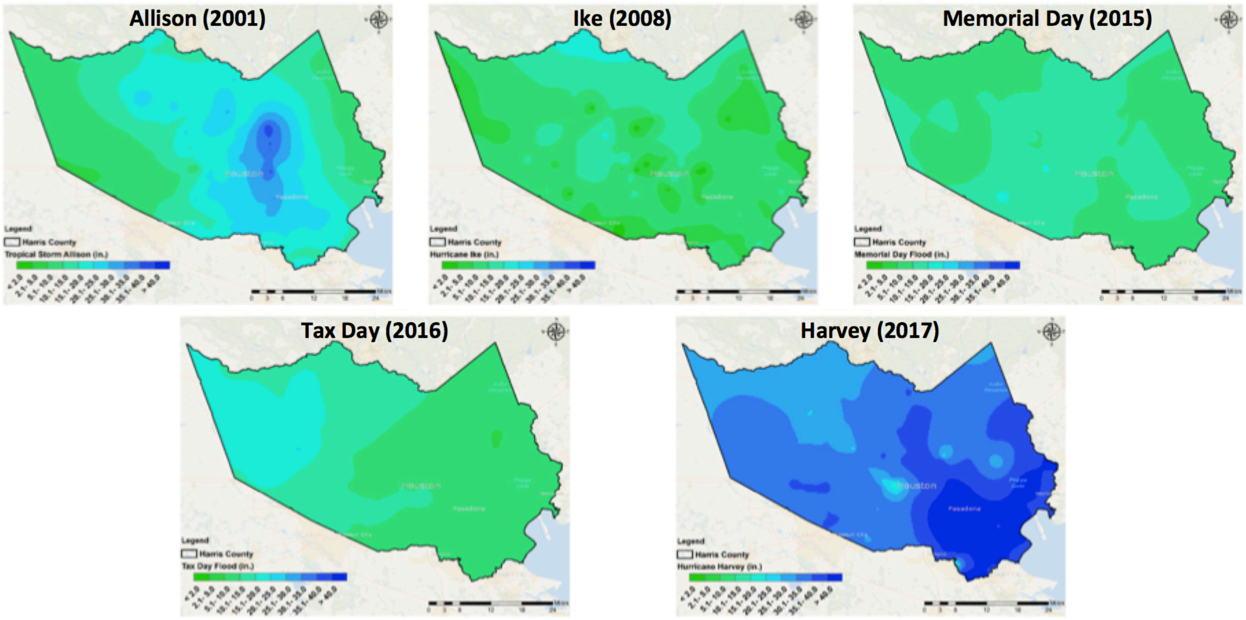

Figure 14. Rainfall depths for the most significant recent hurricanes and severe storms in Harris County in Texas (the scale ranges from greens that start at < 2 inches to dark blue colors that are > 40 inches of rainfall)