GEOTECHNICAL EXTREME EVENTS RECONNAISSANCE (GEER) ASSOCIATION

Turning Disaster in Knowledge

Geotechnical Aspects of the August 29, 2021, Hurricane Ida in LA, PA, NJ and NY

Report of the NSF Sponsored GEER and NEER Association Teams

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(photo source: nola.com)

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1 Introduction

On August 29, 2021, Hurricane Ida made landfall at the coast of Southern Louisiana as a Category 4 Hurricane, bringing approximately 13ft of storm surge at certain locations. The event resulted in substantial flooding of several areas in Southern Louisiana, as well as electrical power disruption that affected more than 1M local citizens for almost a week. A unique aspect of this Hurricane event was the fact that as it moved further inland towards the Northeast US, it merged with another powerful non-tropical front causing it to regain tropical force winds and release record breaking rainfall across Pennsylvania, New York, and New Jersey.

Due to the extent of the flooding and power and gas-shortages, the GEER/NEER team decided to form two sub-teams: the Field team and the Virtual team (Table 1.1). Furthermore, the Field team followed a two-phase approach: a small group (Athanasopoulos-Zekkos, Jafari, Lin) visited the affected areas on September 10-14, 2021, to assess the level of impact of the event across a larger area, and then based on this early reconnaissance, a larger group (GEER, NEER, USACE, ASCE) visited targeted areas on October 9-18, 2021, to collect more information and field data and conduct a more detailed reconnaissance. The Virtual team provided much needed support to the Field team, by collecting information that was becoming available online on the event (social media, other agencies, etc) as well as background information on the affected areas. Finally, certain individual GEER team members (Hubler, Ahmed) also visited sites in Pennsylvania, New Jersey, and New York, to document the impact of the event in these regions.

Table 1.1 GEER/NEER Team Members, Affiliations and Roles

Team Member Name	Affiliation	Team Role
Adda Athanasopoulos-Zekkos	University of California-Berkeley	co-Leader
Navid Jafari	Louisiana State University	co-Leader
Asif Ahmed	SUNY Polytechnic Institute	Virtual Team
Elizabeth Carter	Syracuse University	Virtual Team
Alireza Haji-Soltani	CNA Insurance	Virtual Team
Jonathan Hubler	Villanova University	Field Team (Northeast)
Hai (Thomas) Lin	Louisiana State University	Field Team
Brittany Russo	University of California, Berkeley	Virtual Team
Britt Raubenheimer	NEER Lead, Woods Hole Oceanographic Institution	Virtual Team
Inthuorn Sasanakul	University of South Carolina	Virtual Team
Rune Storesund	Storesund Consulting	Virtual Team
Jasmine Bekkaye	Louisiana State University	Field Team
Jonathan Bray	University of California-Berkeley	Virtual Team
Robert Gilbert	University of Texas-Austin	Field Team

Michael Grilliot	NSF NHERI RAPID Facility	Field Team
Joe Wartman	NSF NHERI RAPID Facility	Field Team

The GEER/NEER team used Slack channels (#hurricane-ida-2021 and #geer) for communications across their members, as well as to communicate updates and progress with the broader geotechnical community. Large datasets (eg 3-D point clouds, bathymetry, streetview, etc) collected as part of this reconnaissance effort have been made available on NSF NHERI Design-Safe website (Athanasopoulos-Zekkos et al. 2023).

The first field visit was three days long and the team covered the areas shown in Figure 1.1, and a total of over 650 miles. The second field visit lasted about 10 days and included targeted site visits to Grand Isle (NHERI RAPID data collection), Golden Meadows, and multiple locations along the Hurricane & Storm Damage Risk Reduction System (HSDRRS) in New Orleans.

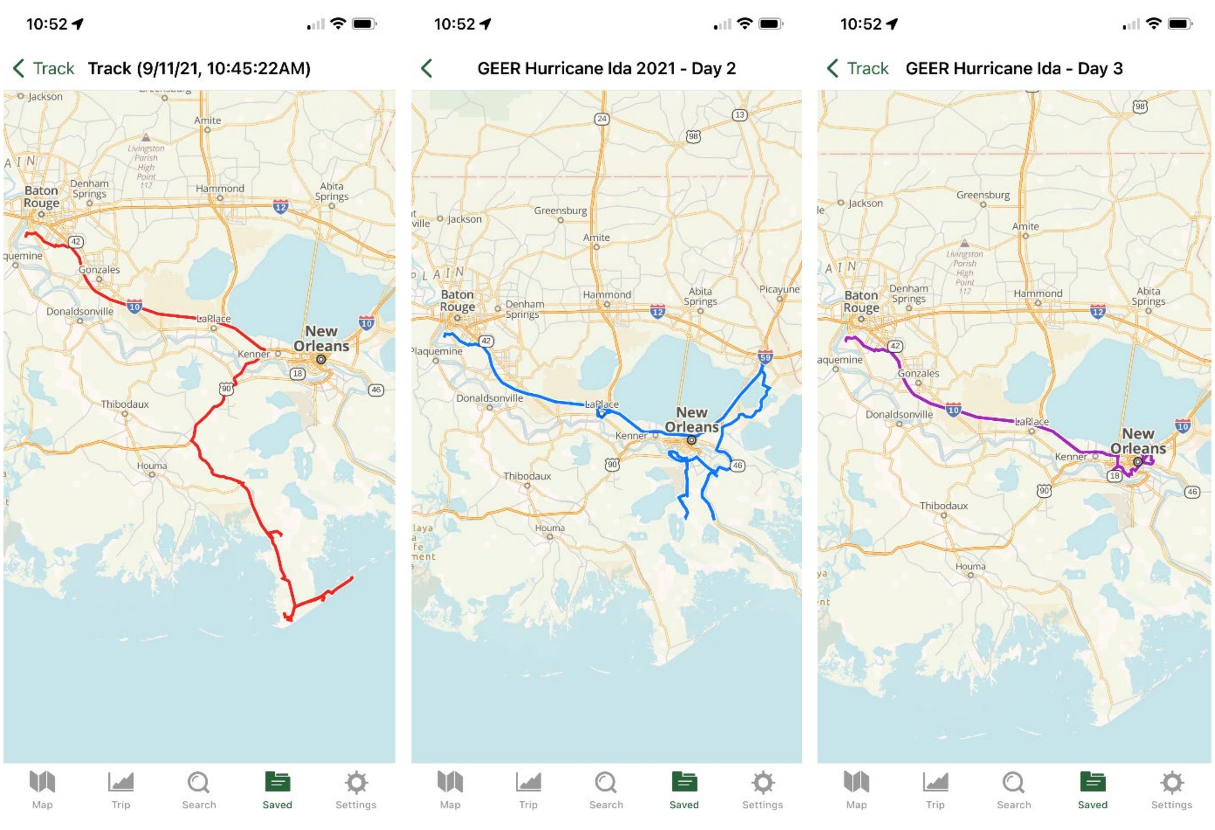

Figure 1.1. Routes covered during first field reconnaissance phase (Day 1 to Day 3, from left to right).

The following chapters provide more information on the meteorological aspects of the event (Ch.2), the impacts in Southern Louisiana (Ch.3), the performance of HSDRRS in NOLA (Ch.4), the electric-grid performance in New Orleans (Ch.5) and finally the impacts in the Northeast US (Ch.6). Team co-Leaders Athanasopoulos-Zekkos and Jafari also gave two presentations as part of the 6th Annual Live Streaming Web Conferences of the ASCE Geo-Institute (https://www.geoinstitute.org/special-projects/6th-annual-web-conference) describing the reconnaissance efforts following Hurricane Ida and discussing our observations and data collection.

2 Hurricane Ida Meteorological Description

2.1 Hurricane Ida Formation

Hurricane Ida formed as a tropical wave in the Caribbean Sea, and was first noted by the National Hurricane Center (NHC) on August 23, 2021 (Figure 2.1). At 11:00 AM EDT on August 26, 2021, the system was reclassified as a Tropical Depression Nine, prompting scheduling of an Air Force Reserve hurricane reconnaissance survey. Tropical Storm Warnings were issued by the governments of the Cayman Islands and Cuba.[1] At 5:20 PM EDT, the Air Force Reserve hurricane reconnaissance survey flyover confirmed that the depression had strengthened to Tropical Storm Ida[2]. At 11:00 PM EDT on August 26th, hurricane warnings were issued for the portion of the Gulf Coast bounded by Cameron, LA and the Mississippi/Alabama border, and storm surge warnings were issued for from Sabine Pass, TX to the Alabama/Florida border. The projected landfall of these forecasts was matched within 50 miles, and its intensity was accurately predicted, making Hurricane Ida the most well-forecasted hurricane in recent history.[3]

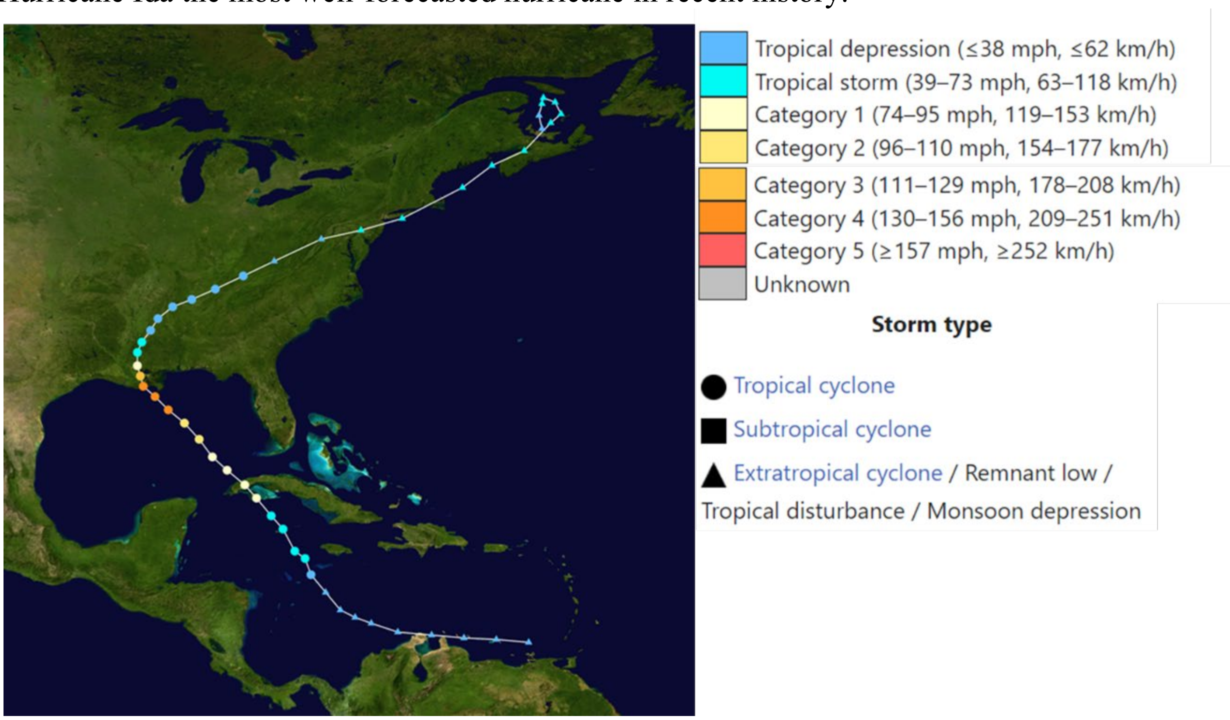

Figure 2.1. The location of Hurricane Ida at 6-hour intervals. The color represents the storm's maximum sustained wind speeds as classified in the Saffir–Simpson scale, and the shape of the data points represent the nature of the storm. Figure produced by Fluer DeOdile, released to the public domain, downloaded from: https://simple.m.wikipedia.org/wiki/File:Ida_2021_track.png.

[1] https://www.nhc.noaa.gov/archive/2021/al09/al092021.public.001.shtml?

[2] https://www.nhc.noaa.gov/archive/2021/al09/al092021.update.08262116.shtml?

[3] https://www.rmets.org/metmatters/impacts-hurricane-ida

On August 27th 5:00 AM EDT, the center of Tropical Storm passed through the Cayman Islands with maximum sustained winds nearing 45mph and a minimal observed pressure of 1003 mb, before veering east, missing Grand Cayman Island.[4] By 11:15 am EDT, Tropical Storm Ida was upgraded to a hurricane based on data from an Air Force Reserve hurricane hunter aircraft.[5] At 2:00 PM EDT, Hurricane Ida made landfall at Isle of Youth, Cuba, having strengthened to a minimum internal pressure of 987 mb with maximum sustained winds near 75 mph.[6] By 7:25 PM EDT, Hurricane Ida made landfall at Pinar Del Rio, Cuba with maximum sustained winds of 80 mph,[7] before entering the Gulf of Mexico.

Around 4:00 PM on August, 28th, Hurricane Ida started to show signs of rapid intensification as it followed the western periphery of a deep subtropical ridge (Figure 2.2a) into a region of the northwest Caribbean sea called the Loop Current, a warm, deep eddy off the Yucatan Peninsula, where low vertical wind sheer overlayed this an already anomalously warm stretch of northwestern Caribbean sea[8] (Figure 2.2b). By 2:00 AM on August 29th, Hurricane Ida had strengthened to a category 4 hurricane, just 160 km south of the Mississippi River.[9] At 7:00 AM on August 29th, Hurricane Ida made landfall at the coast of southern Louisiana with maximum sustained windspeeds of 150 mph and a minimum pressure of 930 hPa, measured from aircraft, just shy of a category 5 storm.[10] By the time the Hurricane Ida northern eyewall had reached the Louisiana coast at 11:55 AM CDT, NOAA C-MAN stations in Southwest Pass, LA had reported sustained winds of over 102 mph with gusts of 116 mph. In Pilot's Station East, sustained ground level windspeeds of 97 mph with gusts of 121 mph were reported. Coastal gages in Shell Point, LA and Bay Waveland, MI reported surge anomalies of 6.8 and 5.4 feet, respectively.[11]

[4] https://www.caymancompass.com/2021/08/28/hurricane-ida-to-hit-us-as-category-4-storm/
[5] https://www.nhc.noaa.gov/archive/2021/al09/al092021.update.08271711.shtml?
[6] https://www.nhc.noaa.gov/archive/2021/al09/al092021.public_a.005.shtml?
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[10] https://www.nhc.noaa.gov/archive/2021/al09/al092021.update.08291653.shtml?
[11] https://www.nhc.noaa.gov/archive/2021/al09/al092021.update.08291354.shtml?

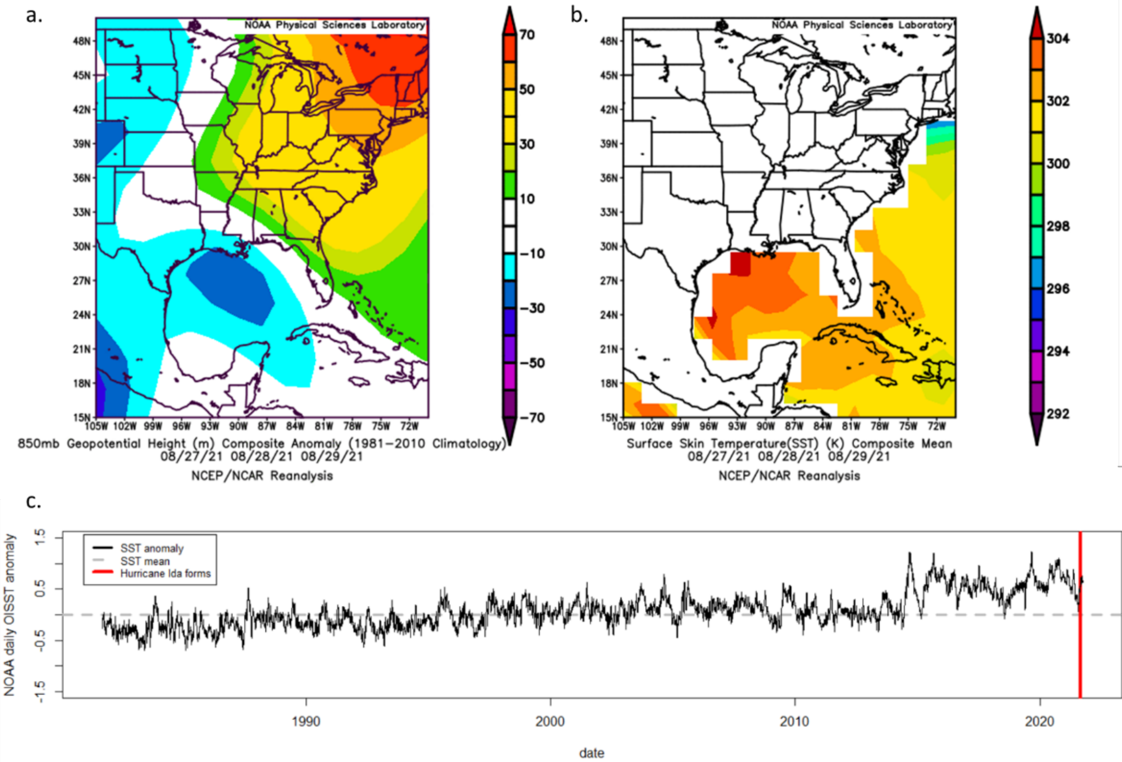


Figure 2.2. a) August 28, 2021 anomaly in near surface pressure steered Ida into b) a positive sea surface temperature anomaly in the Gulf of Mexico that fueled its rapid growth and intensification. c) Sea surface temperatures in the Gulf Coast have been steadily increasing in recent decades. Enhanced westerly ridges of the North Atlantic Subtropical High and increasing sea surface temperatures are both climate change impact associated with stronger and more frequent Atlantic hurricanes.

Once the eye made landfall, a pronounced deceleration in the intensification of Hurricane Ida was observed.[12] By 10:00 PM CST on August 29th, Hurricane Ida had weakened to a category 3 hurricane, with maximum sustained winds observed from aircraft around 105 mph, as it moved northward across Southeastern Louisiana. By 4:00 AM CST on August 30th, the system had been downgraded to a tropical storm over southwestern Mississippi, with threats of heavy rainfall and flooding forecasted over the Tennessee and Ohio Valleys, the Central and Southern Appalachians and the Mid-Atlantic. [13]

Throughout the morning on August 31st, widespread flooding and power-outages impacted Mississippi, western Alabama, and the western Florida panhandle, with the heaviest rainfall associated with tropical storm Ida currently generally isolated to the eastern side of the storm.[14] By 10:00 AM CST, storm surge warnings were discontinued for the Louisiana coast west of the Mississippi River, but new storm surge warnings were issued the mouth of the Pearl River at

[12] https://www.nhc.noaa.gov/archive/2021/al09/al092021.discus.014.shtml?
[13] https://www.nhc.noaa.gov/archive/2021/al09/al092021.public.017.shtml?
[14] https://www.wpc.ncep.noaa.gov/storm_summaries/storm13/stormsum_1.html

Alabama/Florida border.[15] By 4:00 PM CST on August 31st, the system, located over northern Mississippi, Ida had been downgraded to a tropical depression.[16]

The system moved from the Appalachians and into Northeastern United States on September 1–2 where it merged with a powerful non-tropical storm front, causing it to regain tropical force winds and release record breaking rainfall across Pennsylvania, New York and New Jersey. The remnants of Ida exited to the Atlantic off the coast of Cape Cod, Massachusetts, and traversed Nova Scotia and New Brunswick, before extinguishing in the Gulf of State Lawrence on September 4th 2021.

2.2 Hurricane Ida meteorological characteristics and comparison with past storms

Storm surge: Ida's peak storm surge anomaly was just under 4 ft (measured height above high water), measured at Shell Point, LA. Mild to moderate storm surges (associated with a 10-40 year return interval) were recorded consistently between eastern Texas and the Eastern Alabama. The Hurricane Ida storm surge was markedly lower than other recent category 3-5 hurricanes. For example, Hurricane Laura peak measured height above high water of 10.05 ft at Rockefeller Wildlife Refuge with coastal inundation levels of 12 to 18 ft above ground level [17]; Hurricane Ike peak measured height above normal tide levels measured from 5 to 20 along the Bolivar Peninsula of Texas and across the Galveston Bay area; and Hurricane Katrina registered peak measured height above normal tide levels of 25 to 28 ft.[18] Hurricane Ida's reduced relative storm surge is likely associated with its rapid formation and relatively small circumference compared to other storms of equal or greater intensity.[19] Storm surge flooding of up to 10 feet was observed between Golden Meadow and Grand Isle, LA (Figure 2.3).

[15] https://www.nhc.noaa.gov/archive/2021/al09/al092021.public.018.shtml?

[16] https://www.nhc.noaa.gov/archive/2021/al09/al092021.public.021.shtml?

[17] https://www.nhc.noaa.gov/data/tcr/AL132020_Laura.pdf

[18] https://www.nhc.noaa.gov/surge/

[19] https://apnews.com/article/hurricane-ida-katrina-compare-louisiana-88dce72660d0c928f4815eff5a8bfd8f

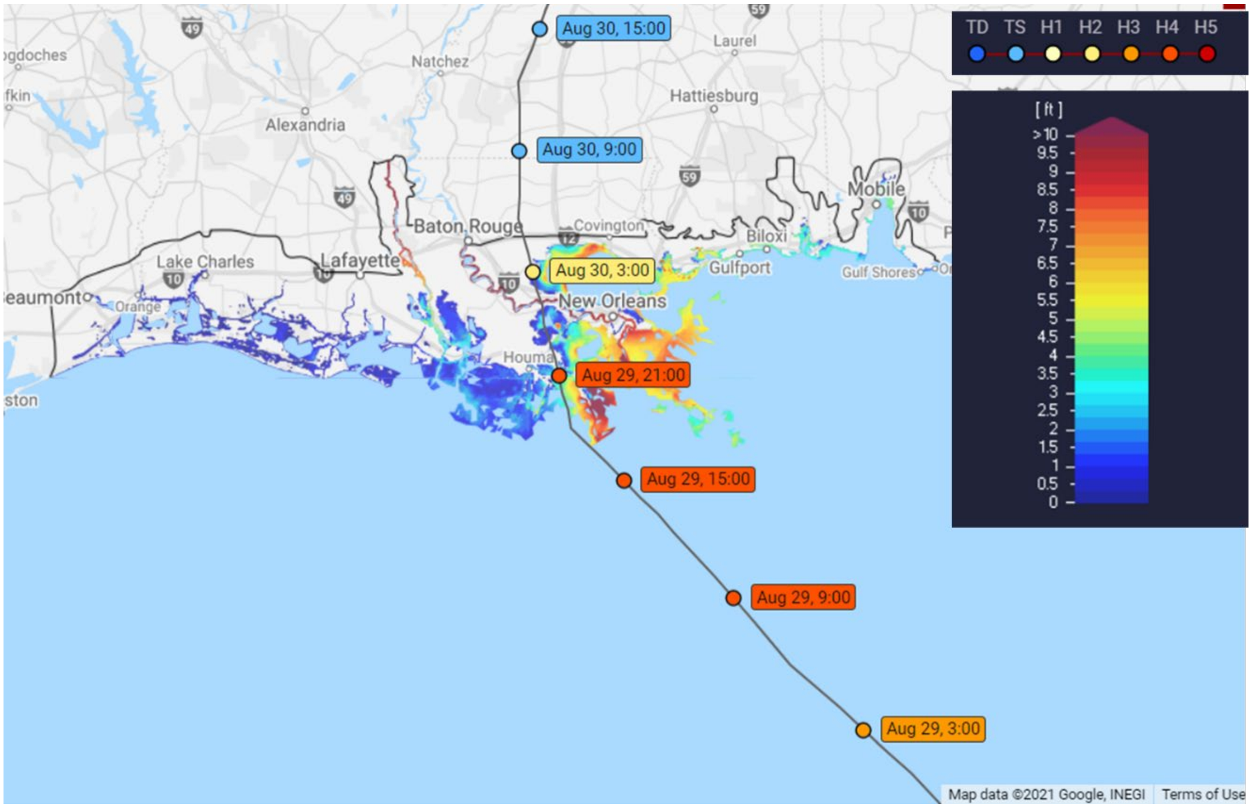


Figure 2.3. Coastal flooding (in feet above land surface) associated with Hurricane Ida storm surge in the Gulf Coast. Figure generated by the Coastal Emergency Risk Assessment online tool, https://cera.coastalrisk.live/cerarisk/, and are the intellectual property of the Coastal Emergency Risks Assessment (CERA) program at the Louisiana State University.

Strengthened after combining with a non-tropical storm front in the Northeastern United States, the remnants of Ida caused additional storm surges in the subpolar northeastern Atlantic and the Bay of Fundy (Figure 2.4).

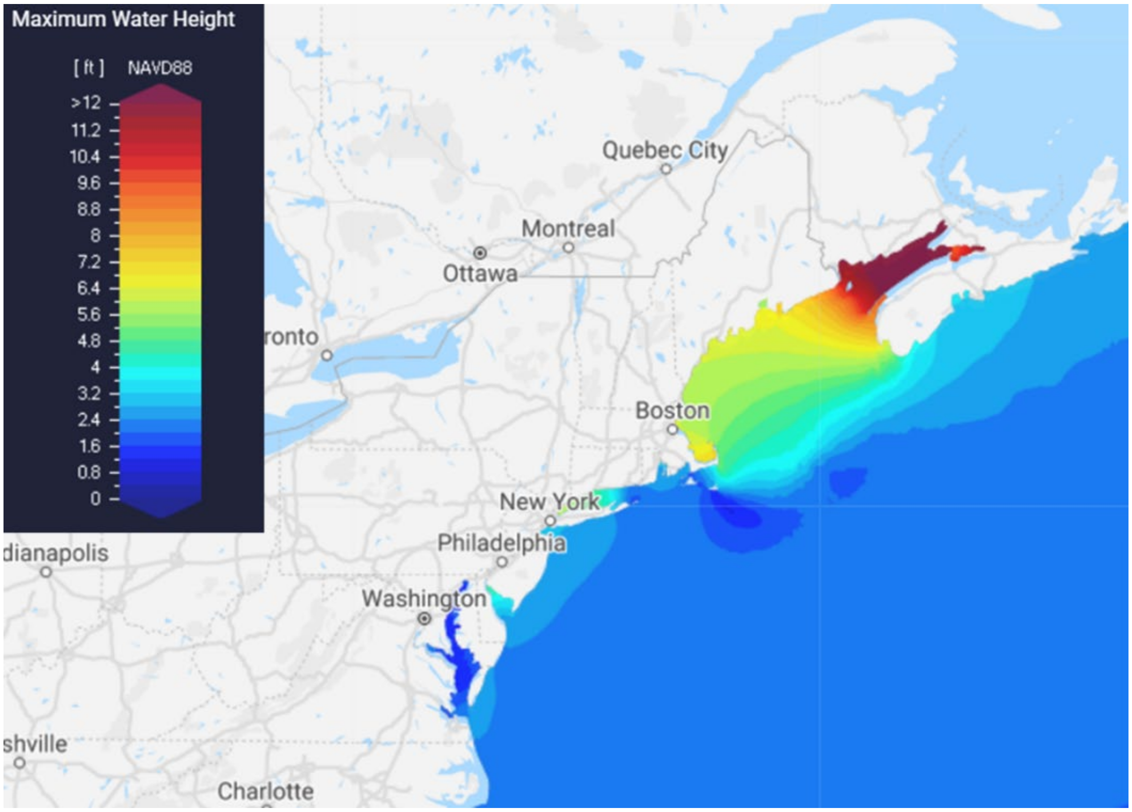


Figure 2.4. Anomalous coastal height (in feet above NAD83 sea level) off the Eastern United States associated with the remnants of tropical depression Ida. Figure generated by the Coastal Emergency Risk Assessment online tool, https://cera.coastalrisk.live/cerarisk/, and are the intellectual property of the Coastal Emergency Risks Assessment (CERA) program at the Louisiana State University.

Winds: Hurricane Ida made landfall with maximum sustained winds of 150 mph, making it just shy of a Category 5 hurricane. A maximum recorded gust of 172 mph was captured by an anemometer in Port Fourchon, LA just after landfall. Unlike other storms in recent history, instead of rapidly deteriorating, Hurricane Ida remained a category 4 storm for 6 hours after landfall, which contributed to prolonged exposure to hurricane-force winds throughout southeastern Louisiana and southern Mississippi, after which point tropical-storm force winds were experience up to 150 miles from the center of the storm throughout southern Mississippi and Alabama. Sustained windspeeds up to 38 mph were recorded up through Appalachia, where Ida progressed as a subtropical depression. Merger with a subtropical storm front greatly enhanced Ida in the last several days of its continental journey, contributing to tropical storm-level windspeeds east of Delaware up through the Northeastern United States.

Precipitation: Hurricane Ida was associated with record-breaking precipitation across the eastern third of the United States. It deposited between 2-12 in of precipitation throughout the Gulf Coast states, with heaviest precipitation concentrated on the eastern side of the storm,[20] leading to

[20] https://www.wpc.ncep.noaa.gov/storm_summaries/storm13/stormsum_1.html

substantial inland pluvial and riverine flooding observed in Mobile and Baldwin Counties, Alabama and Escambia County, Florida.[21] Historical and record-breaking flooding were associated with tropical storm Ida across Mississippi, Alabama, and central-eastern Tennessee. Merger with an atmospheric-river fed subtropical storm in eastern West Virginia markedly enhanced Ida's moisture content as it penetrated into the eastern United States, causing it to break several precipitation records across Pennsylvania, southern New York, and in northern New Jersey. Newark, NJ recorded 8.41 in of water in one day, shattering previous records by 1.5 in. Parts of New York City saw over 3 in per hour, including one station in central park that recorded 4.13 in per hour, causing the city to issue its first ever flash flood warning.[22] Flooding associated with record-breaking precipitation was further compounded by high levels of antecedent moisture from three tropical storms that had impacted the Northeast region in the three weeks preceding Ida: Elsa (July 9, 2021), Fred (August 18, 2021), and Henri (August 21, 2021) (Figure 2.5).

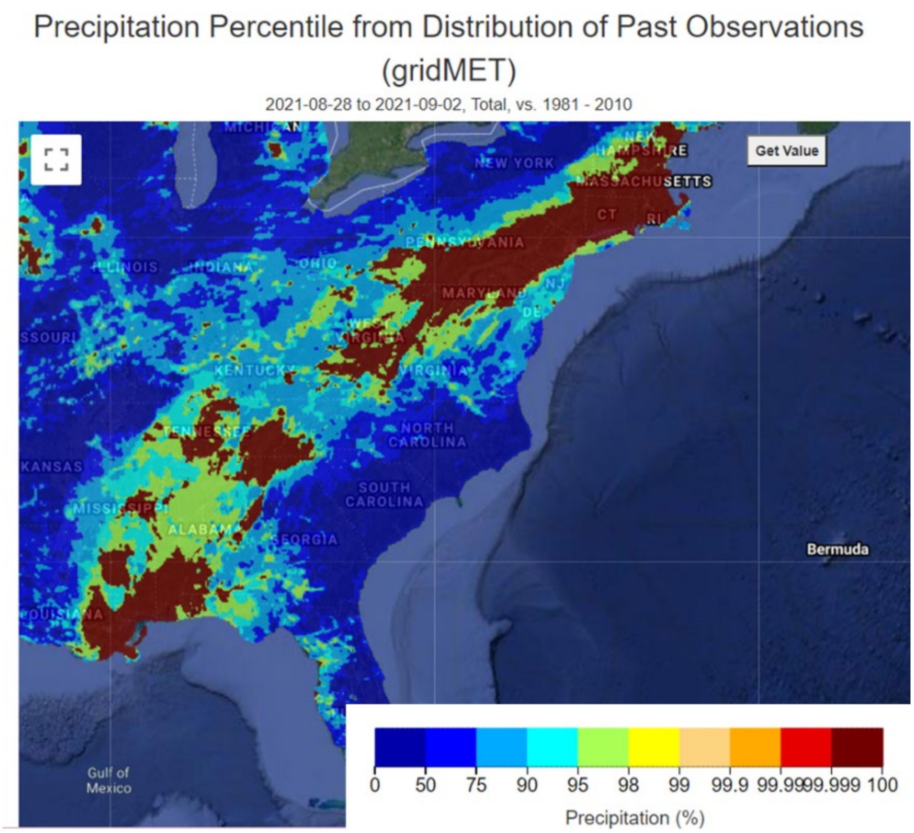


Figure 2.5. Percent deviation from historical distribution of maximum daily precipitation from the ERA5 Reanalysis 8/28/2021 to 9/2/2021 gridded dataset. Climate Engine. (2021). Desert Research Institute and University of Idaho. Accessed on 12/3/2021. http://climateengine.org.

[21] https://www.weather.gov/mob/ida

[22] https://www.rmets.org/metmatters/impacts-hurricane-ida

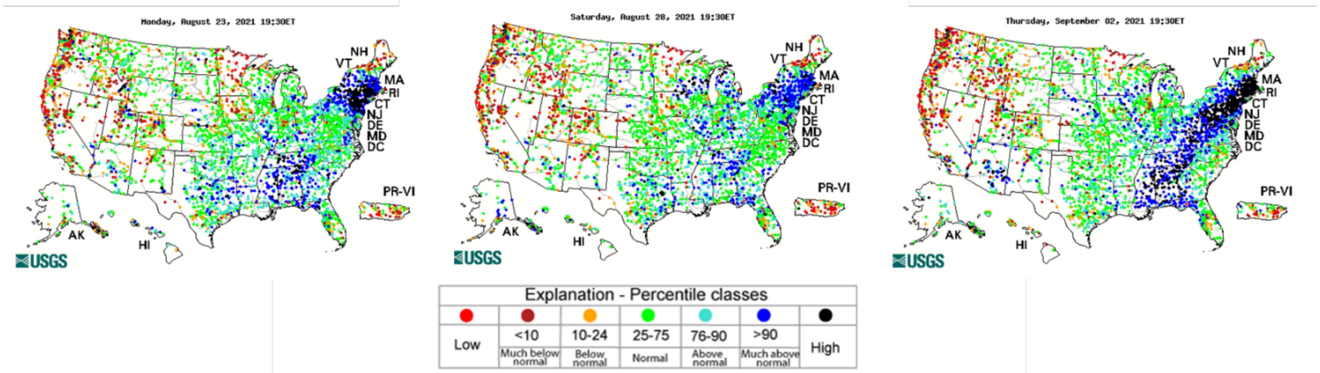


Figure 2.6. USGS stream gage anomalies on August 26th, August 30th, and September 2nd 2021 show that the tropical storm system Ida caused widespread mild to severe flooding across the eastern United States, specifically in the Northeastern United States where many where many watersheds were already at or near flood stage following tropical storms Elsa, Fred, and Henri.

Tornado activity: Hurricane Ida was associated with 35 confirmed tornado touchdowns between Harrison, MI and Barnstable, MA. Twenty-two of these had Enhanced Fujita Scale ratings of 0 (EFS0), nine were ESF1. There tornados, touching down in Anne Arundel MD, Chester PA, and Montgommery PA were ESF2. A tornado that touched down in Glouster, NJ on September 31st was an ESF3 event, with a path length of 12.63 miles and a maximum width of 400 yards. The tornado outbreak associated with Hurricane Ida is comparable to other similar magnitude storms with substantial inland trajectories in the eastern United States: including Hurricane Isaias (August 3–4, 2020, 39 tornados), Hurricane Elsa (July 6–9, 2021, 17 storms), and Tropical Storm Fred (August 17–19, 2021, 30 tornados).

3 Grand Isle, Caminada, Port Fourchon, Golden Meadows

3.1 Grand Isle

Grand Isle is a barrier island located within Jefferson Parish, which is bounded by Barataria Pass on the north and Caminada Pass on the south (Figure 3.1). It is a part of a chain of barrier islands that serve as Louisiana's first line of defense against storm surges. The federal government, state and parish have invested in reinforcing its defenses because it sits directly south of New Orleans, protecting it and wetlands in Jefferson, Lafourche and Plaquemines parishes. Grand Isle also has about 1,400 permanent residents.

Figure 3.1. Overview of Grand Isle along with Port Fourchon and Caminada Headlands.

For more than 60 years, the Grand Isle shoreline has been subjected to multiple projects and hurricane events (Figure 3.2). Based on the Grand Isle coastal engineering history from 1951 to 2015, dune replenishment or dune rehabilitation has occurred on average once every 5.8 years. Grand Isle has also experienced recent tropical storms, including Gustav in 2008, Isaac in 2012, Cristobal and Zeta in 2020, and Ida in 2021. In particular, Tropical Cristobal in the first week of June 2020 damaged nearly 2,000 feet of the levee on the island's west side. Waves gouged deep, cutting through about 85 feet of sand to reach the levee's core, which consists of a geotube covered with about 3 ft of sand. In the last week of October 2020, Hurricane Zeta also made landfall near Grand Isle and exacerbated the damage from Cristobal. In the aftermath of the 2020 hurricane season, the beach was nourished, rip rap was placed, and five breakwaters were constructed on the southwestern tip of Grand Isle. The sand used for nourishment is characteristic of a uniform fine sand with a uniformity coefficient of ~1.7 (APS Engineering and Testing).

The combined GEER/NEER team investigated the damage to Grand Isle. With support from the NHERI RAPID facility, Ebee fixed wing drone imagery, z-boat bathymetry, streetview, and terrestrial LiDAR were performed. The z-boat bathymetry was performed at Caminada Pass bridge. All processed data is available on the NHERI Design-Safe platform (Athanasopoulos-Zekkos et al. 2023).

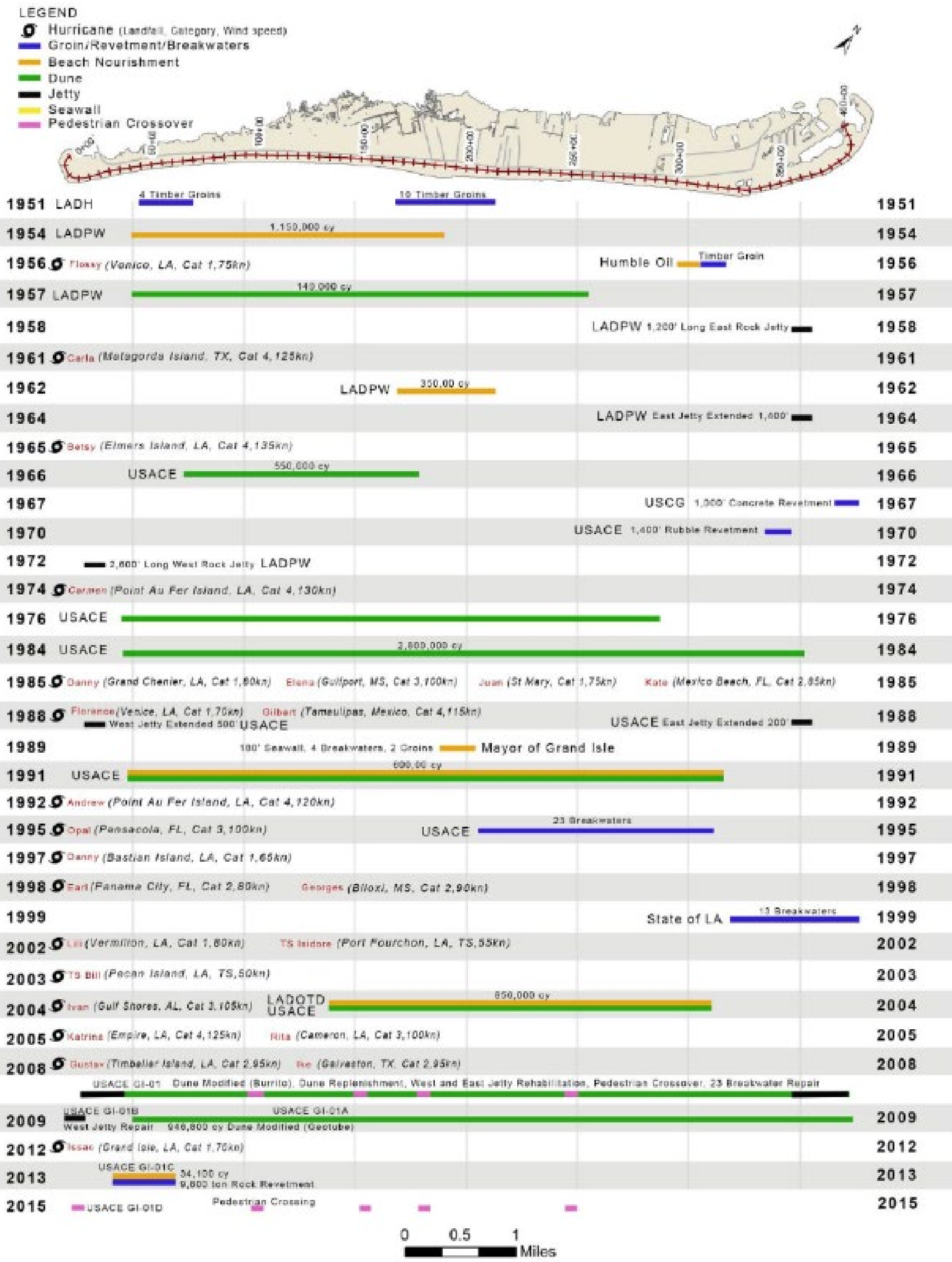


Figure 3.2. History of Grand Isle with hurricanes and infrastructure construction (from Louisiana Coastal Protection and Restoration Authority).

Figure 3.3 shows the Ebee fixed wing drone imagery of the western half of Grand Isle. The digital elevation model can be compared with aerial imagery from the Ebee. Several observations are evident from Figure 3.3. For example, the width of beach in front of the levee increases from west to east. Concomitantly, the degree of damage of the levee decreased in this direction. In sections along the western end, the geotube was exposed. There are two geotube designs present at Grand Isle, with one made of a geotextile tube where sand is pumped inside (Figure 3.4A) and another where compacted fine-grained sediment is encapsulated with a geotextile (Figure 3.4B). The clay geotube experienced significant damage across the western section of Grand Isle. Figure 3.4B shows how the geotextile was torn along the leeside. While the geotextile seam strength was overcome during the hurricane, the clay was not eroded.

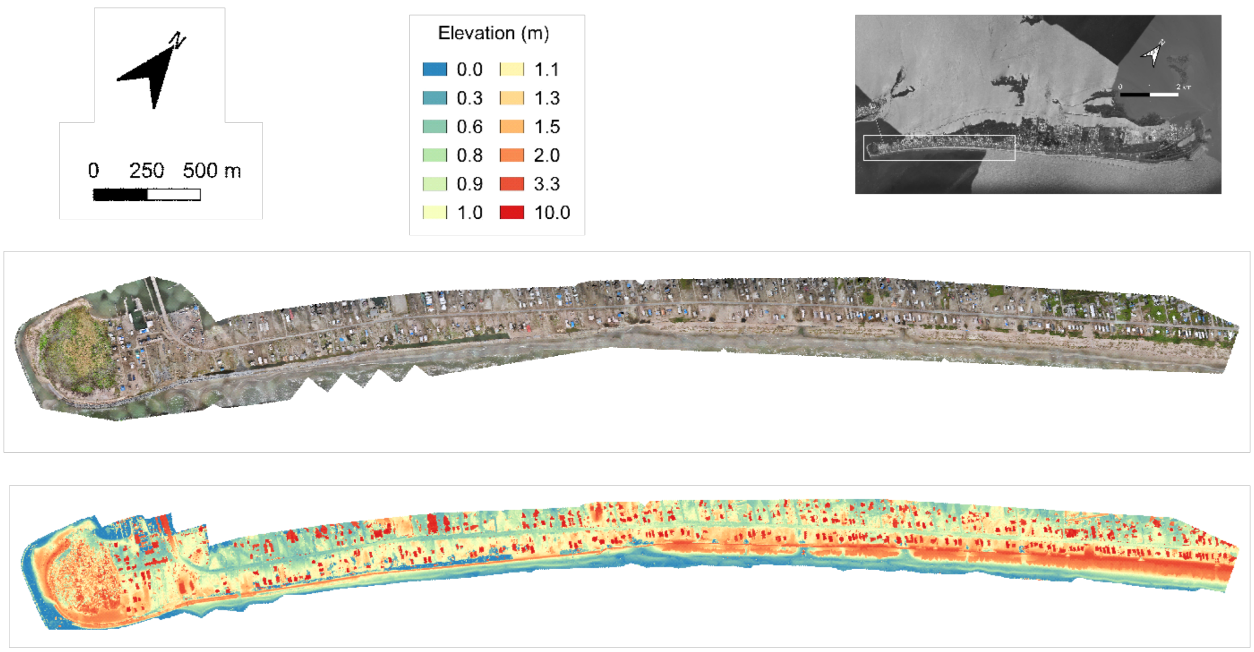


Figure 3.3. Ebee fixed wing drone imagery and digital elevation model (DEM) of the western half of Grand Isle. Drone imagery was supported by NHERI RAPID facility.

Another observation from the Ebee imagery is the presence of a scour trench on the leeside of the levees. This occurs at same locations where the geotube is exposed. This scour trench was about 5 to 10 ft deep and 20 ft wide. The scour trench remained filled with water. Figure 3.5 shows two additional photos of the extent of damage at Grand Isle. In particular, Figure 3.5A shows the levee breached, with the foundation of the sand filled geotube scoured. It is resting inside the scour trench in Figure 3.5A. A close inspection of the DEM in Figure 3.3 shows other areas where a breach occurs. This is evident by looking at the elevation contours, where blue colors are gaps in the red color levee (because it has higher elevation). In some cases, these breaches are located at pathways over the levee that are not covered with grass. This could be an important lesson learned pathways over levees may need to be armored because they provide a conduit for surge and wave overtopping and more erodible material (i.e., sand compared to grass vegetation). Another lesson learned was the important of beach. The east side of the island (see Figure 3.6) exhibited limited to no damage. This is evident from the continuous line of red color contour in the DEM and orange color beach on the sea side of the levee. Both geotubes performed well. However, the compacted fine-grained material wrapped in a geotextile showed that the seam failed in certain areas. Evidence of the compacted material eroding was not found. This still warrants further investigation of the seam strength compared to potential hydrodynamic forcings. An example of the hydrodynamic loading can be found in Figure 3.4A, where the rip rap was picked up and moved into the scour trench. Grass covered sand seemed to provide resistance to surge and wave overtopping erosion. Further studies are needed to better understand grass erodibility and develop overtopping fragility curves for reliability investigations. Hurricane wind and storm surge create vast amounts of disaster debris. Figure 3.7 shows piled debris from Grand Isle, where it is being sorted. The eventual landfill location was unknown. Though, a local landfill is located nearby. There is a need to develop better technologies to classify debris types and estimate disaster debris volumes.

(A) (B)

Figure 3.4. Grand Isle levee geotubes: (A) sand filled geotextile tube (29.2027389, -90.0379722), and (B) compacted fine-grained soil wrapped in geotextile. (29.2037444, -90.0369806) (Photos: N.H. Jafari)

(A) (B)

Figure 3.5. Grand Isle levee damage: (A) Breach and scouring of geotube (29.2143639, -90.0246056), and (B) Erosion of overlying grass and sand on geotube (29.2259472, -90.0055778) (Photos: N.H. Jafari).

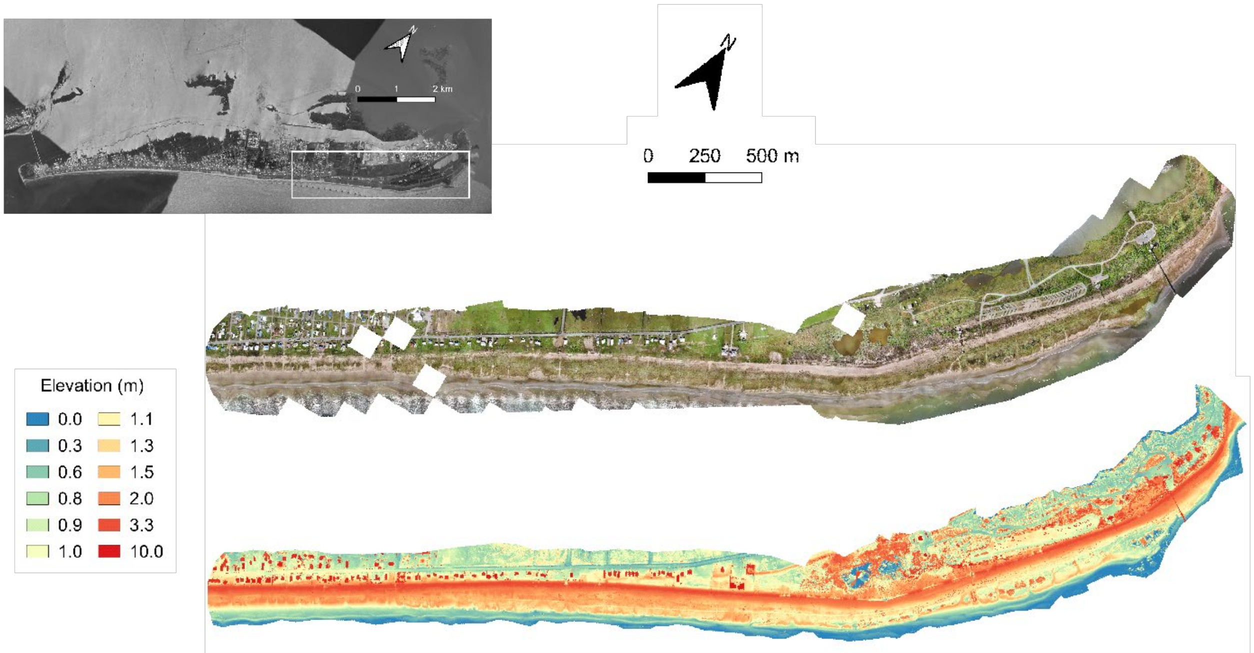


Figure 3.6. Ebee fixed wing drone imagery and digital elevation model (DEM) of the eastern half of Grand Isle. Drone imagery was supported by NHERI RAPID facility (Photo: J. Bekkaye).

Figure 3.7. Drone image of disaster debris from Grand Isle (29.1892583, -90.0818028). (Photo: J. Bekkaye).

3.2 Caminada Headlands Beach and Dune

Coastal barrier islands, including Grand Isle and Caminada Headlands) are dynamic natural infrastructure that serves as the first line of defense to protect salt marshes, inland bays, and mainland regions from the direct impacts of waves and storm surges. Barrier systems reduce inundation during storm surge events, provide relief from direct ocean wave attack which can accelerate interior bay fringe erosion rates, and maintain hydraulic gradients between saline and freshwater to preserve estuarine biogeochemistry systems. Therefore, restoration and periodic maintenance of barrier islands enhance the resilience of vulnerable coastlines which are threatened by more frequently occurring tropical cyclones and sea-level rise (Johnson et al. 2021).

The Caminada Headlands have historically experienced significant shoreline erosion about 45 ft/year) and land loss in its marsh, wetland, beach, and dune habitats as a result of storm overtopping and breaching, saltwater intrusion, wind and wave induced erosion, sea level rise, and subsidence. To address this significant land loss rate, the Louisiana Coastal Protection and Restoration Agency (CPRA) began to dredge and transport high quality beach compatible offshore sand to create dune and beach habitat (Jafari et al. 2018). Approximately 8.71 million cubic yards of sandy sediment dredged from an outer continental shelf at the Ship Shoal sand body (~31 mi from the site) was placed on the 14 mi long project site (CEC Inc., 2012; CEC Inc., 2015). In Figure 3.8, the restoration was divided into two project increments, which was completed in 2015 for about $217.8 million.

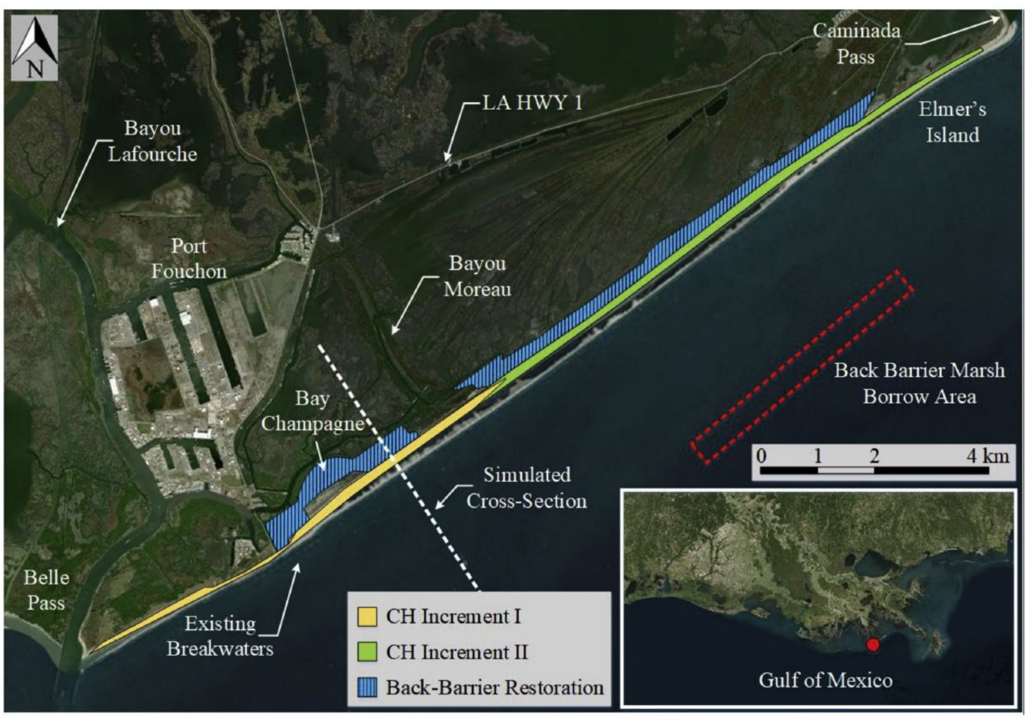


Figure 3.8. Caminada-Moreau Headland site showing completed headland restorations and proposed back barrier marsh areas.

Figure 3.9 shows the as-built cross-sections for three locations along the restored Caminada Headlands beach and dune system. It demonstrates that the elevation of the dune was increased from 1 m (3.3 ft) NAVD88 to about 2.5 m (8.2 ft) NAVD88. However, the beach fill added new loading to the underlying compressible soils, which was found to be about 30 cm (1 ft) after about 2 years (Jafari et al. 2019). This restored dune and beach was immediately tested in 2020 by Hurricane Zeta, which caused overtopping and washover of the dune sediment. This caused a lowering of the dune elevation and inland migration. Then, Hurricane Ida again caused overtopping and washover of the dune. The effect was that the dune was completely lowered to the pre-existing conditions before restoration. Louisiana CPRA conducted aerial LiDAR surveys after Zeta and Ida. Figure 3.10A and 3.10B shows Caminada after restoration (April 2016) and after Hurricane Ida (September 2021). A qualitative comparison of both imagery show the transport of dune into the back barrier marsh and shoreline erosion. Even with this landward migration of sand sediment, Caminada provided storm surge and wave protection to Port Fourchon and Louisiana Highway 1, which is the only evacuation route for Grand Isle.

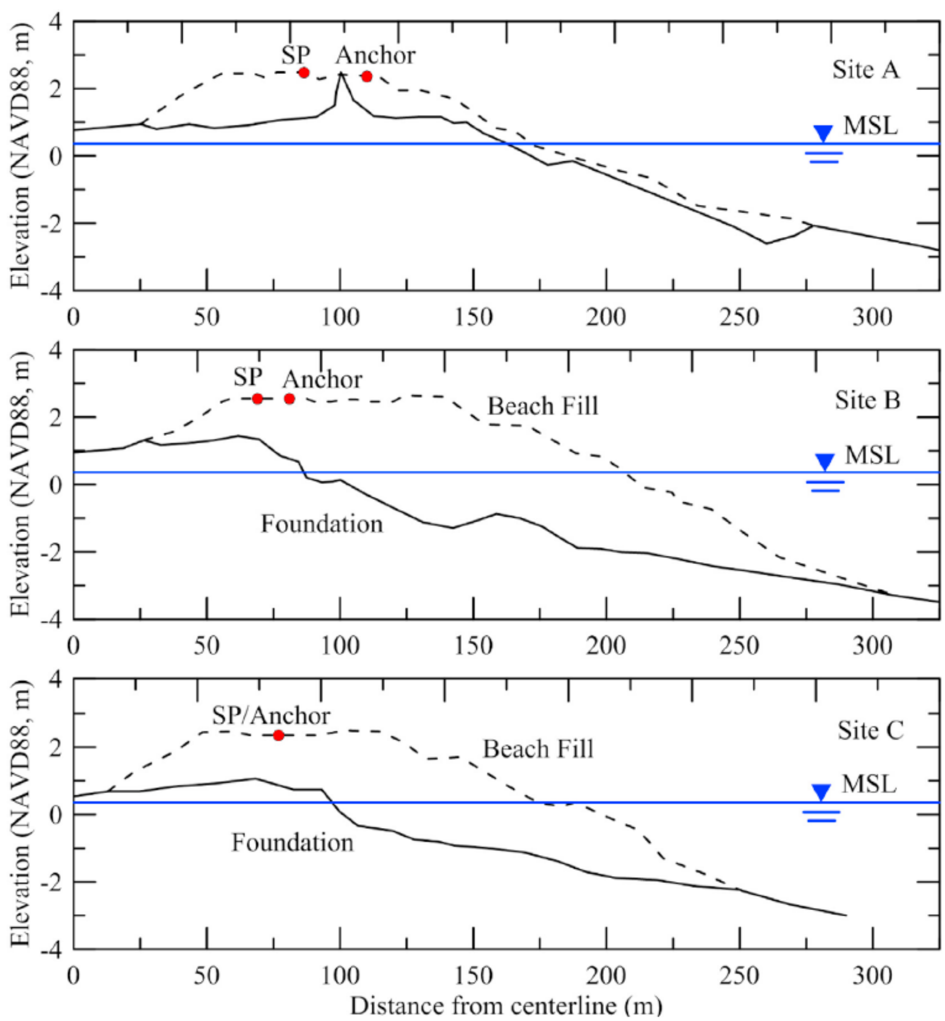


Figure 3.9. As-built cross-sections of restored Caminada Headlands dune and beach system (Site A: 29.1048083, -90.1940556, Site B: 29.1119083, -90.1780389, and Site C: 29.1191806, -90.1692639) (Jafari et al. 2018).

(A)

(B)

Figure 3.10. Comparison of Caminada Headlands dune and beach system: (A) after restoration in 2016 (29.1772722, -90.0729361), and (B) after Hurricane Ida in September 2021 (29.1754278, -90.0747278) (Photos: N.H. Jafari).

3.3 Port Fourchon

Port Fourchon is critical infrastructure to U.S. energy security. For example, Port Fourchon is land base for the Louisiana Offshore Oil Port (LOOP), which handles 10-15% of the nation's domestic oil, 10-15% of the nation's foreign oil, and is connected to 50% of US refining capacity. Port Fourchon also services over 95% of the Gulf of Mexico's deepwater energy production. Overall, Port Fourchon plays a strategic role in furnishing this country with about 18% of its entire oil supply (statistics from www.portfourchon.com).

Port Fourchon was one of the first points of landfall of Hurricane Ida (see Figure 3.11). The Executive Director of the Greater Lafourche Port Commission, Chett Chiasson, briefed the team on the history of the Port, performance of the Port and its supporting structures during Hurricane

Ida, and the future plans for the Port with regards to flood risk management. Despite the Port's wind gauges registering up to 175 mph during Hurricane Ida, the majority of the Port structures that were constructed after Hurricane Katrina performed well with minor damage. This includes water loading up to 10 ft up the side of structures. Structures that were constructed prior to Hurricane Katrina appeared to have performed worse, with significant wind and water damage. The Port also observed sediment deposition from Hurricane Ida, which was resuspended from the Gulf of Mexico.

(A)

(B)

Figure 3.11. Site visit to Port Fouchon: (A) Presentation and discussion at the command center, and (B) Investigation of retaining structures.

3.4 South Lafourch Levee District (SLLD)

The team visited the Larose to Golden Meadow Levee System, starting at the South Lafourche Levee District office, where the team discussed the system with the Levee District General Manager, Windell Curole. Figure 3.12 shows the SLLD system, with two locations identified. The magenta box corresponds to the location where the levee intersects Highway 1 and Bayou Lafourche floodgate. The green box corresponds the "Crawfish Ponds". The numbers in both magenta and green boxes are also color coordinated, with green representing the levee elevation and blue meaning storm surge levels.

During the initial system discussions, approximately 2 ft of overtopping occurred on the system near the "Crawfish Ponds". The Sponsor was unsure of the duration of overtopping, but it is believed to be on the order of a few hours. This overtopping led to scour behind the A-frame supported sheetpile floodwall (which the sponsor has repaired), along with scour and erosion of the adjacent levee embankments. In particular, Figure 3.13A shows the scour at the intersection of levee and concrete transition. Articulated concrete block mat was previously located at the bottom of the concrete on the landside. However, it was displaced during the hurricane, likely when surge and wave overtopping occurred. Figure 3.13B shows examples of erosion on both sides of the levee embankment, which substantiates overtopping at this site. Prior to Hurricane Ida, grass covered the levee embankment. Fixed wing drone imagery was captured at this site to determine the amount of erosion. Future deployments of storm surge and wave gages would be beneficial to determine the overtopping rate, as it could be linked to the observed damage to develop higher-fidelity fragility curves of levees. In addition to the scour repair along the floodwall, the Sponsor is attempting to weld metal to the top of the sheetpile to get additional floodwall height. The Sponsor believes this floodwall "raise" will result in a top of wall elevation of 18 ft NAVD88, which is approximately 5 ft taller than the current elevation of 13 ft NAVD88 (elevation of 18 ft would match the floodwall with the adjoining levee).

Figure 3.14A shows the levee damage at the Highway 1 floodgate. The levee experienced floodside erosion of grass turf. No overtopping was observed but the direct impact of wave action removed the grass and resulted in scouring around pipelines used for interior drainage (Figure 3.14B). These pipelines penetrate through the levee embankment. An important lesson learned from Hurricane Katrina was the need to reinforce pipelines that penetrated levee embankments because of the vulnerability to localized scouring. The erosion of earthen embankment at this location also highlights the need for the development of levee damage models that can predict erosion from wave runup, compared to current state-of-practice which is focused on surge and wave overtopping.

In addition to the overtopping that occurred at the "Crawfish Ponds" area, a small amount of overtopping occurred at the northeast corner of the system, where the levee height is only elevation 11 ft NAVD88. In conjunction with the overtopping that occurred, Figure 3.15 shows large amounts of marsh that were deposited on the levee embankment (up to 5 ft thick) and in the borrow canal directly adjacent to the levee embankment (the marsh filled in the borrow canal, which was previously 15 ft deep and approximately 20 to 30 ft wide). These marsh deposits not only must be removed from the embankment to perform necessary levee improvement construction, but they also have killed the existing embankment turf, which will need to be replaced following the levee repairs. These deposits also highlight the loss of approximately 60 square miles of marsh, which plays a critical role in attenuating the effects of hurricanes in southern Louisiana.

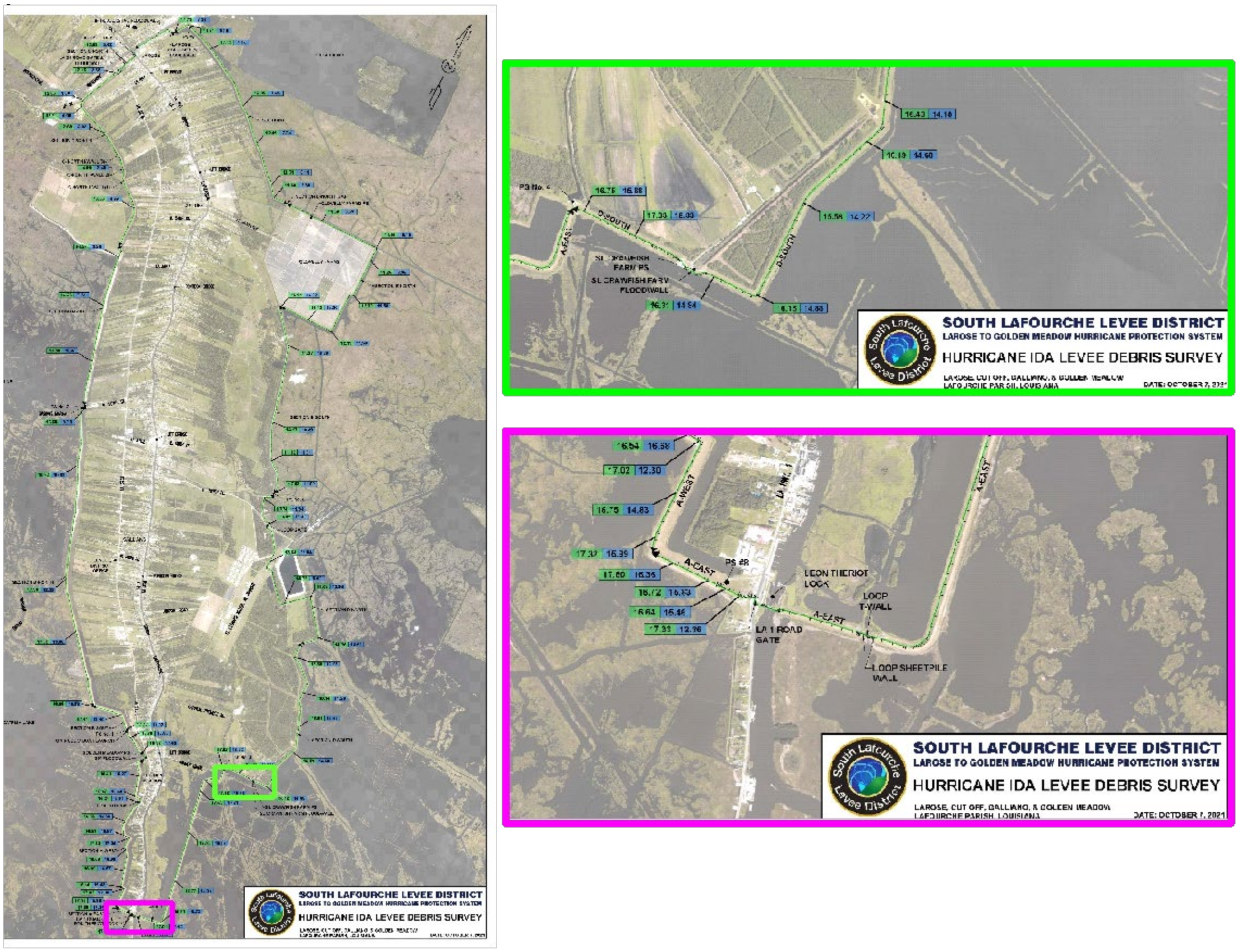


Figure 3.12. Overview of SLLD levee system (from SLLD Director).

(A)

(B)

Figure 3.13. Crawfish Ponds area at SLLD: (A) Scour around sheetpile and concrete transition (29.3950944, -90.2306583), and (B) Erosion of grass and soil from levee embankment (29.3950888, -90.2361583) and (29.3950722, -90.2348333) (Photos in B: N.H. Jafari).

(A)

(B)

Figure 3.14. SLLD at Highway 1: (A) Grass turf and soil erosion at levee embankment (29.3426333, -90.2489389), and (B) Localized scour around pipelines penetrating levee embankment (29.3425833, -90.2488944) (Photos: N.H. Jafari).

Figure 3.15. Marsh deposits on levee embankment near Larose, Louisiana (29.5247111, -90.2868417) (Photos: N.H. Jafari).

4 Hurricane Ida in New Orleans

4.1 Impact of Hurricane Ida in the Greater New Orleans Area

Following the devastating consequences of Hurricanes Katrina and Rita in 2005, the USACE was authorized and funded to design and construct the Hurricane & Storm Damage Risk Reduction System (HSDRRS) in southeastern Louisiana. The total project cost was over $14.6 billion, construction lasted over 14 years and includes 350 miles of levees, as well as several floodgates, pump stations and canal closures. Figure 4.1 shows an overview of HSDRRS as of 2018.

Figure 4.1. Overview of the nearly completed Hurricane & Storm Damage Risk Reduction System in New Orleans and Southeast Louisiana (https://www.mvn.usace.army.mil/Missions/HSDRRS/).

Part of HSDRRS had been complete by the time Hurricane Gustave made landfall in 2008, and these improvements along with their performance have been documented in the GEER report published following the event (https://geerassociation.org/components/com_geer_reports/geerfiles/GEER_Recon_of_NOLA_HSDRRS_after_Gustav_r1a.pdf). However, there have been many additional improvements and additions since, and they are described in the USACE Facts Sheet provided in Appendix B.

The GEER/NEER Field team, together with representatives from the USACE and ASCE, visited several locations along HSDRRS and documented its performance during Hurricane Ida. *Overall, the system components performed well, with only minor operational issues occurring, none of which caused additional inundation in the leveed areas. There were no floodwall-related concerns and both the Western Closure Complex (WCC) and the 17th Street Canal Pump Station (Permanent Canal Closures & Pumps) successfully pumped interior drainage water to maintain appropriate operational water levels within the system. Relative to the design of the system and to previous Hurricanes, the system was not greatly tested with regards to rainfall and storm surge loading. The East portion was loaded to ~40% and the Southwestern portion was loaded to ~100%.* (USACE Draft Report, Appendix C).

4.2 Permanent Canal Closures and Pumps (PCCP)

The three Canal Closures and Pumps are located at the three Canals: 17th Street Canal, Orleans Ave. Canal and London Ave. Canal and run south to north near the Orleans Parish between the Jefferson Parish line and the Inner Harbor Navigation Canal (IHNC). The PCCP are composed of permanent gated storm surge barriers and brick façade pump stations at or near the lakefront. The pumps move rainwater out of the canals, around the gates and into Lake Pontchartrain during a tropical weather event, and are equipped with stand-alone emergency power supply capacity for 5 days to operate independently of any publicly provided utility.

The field team visited all three canals and the 17th Street PCCP. The following photographs contrast the condition of the levees in the canals following Hurricane Katrina and Hurricane Ida. It is important to note that the levees lining the canals were not loaded in similar ways between these two Hurricane events, because the presence of the PCCP prevented a substantial storm surge from taking place within the canals (which is the objective of the PCCP).

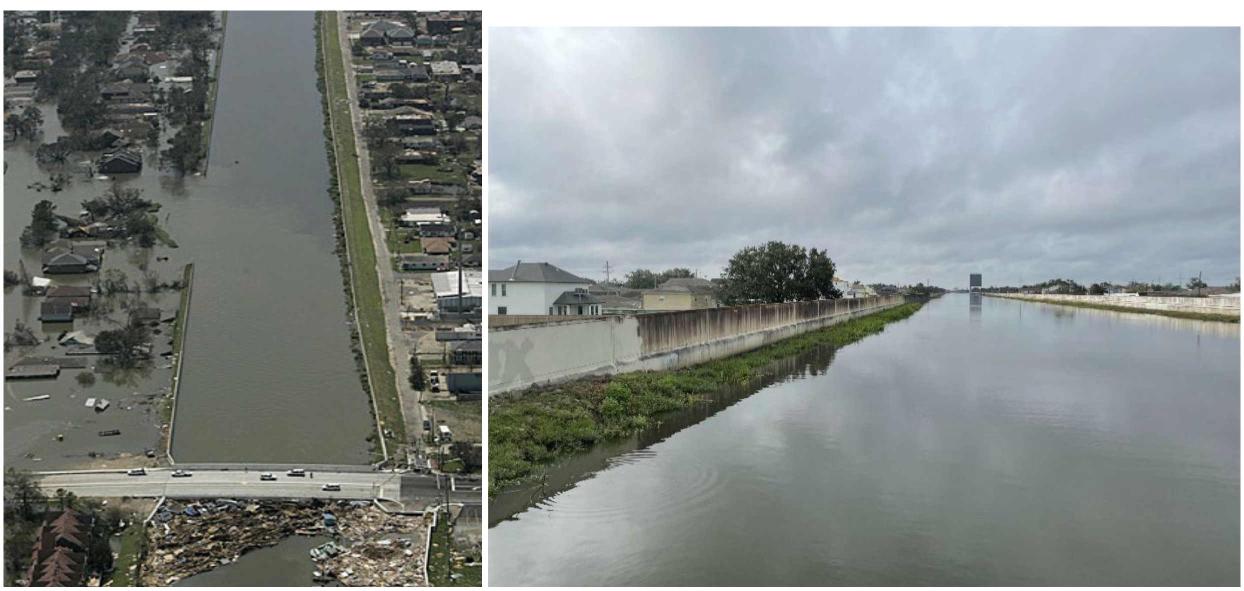


Figure 4.2. 17th Street Levee failure on the east following Hurricane Katrina (left) (ILIT Report, 2006), 17th Street Canal after Hurricane Ida (right) (lat: 30.017342, long: -90.121641) (photo by A. Athanasopoulos-Zekkos).


Figure 4.3. London Ave North Levee failure on the west following Hurricane Katrina (left) (ILIT Report, 2006), London Ave Canal North after Hurricane Ida (right) (lat: 30.027667, long: -90.073439) photo by A. Athanasopoulos-Zekkos.


Figure 4.4. London Ave South Levee failure on the west following Hurricane Katrina (left), London Ave Canal South after Hurricane Ida (right) (lat: 30.004702, long: -90.069147) (photo by A.Athanasopoulos-Zekkos).

Figure 4.5. 17th Street Permanent Canal Closure and Pumps (capacity 12,600 cfs, 11 gates) (lat: 30.017342, long: -90.121641) (photo by A. Athanasopoulos-Zekkos.

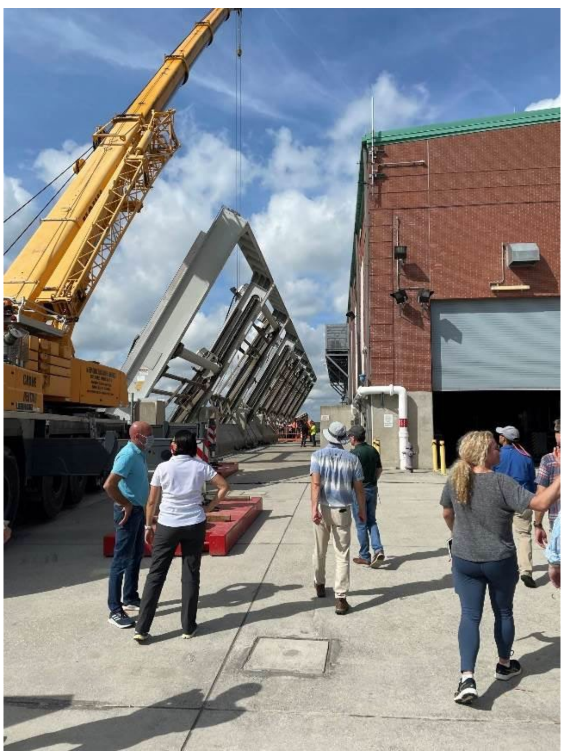


Figure 4.6. 17th Street Permanent Canal Closure and Pumps (lat: 30.017342, long: -90.121641) (photos by A. Athanasopoulos-Zekkos).

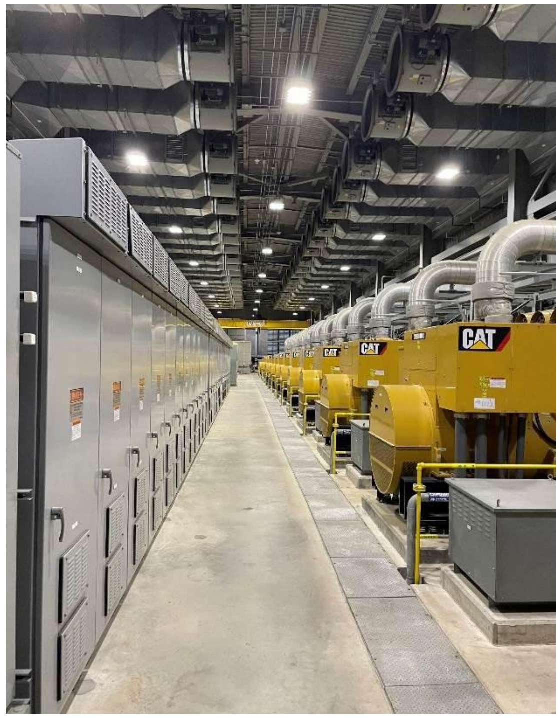


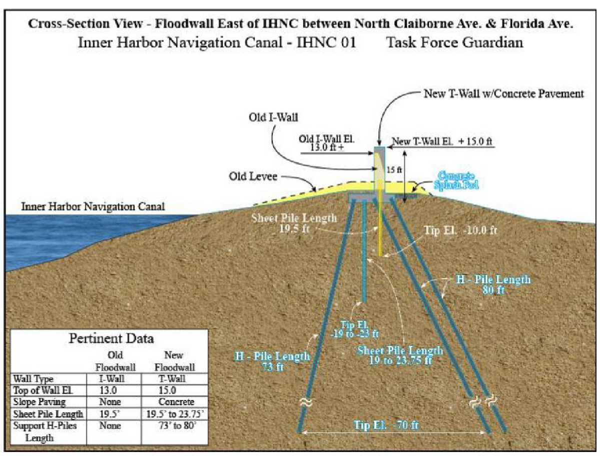
Figure 4.7. 17th Street Pump Station Generators (15 2.6MW Generators) (lat: 30.017342, long: -90.121641) (photo by A. Athanasopoulos-Zekkos).

Figure 4.8. London Avenue Permanent Canal Closure and Pumps (capacity 9,000 cfs, 7 gates) (lat: 30.027667, long: -90.073439) (photo on left by A. Athanasopoulos-Zekkos, photo on right by USACE).

4.3 IHNC Surge Barrier Wall & Lower 9th Ward

The 42ft tall, 150ft long sector gate that is part of the IHNC Surge Barrier was closed prior to Hurricane Ida's landfall (Figure 4.9 and Figure 4.10). The recorded surge at that location was 11ft. There were no issues recorded or observed at this location. This barrier protects the Lower 9th Ward area that suffered significant damage following Hurricane Katrina. The levees in the Lower 9th Ward area had been reinforced even prior to Hurricane Gustave, and performed well even though they were heavily loaded. The presence of the Surge Barrier that was constructed later, further protects these areas by not allowing the surge to increase within the IHNC. Our field team did observe evidence of approximately 3" of settlement at the Lower 9th Ward T-wall base (Figure 4.11). A similar observation was also made by the GEER reconnaissance team following Hurricane Gustave, who measured approximately 1" of settlement. This is expected in areas of this type of geology and soil stratigraphy that includes soft compressible clays, so it is important that this is accounted for and tracked within the maintenance of the system.

Figure 4.9. IHNC Lower 9th Ward Levee failure following Hurricane Katrina (left) (ILIT Report, 2006), IHNC after Hurricane Ida (right) (lat: 29.978591, long: -90.020675) (photo by A. Athanasopoulos-Zekkos).



	Old Floodwall	New Floodwall
Wall Type	I-Wall	T-Wall
Top of Wall El.	13.0	15.0
Slope Paving	None	Concrete
Sheet Pile Length	19.5'	19.5' to 23.75'
Support H-Piles Length	None	73' to 80'

Figure 4.10. IHNC Floodwall cross-section following reinforcement (left), IHNC lower 9th ward floodwall during Hurricane Gustave (right) (lat: 29.978591, long: -90.020675) (GEER Report, Gilbert et al. 2009).

Figure 4.11. Floodwalls at the Lower 9th Ward following Hurricane Ida (left and insert showing measured settlement), same location after Hurricane Gustave showing observed settlement (lat: 29.978591, long: -90.020675) (GEER Report, Gilbert et al. 2009).

Figure 4.12. IHNC Surge Barrier Wall (lat: 30.002336, long: -89.894279) (left photo by USACE, right photo by A. Athanasopoulos-Zekkos).

4.4 The Gulf Intracoastal Waterway - West Closure Complex

The Gulf Intracoastal Waterway - West Closure Complex is a major feature of the HSDRRS which reduces risk for residences and businesses in three parishes on the west bank of the Mississippi River: Orleans, Jefferson and Plaquemines parishes.

During Hurricane Ida, the Complex experienced the highest level of surge since its construction following Hurricane Katrina, with peak surge reaching EL 6.8 ft. The structure is designed for surge up to EL 16 ft, so no overtopping occurred; however, there were waves that resulted in a small amount of water splashing over the sector gate.

Furthermore, one of the 11 pumps lost capacity due to a coolant leak leading to a small fire at the pump. Although this pump was temporarily offline, the remaining 10 pumps had more than enough pumping capacity to keep up with the needed outflow of water during the event.

Figure 4.13. The Gulf Intracoastal Waterway - West Closure Complex (USACE). (lat: 29.771008, long: -90.074640)

4.5 Other topics

An area that created many problems during Hurricane Katrina was the transition zones between different types of levees and floodwalls, as well as connections between the flood protection system and other infrastructure. Prior to Hurricane Ida, as part of further reinforcements, armoring had been constructed and placed at several of these transition locations. This resulted in a much better performance even at locations that did overtop and experienced significant water flow.

Figure 4.14. Scouring and erosion as a result of a transition zone between different type of levees following Hurricane Katrina (left), scour along a levee section in Grand Isle following Hurricane Ida (right) (lat: 29.244278, long: -89.977038) (photos by A. Athanasopoulos-Zekkos).

Figure 4.15. Examples of armoring along levee and floodwall transitions prior to Hurricane Ida (lat: 29.244278, long: -89.977038) (photos by A. Athanasopoulos-Zekkos).

5 Electric Grid

5.1 Electric Grid Reconnaissance & Observations

As part of the field reconnaissance effort, performance of the physical electrical transmission system was documented at select locations between Saturday, September 11, 2021 and Sunday, September 12, 2021. Figure 5.1 shows an overlay of the electric transmission system in southern Louisiana with an overlay of the field reconnaissance performed.

Three specific locations were visited where the performance of the electrical transmission was noted in detail.

- Location "A" -**Failure** - (29.928702, -90.1790472) – This is an overhead AC bulk power transmission river crossing, where the south tower experienced a structural failure with no observed associated foundation failure. This tower failed in the evening of Sunday, August 29, 2021. The northern tower (on the other side of the Mississippi River) was not documented as being damaged. Figure 5.2 shows a view of the remnant foundations at the time of the GEER reconnaissance. Figure 5.3 shows an aerial oblique view of the downed southern tower as posted on the website "DailyMail.com." Figure 5.4 shows an image of the northern tower during the GEER reconnaissance, with no observable foundation or structural distress. Figure 5.5 shows an aerial oblique view prior to Hurricane Ida (from Google Earth) looking southwest. The two tower locations have been highlighted in the yellow box and a dashed yellow line added to indicate the alignment of the electric transmission lines.

- Location "B" - **No Failure** - (29.95475, -90.138175) – This is an overhead AC bulk power transmission river crossing. There are four lines in total, two on each tower set. No structural or foundation failures were observed at this location as a result of Hurricane Ida. Figure 5.6 shows an image of the northern tower during the GEER reconnaissance. shows an aerial oblique view prior to Hurricane Ida (from Google Earth) looking northwest. The tower locations have been highlighted in the yellow box and a dashed yellow line added to indicate the alignment of the electric transmission lines. Location "A" can be seen in the upper left.

- Location "C" – **Failure** – (29.266739, -90.2192917) – This is an overhead AC bulk power transmission line following Highway 1. Figure 5.8 shows an instance where the actual pole buckled, resulting in a structural failure. No damage to the deep foundation was observed. This tower was located near Leeville.

While the locations visited by the GEER team are not exhaustive, they do provide some indication of the overall electric transmission system, as well as some insights as to the performance during Hurricane Ida. Overall, there were no observed/documented cases of formal foundation failures of major transmission towers. There were, however, numerous failures of distribution poles throughout the area. GEER did not map occurrences of these distribution pole failures as they were too numerous.

The documented wind speeds and gusts largely fall below 120 mph in the greater New Orleans area. The failed tower at Location “A” had documented maximum gusts below 100 mph. The design wind speeds (per ASCE 74-10, 2010) were on the order of 130 mph (Figure 5.1).

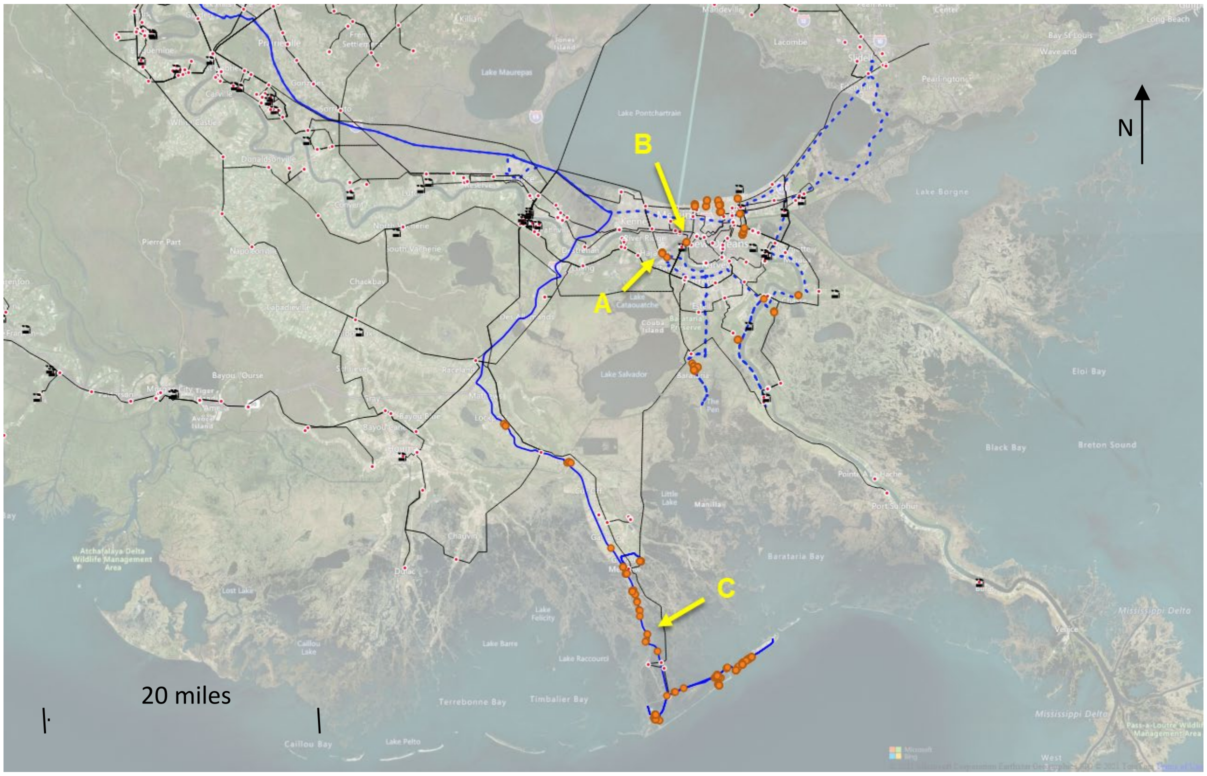


Figure 5.1. Overview of field reconnaissance relative to the electrical transmission system in southern Louisiana.

Figure 5.2. View of electric transmission tower foundations following removal of the failed transmission tower. (29.928703, -90.179047). (Photo by: A. Athanasopoulos-Zekkos)

Figure 5.3. Aerial oblique view of the downed transmission tower at Location "A". Photo from DailyMail.com (https://tinyurl.com/pd8k9t7w). (29.928703, -90.179047)

Figure 5.4. North Tower intact and no observable foundation or structural issues. (29.936753, -90.188278). (Photo by: A. Athanasopoulos-Zekkos)

Figure 5.5. Aerial oblique view from Google Earth showing the overhead transmission line crossing over the Mississippi River. The North Tower did not fail. The South Tower did fail.

Figure 5.6. Southerly view of the east towers conveying transmission lines across the Mississippi River from Nine Mile Point. (29.955778, -90.138367). (Photo by: A. Athanasopoulos-Zekkos)

Figure 5.7. Aerial oblique view from Google Earth showing the overhead transmission line crossing over the Mississippi River. All four towers remained in service and no observable structural, or foundation damage was found during the GEER reconnaissance.

Figure 5.8. Observed structural failure of a transmission pole along Highway 1 near Leeville in Bayou Lafourche. (29.266739, 90.219292). (Photo by: A. Athanasopoulos-Zekkos)

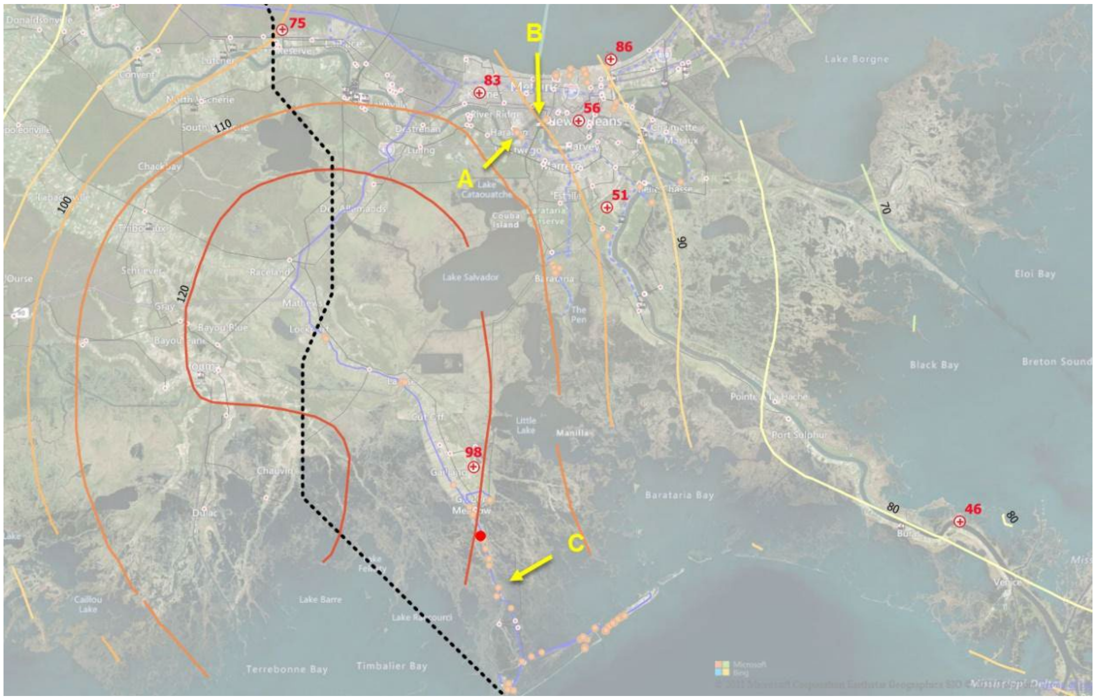


Figure 5.9. Overview of storm track (dashed black line) and predicted wind gust contours with reported maximum gusts (red) relative to Locations A, B, and C.

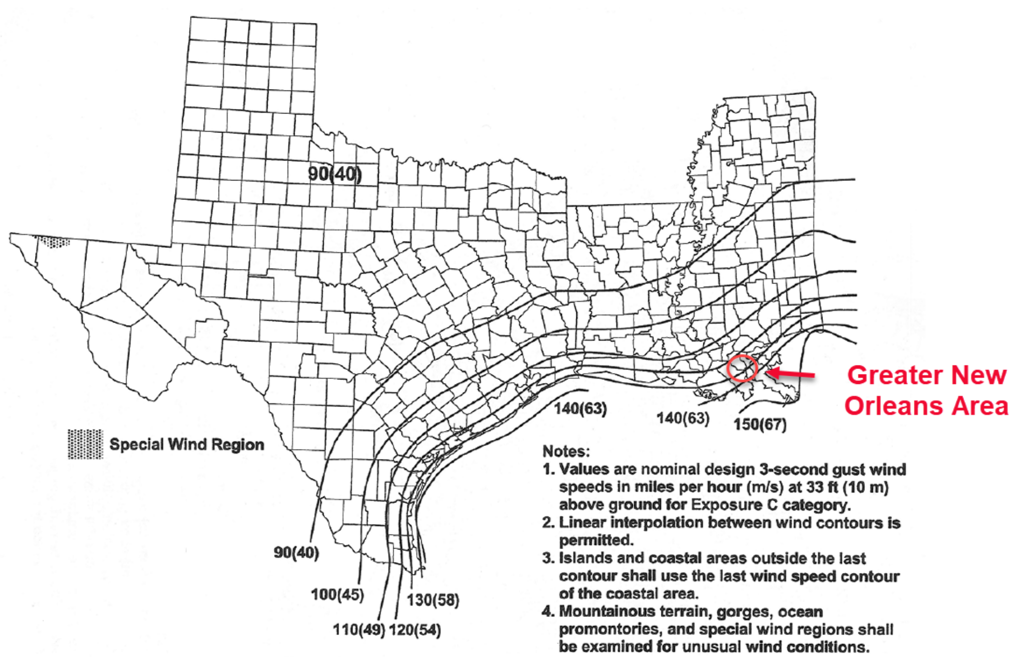


Figure 250-2(c)—Western Gulf of Mexico hurricane coastline

NOTE: Figure 250-2(c) reprinted with permission from ASCE, 1801 Alexander Bell Dr., Reston, VA 20191 from ASCE 74-10, Guidelines for Electrical Transmission Line Structural Loading. Copyright © 2010.

Figure 5.10. Design wind speeds for the western Gulf of Mexico coastline. Source: National Electric Code, 2017.

5.2 Electric Grid Disruptions

Hurricane Ida had a dramatic impact on the electric grid serving the greater New Orleans area and southern Louisiana. Figure 5.11 shows an evening satellite image from August 9, 2021 of the greater New Orleans area. Figure 5.12 shows a similar view, but on August 31, 2021 after Hurricane Ida. Entergy estimated[23] that the total damage experienced during Hurricane Ida resulted in damage to 30,679 poles (Figure 5.13), 36,469 spans of wire and 5,959 transformers. In total, the number of damaged or destroyed poles from Ida is more than hurricanes Katrina, Ike, Delta and Zeta combined.

Almost one million customers lost power as a result of system failures of the electric grid, which was the result of disruptions to all eight incoming transmission routes (Figure 5.14). It took several weeks to restore service to most customers (see Table 5.1); using one of two restoration schemes outlined by Entergy (Figure 5.15).

Table 5.1 Summary of Restored Entergy Customers Following Hurricane Ida

Date	Reported Restored Customers	Source
09/03/2021	225,000 / 950,000	https://tinyurl.com/3htc276a
09/06/2021	511,000 / 950,000	https://tinyurl.com/ynv4a722
09/06/2021	946,000 / 950,000	https://tinyurl.com/32bp2ad2

[23] https://www.entergynewsroom.com/article/ida-damage-greater-than-katrina-ike-delta-zeta-combined/

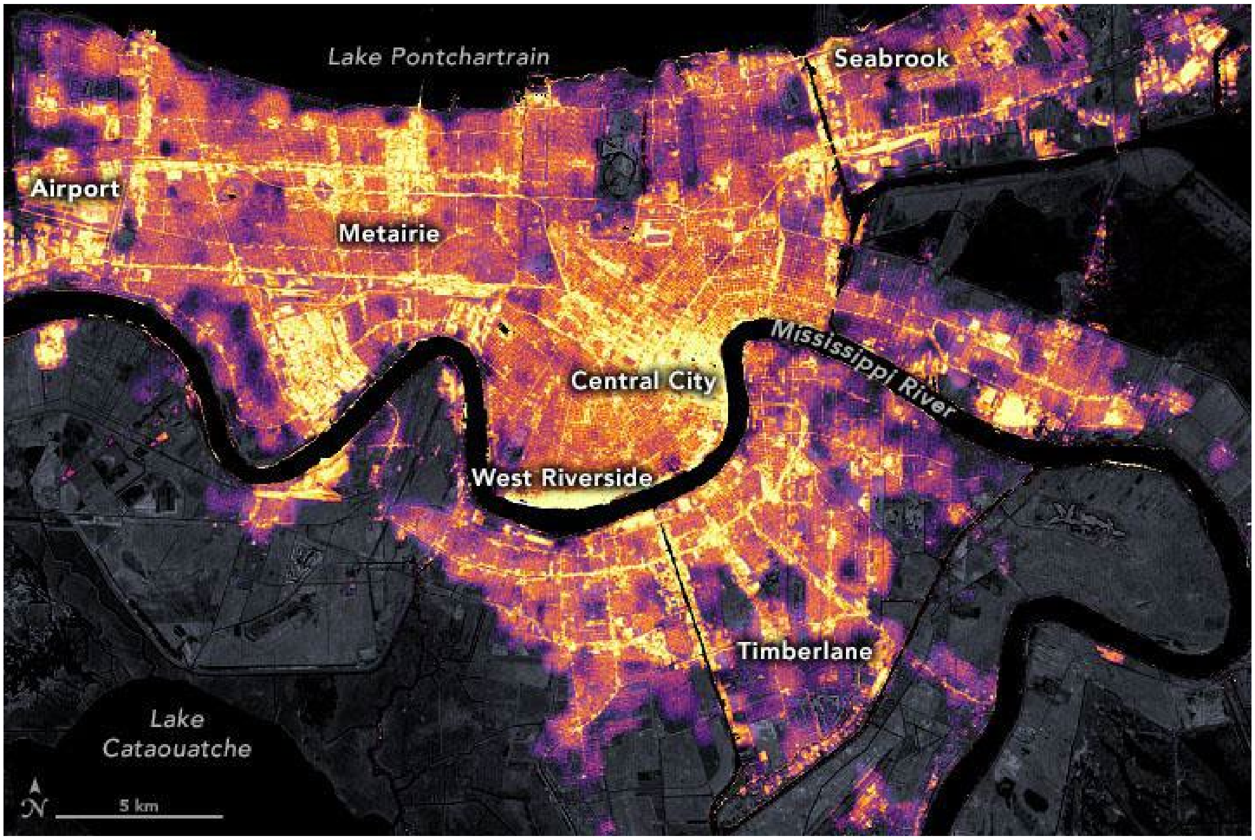


Figure 5.11. Satellite image at night of the greater New Orleans area taken by NASA Earth Observatory system on August 9, 2021. Source: https://tinyurl.com/2p8z6rrn.

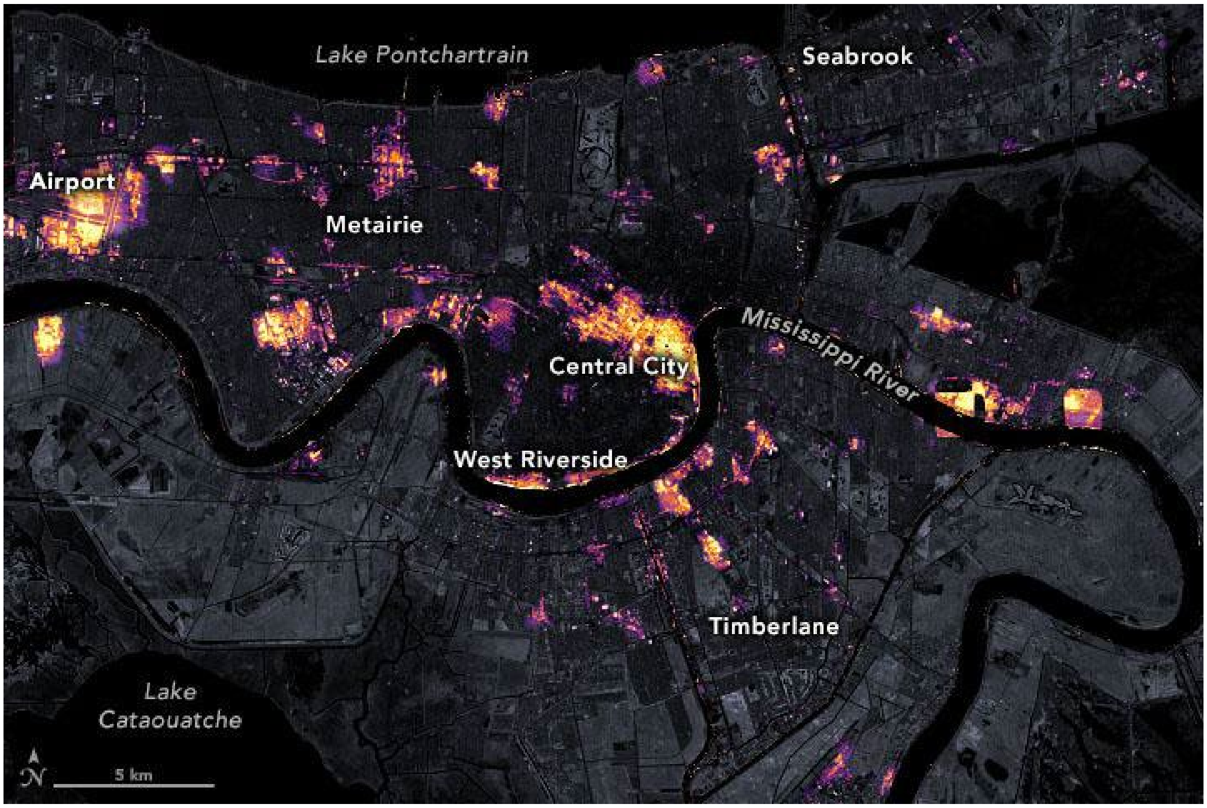


Figure 5.12. Satellite image at night of the greater New Orleans area taken by NASA Earth Observatory system on August 31, 2021. Source: https://tinyurl.com/pwcynwzy.

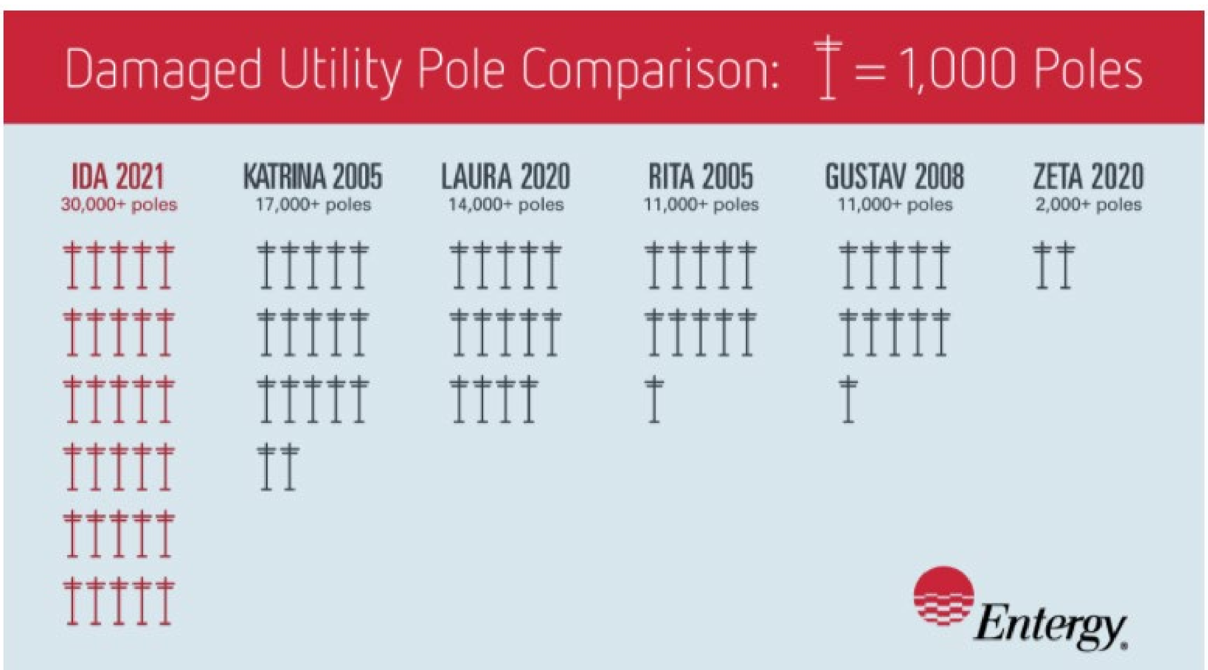
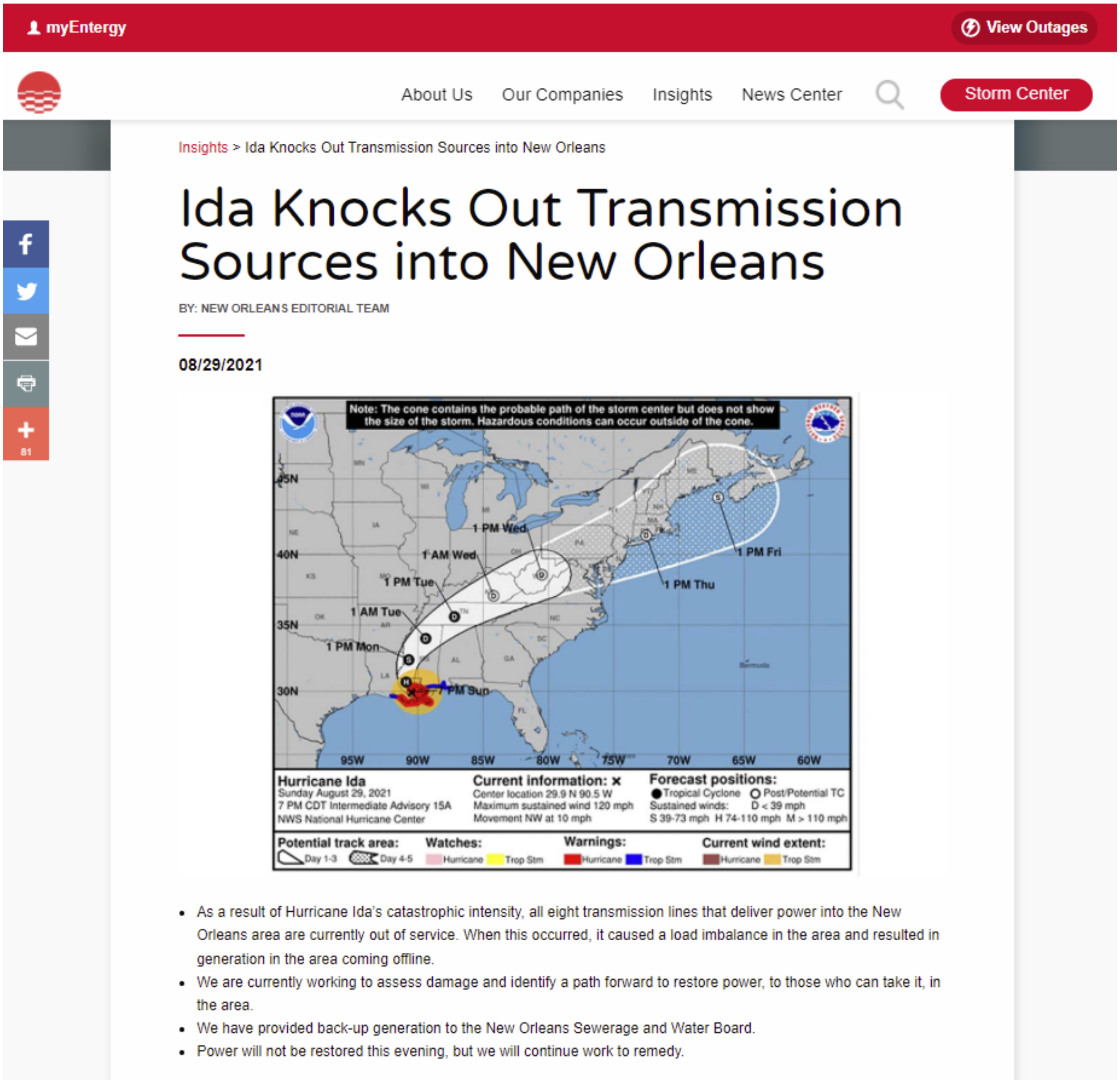


Figure 5.13. Over 30,000 utility poles were reported damaged or destroyed by Energy. Source: https://www.entergy.com/hurricaneida/etr/.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Insights > Ida Knocks Out Transmission Sources into New Orleans

Ida Knocks Out Transmission Sources into New Orleans

BY: NEW ORLEANS EDITORIAL TEAM

08/29/2021

- As a result of Hurricane Ida's catastrophic intensity, all eight transmission lines that deliver power into the New Orleans area are currently out of service. When this occurred, it caused a load imbalance in the area and resulted in generation in the area coming offline.
- We are currently working to assess damage and identify a path forward to restore power, to those who can take it, in the area.
- We have provided back-up generation to the New Orleans Sewerage and Water Board.
- Power will not be restored this evening, but we will continue work to remedy.

Figure 5.14. Entergy notice that all incoming electric transmission sources were out of service. Source: https://www.entergynewsroom.com/article/ida-knocks-out-transmission-sources-into-new-orleans/.

Insights > Entergy System Hurricane Ida Update – 8/31/21 @ 6:30 p.m.

Entergy System Hurricane Ida Update – 8/31/21 @ 6:30 p.m.

BY: CORPORATE EDITORIAL TEAM

08/31/2021

Just two days after Hurricane Ida delivered a catastrophic blow to Louisiana, Entergy has determined two options to bring first lights into the Greater New Orleans area by late evening Wednesday, Sept. 1.

- Restoration of certain critical transmission lines that tie the Greater New Orleans region to the larger electric grid – this is the preferred solution; or
- Creating an "island" that would temporarily isolate the Greater New Orleans region from the larger electric grid. This stand-alone grid will operate on a limited basis supplied by local generation from the New Orleans Power Station in Eastern New Orleans and Ninemile 6 in Bridge City.

Under either scenario, New Orleans Power Station and Ninemile Point Power Station will be extremely valuable and important local sources of generation providing power to customers.

Any power to the region will allow the company to begin powering critical infrastructure in the area such as hospitals, nursing homes and first responders in Orleans, Jefferson, St. Bernard and Plaquemines parishes, as well as parts of St. Charles and Terrebonne parishes. Restoration will vary by parish and neighborhood based on local transmission and distribution damage.

Figure 5.15. Entergy's two operational scenarios to restore power to the greater New Orleans area. Source: https://www.entergynewsroom.com/article/entergy-system-hurricane-ida-update-8-31-21-6-30-p-m/.

6 Hurricane Ida in the Northeast and Middle Atlantic

6.1 Introduction to Ida in Northeast/MidAtlantic

After making landfall in Louisiana on August 29th, Hurricane Ida moved towards the east coast and the Northeast corridor. Table 6.1 shows a timeline of the storm from formation to impacts on the east coast of the US. The storm weakened from a Hurricane following landfall in Louisiana. As it progressed towards the I-95 corridor in the eastern US, the storm interacted with a frontal system and became a post-tropical cyclone. From the early morning through late evening on September 1, Ida produced hours of torrential rainfall in the PA/NY/NJ region. Preliminary statistics report that 22 people unfortunately lost their lives due to the storm in this region (National Weather Service Philadelphia/Mt. Holly, 2021). This chapter will summarize some of the key aspects and impacts that caused billions of dollars in estimated damages. Focus will be on the Philadelphia and New York City regions.

Table 6.1 Key Dates of Hurricane Ida

Date	Event
August 26	Ida forms
August 26	US HU Watches
August 27	Upgraded to Hurricane
August 28-29	Rapid Intensification
August 29	Louisiana Rainfall
August 29	Ida moves inland
August 30	Weakening
August 31- September 2	Ongoing rainfall: Ida moves to Mid-Atlantic

6.2 Storm Impact in Philadelphia Region

The Philadelphia area, including suburbs in Southeastern PA, saw significant impacts from torrential rainfall that occurred on September 1 causing flooding and infrastructure damage. Damage to infrastructure in southeastern PA was estimated at $120 million (Rushing, 2021). As shown in Figure 6.1, a large portion of PA-NJ-NY was predicted to receive excessive rainfall leading to flooding, with areas north and west of Philadelphia having a probability of High Risk (greater than 50%). The observed rainfall for a 6-hr period on 9/1/2021, shown in Figure 6.2, was between 7-10 inches in some suburbs north and west of Philadelphia as well as in areas of northern New Jersey. Figure 6.3 shows a similar observed rainfall total for the 24-hr period, with greater totals north of observed totals in Figure 6.3 and a larger area for the 7-10+ inch zone. This rainfall led to a return period of over 200 years in these areas (Figure 6.4). There were seven confirmed tornadoes in the Philadelphia region, with areas in Montgomery County, PA and Gloucester County, NJ receiving the most damage (National Weather Service Philadelphia/Mt. Holly, 2021).

The resulting levels of flooding were historic, as shown in Figure 6.5, where the Vine Street Expressway, a major throughfare through downtown Philadelphia, completely filled with water and remained this way until it could be pumped out several days later. Reports stated that pumping stations along the Vine Street Expressway failed and drains were potentially clogged by tree debris. Flooding was caused by historic flood levels observed in the Schuylkill River. The flood level reached 16.35 feet at a stream gauge in Philadelphia (near the Art Museum), which neared the record of 17.0 feet from 1869 (National Weather Service, 2020). Further upstream severe flooding was observed in Manayunk as shown in Figures 6.6 and 6.7, which show flooding on Main Street and the Green Lane Bridge, respectively. For perspective, Figure 6.7 shows the Green Lane Bridge under normal flow conditions and during flooding caused by Ida. Images across the region were similar. Many popular trails along the river were closed following the event due to damage and excessive debris according to the Philadelphia Parks and Recreation Department.

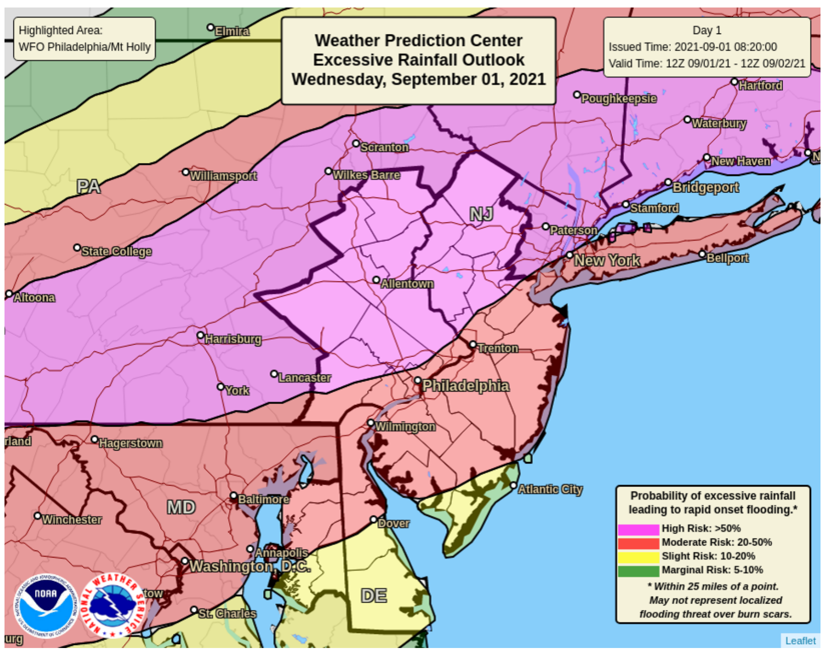

Figure 6.1. Weather Prediction Center Forecast for Probability of Excessive Rainfall Leading to Rapid Flooding in PA-NJ-NY (National Weather Service Philadelphia/Mt. Holly, 2021).

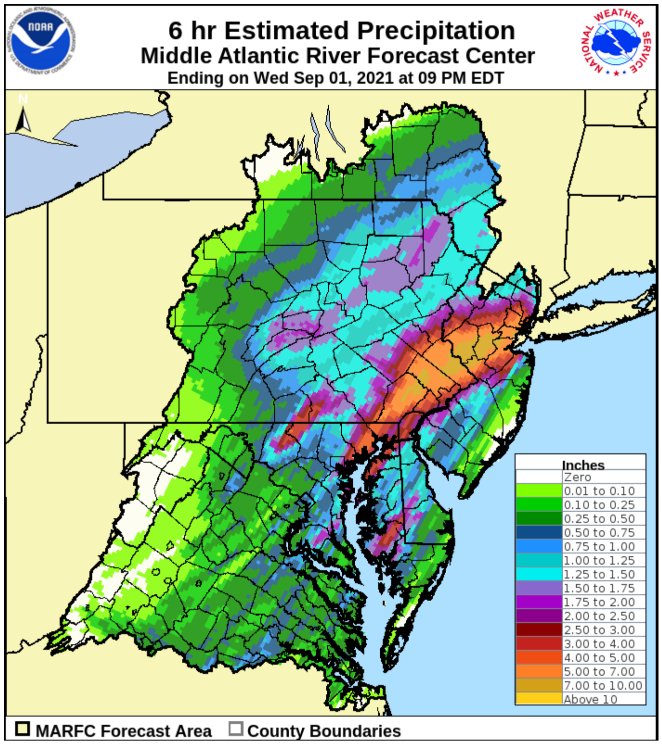

Figure 6.2. Observed 6-hr rainfall totals in PA-NJ-NY (National Weather Service Philadelphia/Mt. Holly, 2021).

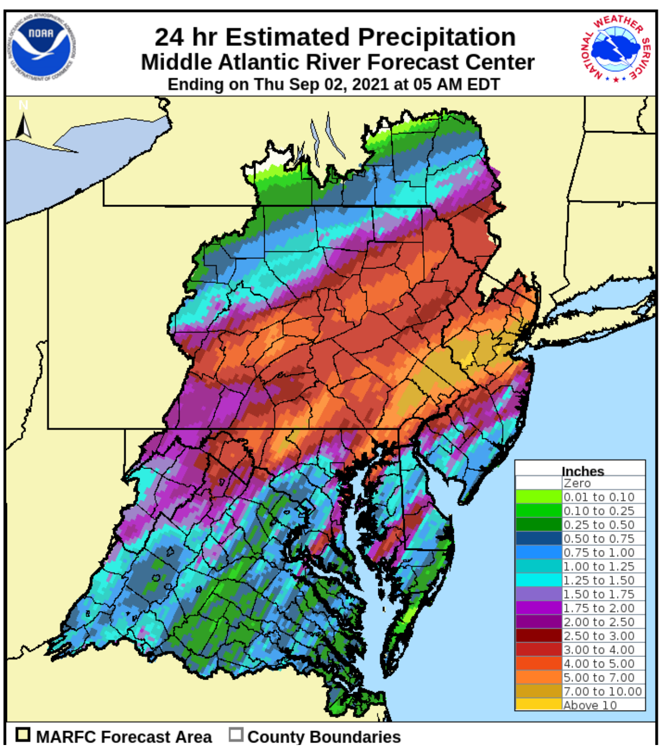

Figure 6.3. Observed 24-hr rainfall totals in PA-NJ-NY (National Weather Service Philadelphia/Mt. Holly, 2021).

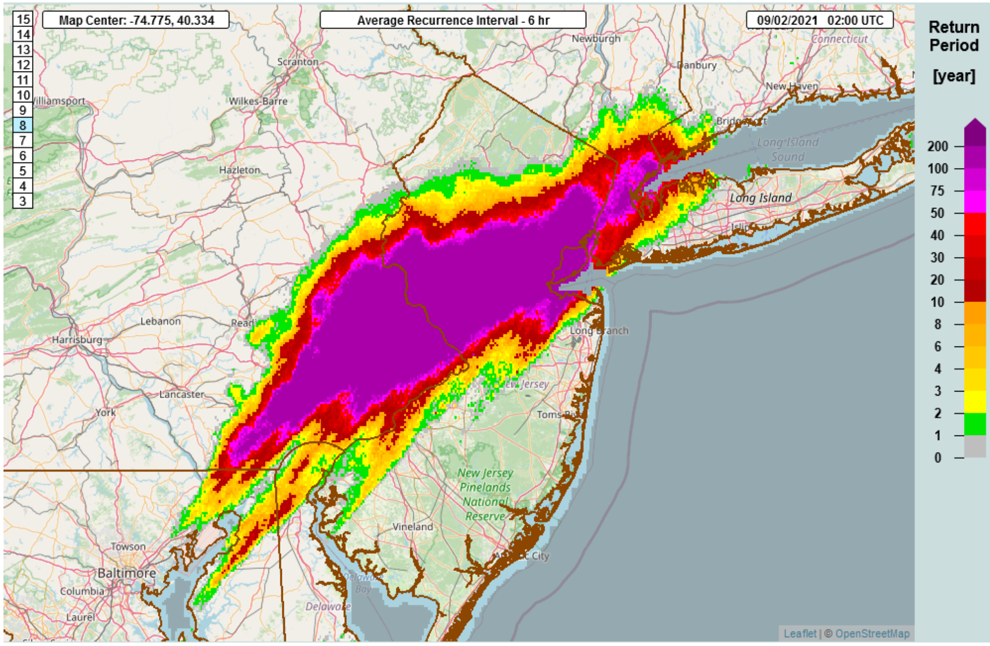

Figure 6.4. Return Period for 6-hr rainfall totals in PA-NJ-NY. Note Return Period at 200 years and above (National Weather Service Philadelphia/Mt. Holly, 2021).

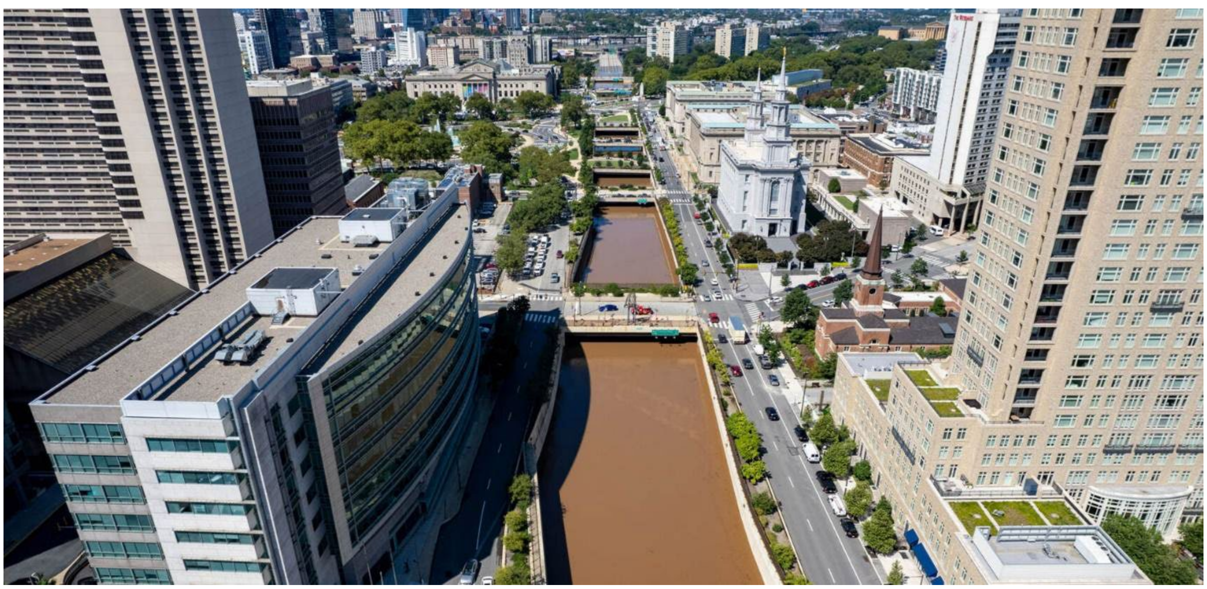

Figure 6.5. Observed Flooding of the Vine Street Expressway in Downtown Philadelphia, PA (Source: Mark Henninger/Imagic Digital).

Figure 6.6. Observed Flooding of the Schuylkill River in Manayunk neighborhood of Philadelphia, PA. Location is upstream of Downtown Philadelphia as shown in Figure 6.5. (Source: AP Photo/Matt Rourke).

Figure 6.7. Green Lane Bridge across the Schuylkill River in Manayunk neighborhood of Philadelphia, PA. Bridge shown under (a) normal conditions (Source: Historic Bridges of Philadelphia) (b) flood conditions during Ida (Source: Manayunk Council).

6.3 Stream Gauge Data

To further investigate the level of flooding in the southeastern PA region, stream gauge data was compiled for select locations in the region. As shown in Figure 6.8, flow levels reached 10 m^3/s per km^2 in the Philadelphia suburbs and northern New Jersey regions as the storm moved eastward. Figure 6.9 displays a map of stream gauges for a few rivers and creeks in southeastern PA. Data for stream level during the storm is shown in Figure 6.10 for: (a) Brandywine Creek at Chadds Ford; (b) West Brandywine Creek at Coatesville; (c) East Branch Brandywine Creek below Downingtown; (d) Neshaminy Creek near Langhorne; (e) East Branch Perkiomen Creek at

Shwenksville; and (f) Perkiomen Creek at Graterford. The stream levels show that many creeks (e.g., Brandywine Creek, East Branch Brandywine Creek, Perkiomen Creek) reached record levels during the storm, while others (i.e., Neshaminy Creek) reached near record level. One creek, the West Branch Brandywine Creek at Coatesville) observed only moderate flood level. This data is only a subset of the many stream gauges in the area and is meant to show that there were a variety of flood levels observed in different creeks, but most were near or above record flood levels.

The Schuylkill River, which flows through the city of Philadelphia, was examined at three locations: Berne, Norristown, and Philadelphia as depicted in Figure 6.11. The upstream location of Berne reached moderate levels of flooding. Moving downstream the Norristown stream gauge recorded a record level of 26.85 feet, approximately 15 feet above the flood stage and 18 feet above the stream level before the storm. Further downstream in Philadelphia a level of 16.35 ft was recorded, narrowly missing the record flood level.

An additional gauge for the Delaware River (Figure 6.12), which is that largest river in the region and separates PA from NJ, was examined and showed only minor levels of flooding.

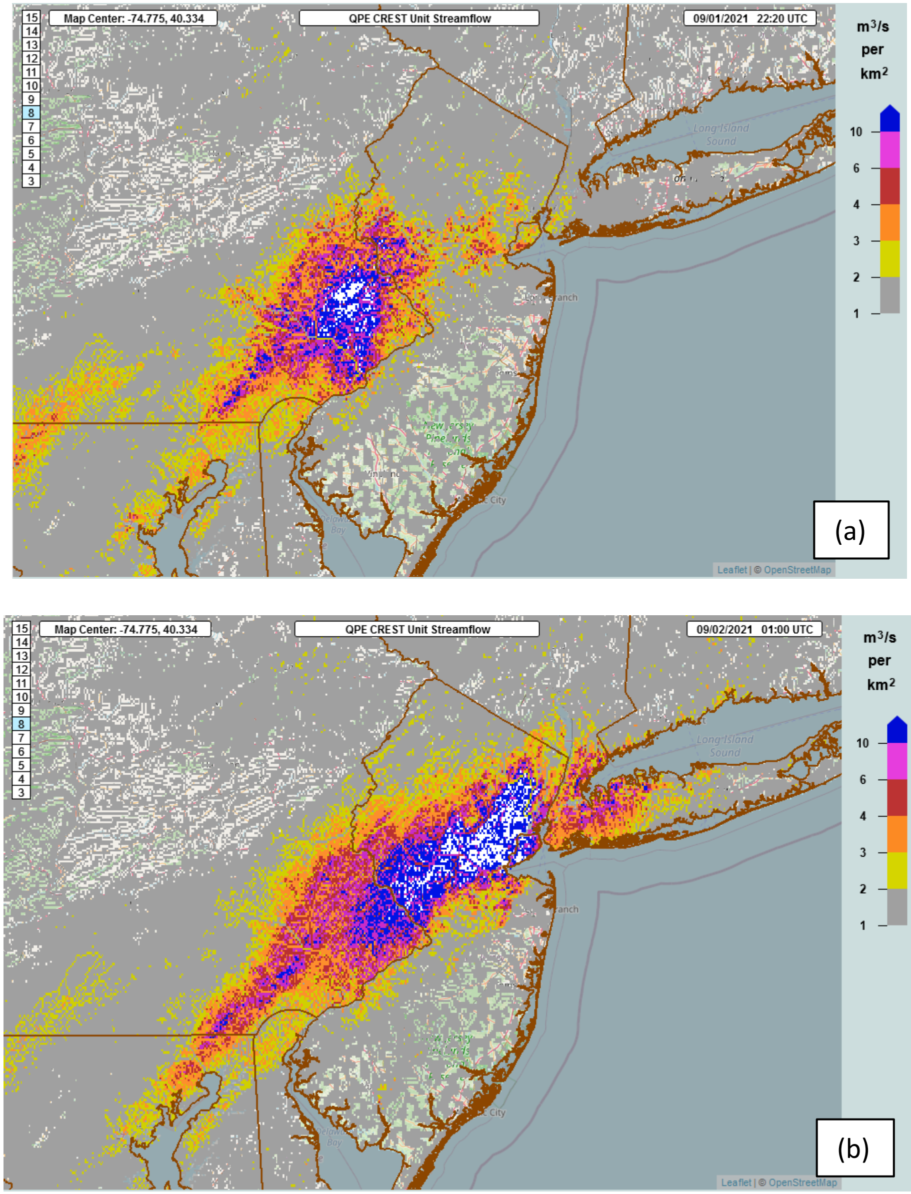

Figure 6.8. Stream Gauge information for PA-NJ-NY for (a) 9/1/2021 at 22:50 UTC and (b) 9/2/2021 at 01:00 UTC (National Weather Service Philadelphia/Mt. Holly, 2021).

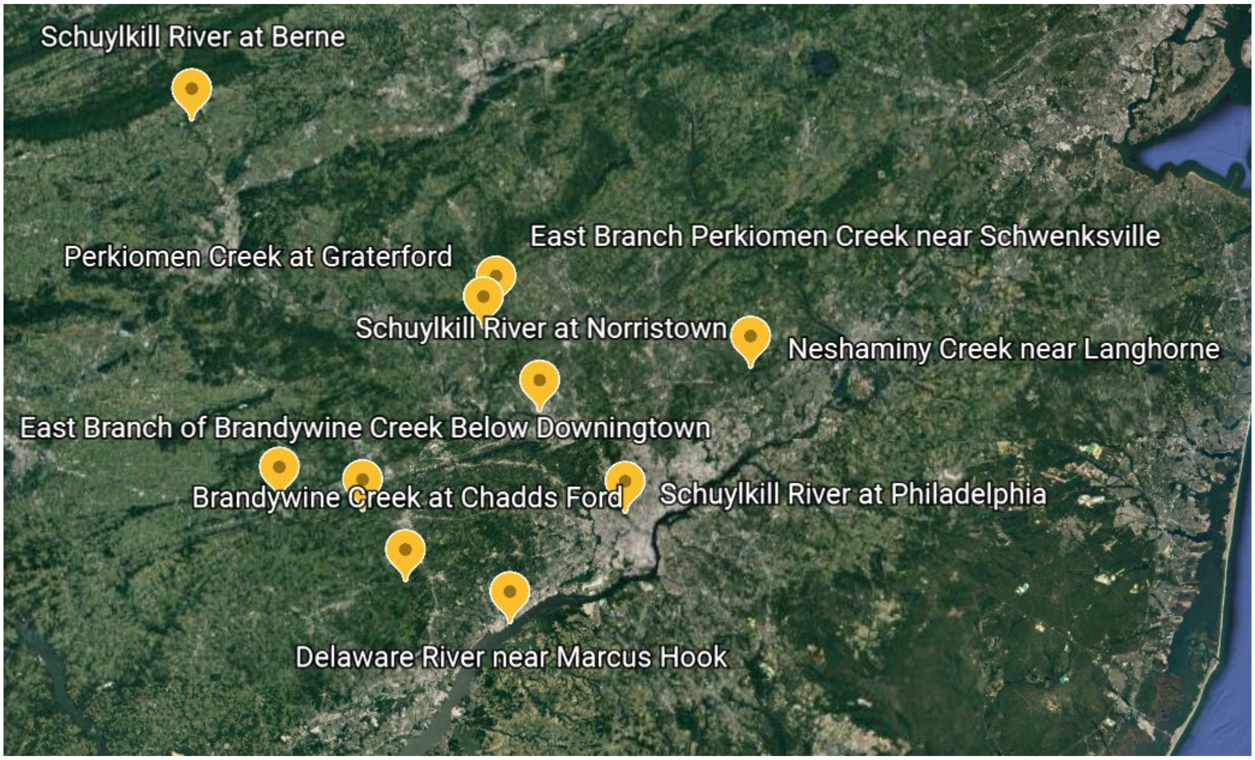

Figure 6.9. Locations of Select Stream Gauges throughout Southeastern PA.

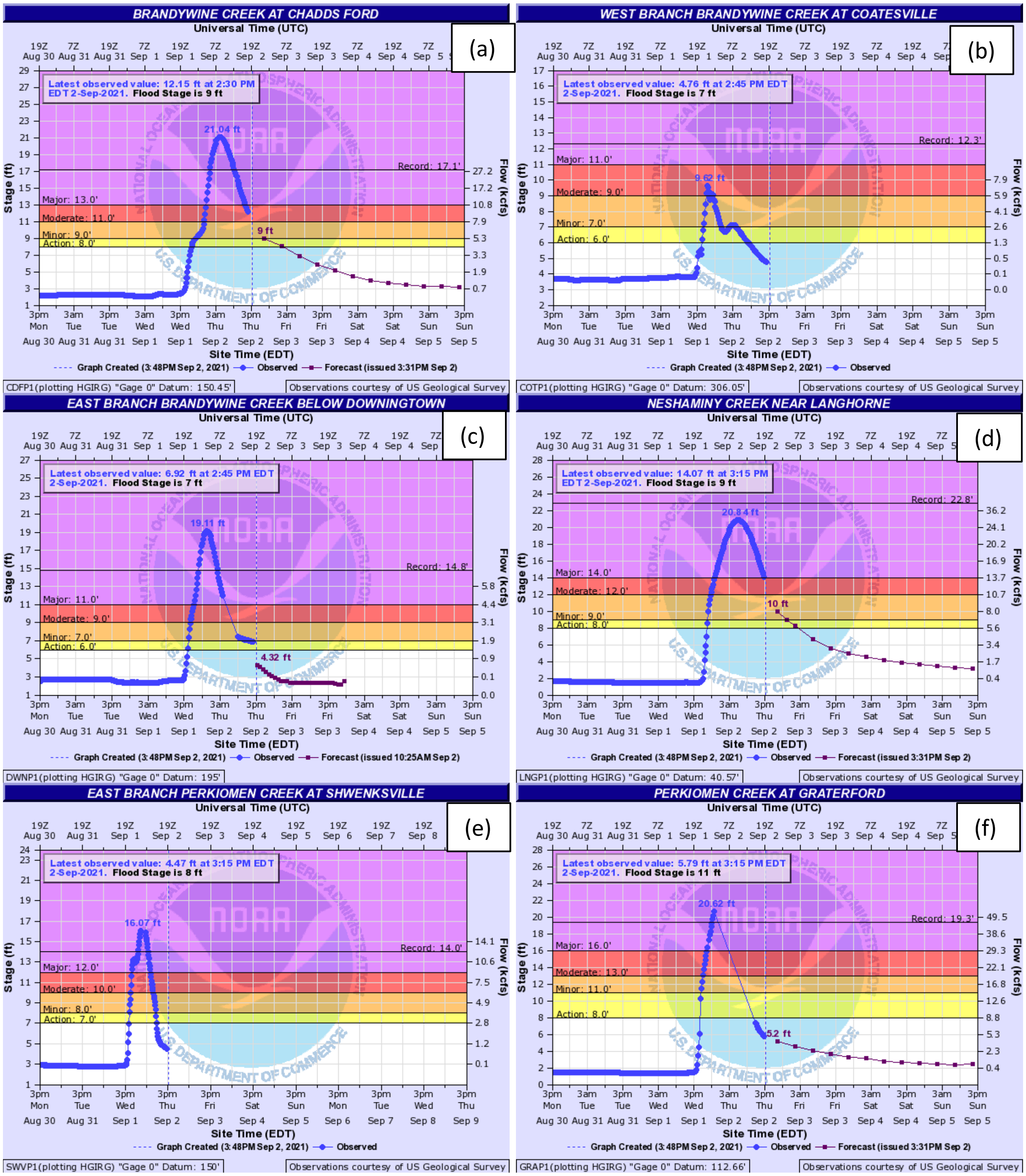

Figure 6.10. Stream Gauges corresponding to those shown in Figure 6.6 for (a) Brandywine Creek at Chadds Ford; (b) West Brandywine Creek at Coatesville; (c) East Branch Brandywine Creek below Downingtown; (d) Neshmaniny Creek near Langhorne; (e) East Branch Perkiomen Creek at Shwenksville; and (f) Perkiomen Creek at Graterford (National Weather Service Philadelphia/Mt. Holly, 2021).

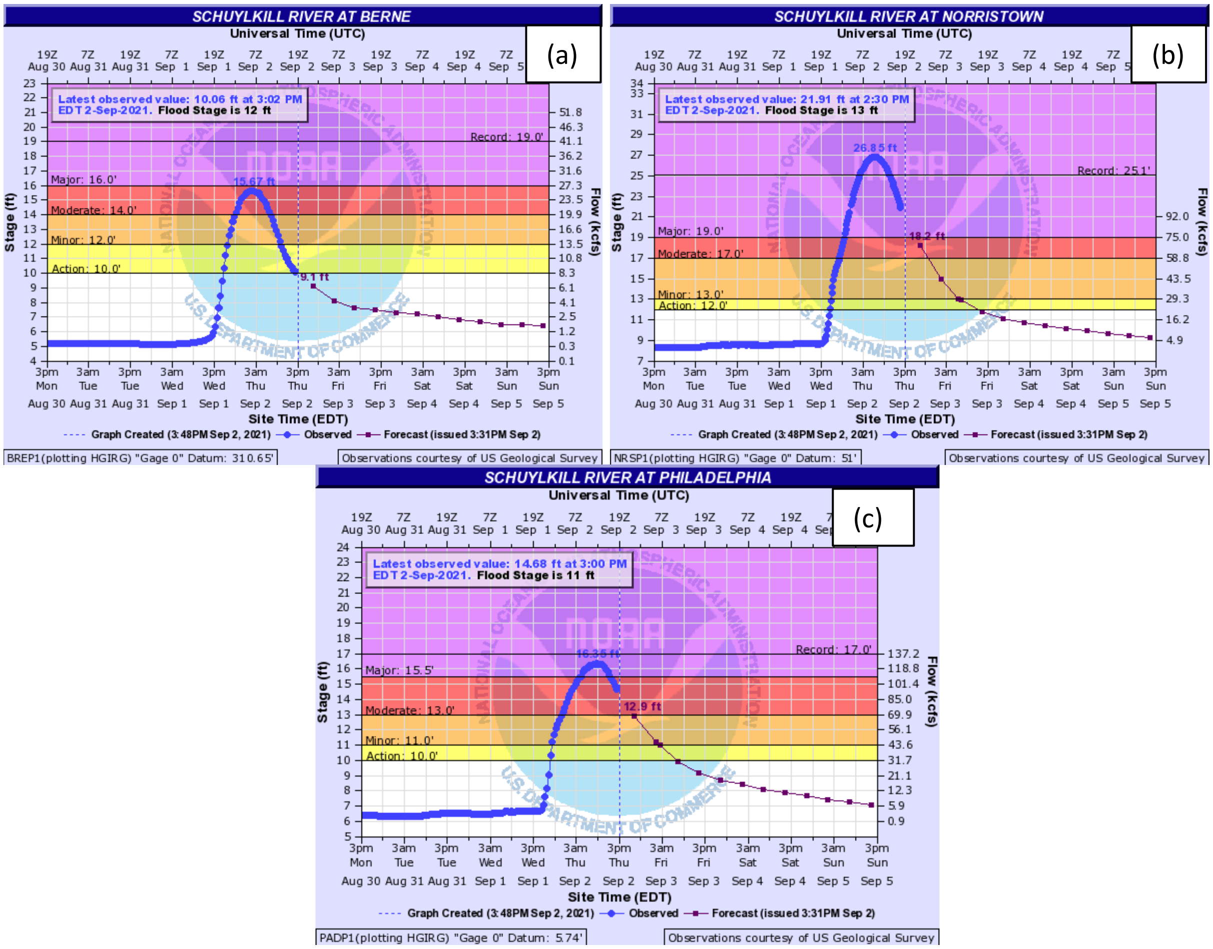

Figure 6.11. Stream Gauges corresponding to those shown for the Schuylkill River as it flows from Upstream of Philadelphia ([a]Berne to [b] Norristown to [c] Philadelphia) (National Weather Service Philadelphia/Mt. Holly, 2021).

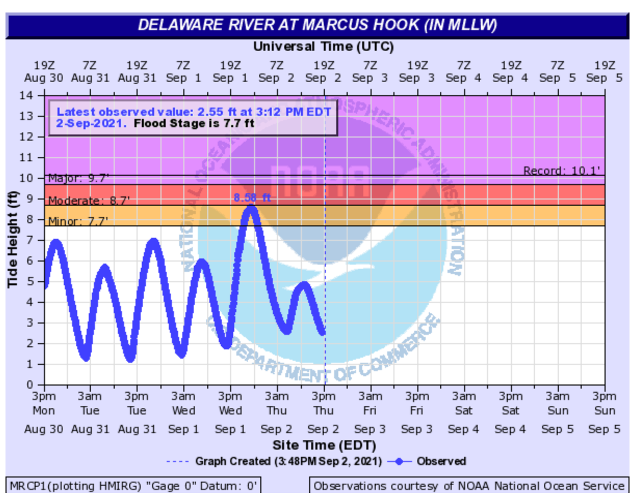

Figure 6.12. Stream Gauge for Delaware River at Marcus Hook (National Weather Service Philadelphia/Mt. Holly, 2021).

6.4 Damage to Infrastructure

Significant damage to infrastructure was observed throughout Southeastern PA due to the historic levels of flooding. Reports from PennDOT commonly cited bridge scour, bridge overtopping, and road washout/instability. Figure 6.13 provides an overview of the damage throughout the suburbs surrounding Philadelphia. Damage in Philadelphia was observed primarily along the Schuylkill River as depicted in Figures 6.5-6.7. The focus of this section is on damage to infrastructure, primarily vehicular bridges, in the region. Some of these bridges are still closed as of December 2021. Table 6.2 summarizes the locations shown in Figure 6.13 and provides information for type of infrastructure and any observed damage. A few locations will be highlighted that were visited following the storm to evaluate damage. A common observation at many of the bridge locations was that relatively shallow creeks under normal flow conditions caused extensive damage during flood conditions. It should be noted that there were other locations of infrastructure damage and this is not a comprehensive list for the region.

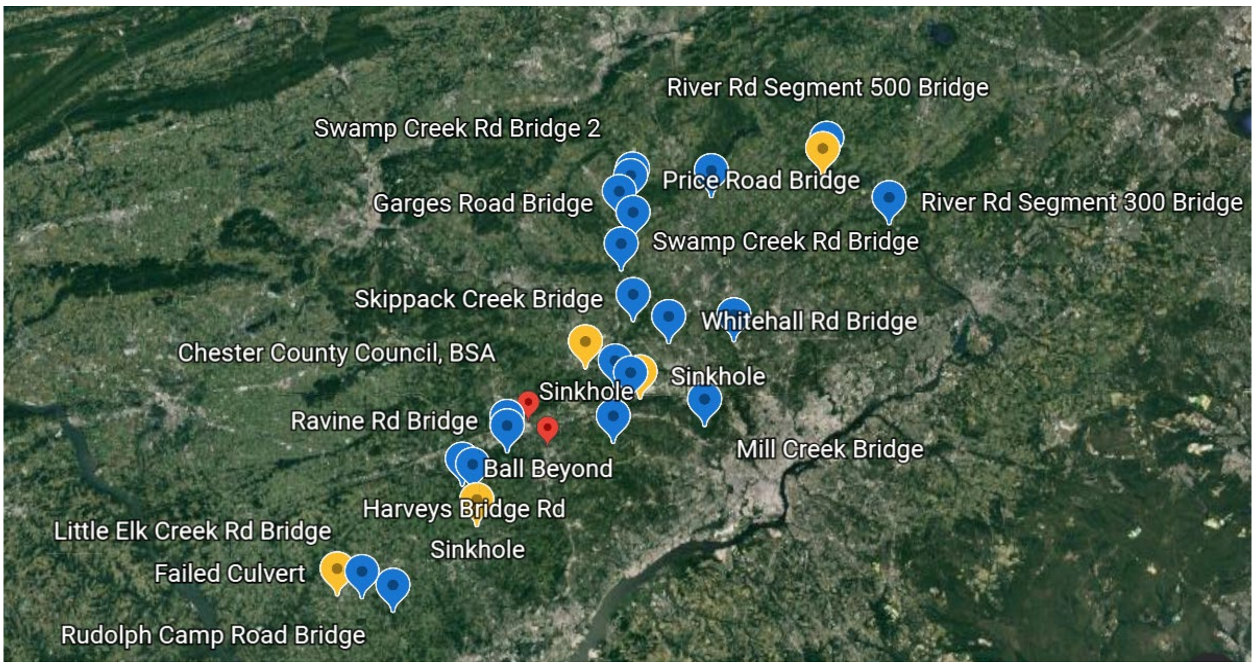

Figure 6.13. Infrastructure Damage Locations throughout Southeastern PA. Blue markers show damage to bridges, while yellow markers show damage to other types of infrastructure.

Table 6.2. Locations of Infrastructure Damage throughout Southeastern PA

Location	Latitude	Longitude	Altitude (m)	Type of Infrastructure	River	Comments
Rudolph Camp Road Bridge	39.746	-75.882	70.9	Bridge	Big Elk Creek	Covered Bridge
Little Elk Creek Bridge	39.766	-75.942	123.7	Bridge	Little Elk Creek	
Failed Culvert	39.770	-75.990	171.9	Culvert		
Street Rd Sinkhole	39.874	-75.722	112.4	Sinkhole		
Embreeville Rd Bridge	39.927	-75.730	66.9	Bridge	West Branch Brandywine Creek	Closed in both directions due to collapsing
Harveys Bridge Rd	39.935	-75.754	90.9	Bridge	West Branch Brandywine Creek	Washed out approaches
Harmony Hill Rd Bridge	39.984	-75.665	69.8	Bridge	Valley Creek	
Ravine Rd Bridge	39.999	-75.664	78.3	Bridge	Valley Creek	
Grubbs Mill Rd Bridge	39.999	-75.460	91.8	Bridge	Crum Creek	
Mill Creek Bridge	40.024	-75.285	56.6	Bridge	Mill Creek	
Pugh Rd Bridge	40.064	-75.427	122.9	Bridge	Trout Creek	Culvert Collapse
Upper Weadley Rd Sinkhole	40.063	-75.408	160.8	Sinkhole		
Wilson Rd Bridge	40.082	-75.456	64.4	Bridge	Valley Creek	Abutment Damage
Sinkhole	40.111	-75.514	39.4	Sinkhole	Pickering Creek Area	5 ft sinkhole
Whitehall Rd Bridge	40.147	-75.353	69.2	Bridge	Kepner Creek	Severe undermining
Skippack Creek Bridge	40.180	-75.422	39.0	Bridge	Skippack Creek	
Garges Rd Bridge	40.255	75.445	41.1	Bridge	East Branch Perkiomen Creek	
Old Sumneytown Pike Bridge	40.304	-75.421	70.9	Bridge	East Branch Perkiomen Creek	
Swamp Creek Rd Bridge	40.335	-75.450	0.0	Bridge	Unami Creek	
Price Rd Bridge	40.358	-75.426	111.9	Bridge	Unami Creek	
Swamp Creek Rd Bridge 2	40.368	-75.423	101.2	Bridge	Unami Creek	
Callowhill Rd Bridge	40.365	-75.271	0.0	Bridge	-	
Fleecy Dale Rd Soldier Pile Wall	40.398	-75.055	0.0	Soldier Pile Wall	Paunnacussing Creek	Erosion at toe and behind wall
River Rd Segment 500 Bridge	40.413	-75.047	0.0	Bridge	None	Rockslide above road in stream - overtopped bridge
River Rd Segment 300 Bridge	40.324	-74.928	0.0	Bridge	-	Scour led to undermining. 2' of scour occurred

Locations that were visited following the storm on September 20, 2021 included:

- Whitehall Road Bridge
- Wilson Rd Bridge
- Pugh Rd Bridge
- Wissahickon Trails Bridge

Whitehall Rd Bridge is a stone masonry deck arch bridge that is 41 feet long, 35 feet wide. It carries approximately 12, 729 vehicles per day. There was significant scour and undermining of bridge foundations that led to closure of the bridge. The bridge is still closed as of December 2021. There were repairs completed to washout of the downstream approach when the bridge was visited on 9/20/21. Access to the bridge foundations was difficult, so photographs were not taken. Figure 6.14 provides a view of the Bridge prior to Ida. The Wilson Rd Bridge is located in Valley Forge Park and is shown in Figures 6.15 and 6.16. The bridge suffered extensive damage to the abutment walls and was closed following the storm. The bridge was overtopped by flood waters from Valley Creek. Flooding caused erosion of abutment approach soils of several feet. The stone masonry abutment walls were washed away. Several other locations throughout Valley Forge Park were damaged, including Knox Covered Bridge, Valley Creek Trail, and Washington's Headquarters.

The Pugh Rd Bridge is located in Wayne, PA along Trout Creek and is shown in Figure 6.17. There was erosion of soil downstream of the bridge and culvert damage.

The Wissahickon Trails Bridge is a pedestrian bridge that is located within Wisshickon Trails (Ambler, PA). Extensive scour was observed for concrete foundations for the bridge abutment as shown in Figures 6.18 and 6.19.

Locations that were visited on October 4, 2021 included several sites in the northern suburbs of Philadelphia along the Delaware River, where significant damage to infrastructure was observed. These locations included:

- River Rd Segment 300 Bridge
- River Rd Segment 500 Bridge
- Fleecy Dale Rd Soldier Pile Wall

The River Rd Segment 300 Bridge is located near Washington Crossing, PA and is shown in Figures 20 -22. The stone arch bridge was built in 1870 and is 12 ft long and 28 ft wide. The bridge carries approximately 6,370 vehicles per day. Due to flooding in the small creek that runs beneath the bridge, significant scour was observed. Scour lowered the streambed elevation by 2 ft as shown in Figure 20, and 97% of the abutment length was undermined due to the scour.

The River Rd Segment 500 Bridge is located in Lumberville, PA and is shown in Figures 6.23 – 6.28. The bridge is adjacent to the Delaware River and has a steep rock slope above the road. A rock slide filled the upstream channel and overtopped the bridge, leading to roadway failure and washout of the bridge abutment.

The Fleecy Dale Rd Soldier Pile Wall is located near the River Rd Segment 500 Bridge in Lumberville, PA and is shown in Figures 6.29 – 6.39. There was significant erosion on both sides of the soldier pile wall. Similar to the Segment 500 Bridge, there was a steep slope above the roadway, leading to potential runoff at high velocities and volumes. There was significant washout of the roadway and behind the wall with settlement of the roadway in a few locations. The guide rail was no longer supported for long distances along the wall. Figure 6.39 shows some HDPE drainage pipes and geotextiles that were utilized in wall construction. Figures 6.40 and 6.41 show slope/roadway washout in several locations along Fleecy Dale Rd, not far from the soldier pile wall.

Additional photographs of damage for Swamp Creek Rd and Price Rd Bridges were taken by David Ebling. Figure 6.42 and 6.43 show the Swamp Creek Rd Bridge, which suffered significant washout of the approach roadway. Figure 6.43 shows that there was a geosynthetic beneath the roadway. Figures 6.44 – 6.46 shows the Price Rd Bridge which was damaged and suffered a loss of some of the stone arch bridge and the parapet wall. Figure 6.47 shows the Swamp Creek Bridge 2 which had damage to the parapet wall.

Figure 6.14. Whitehall Rd Bridge prior to Ida Damage (Photo by Raymond Klein).

Figure 6.15. Wilson Rd Bridge Abutment and Wingwall Damage Upstream Side (40.082212, -75.456375).

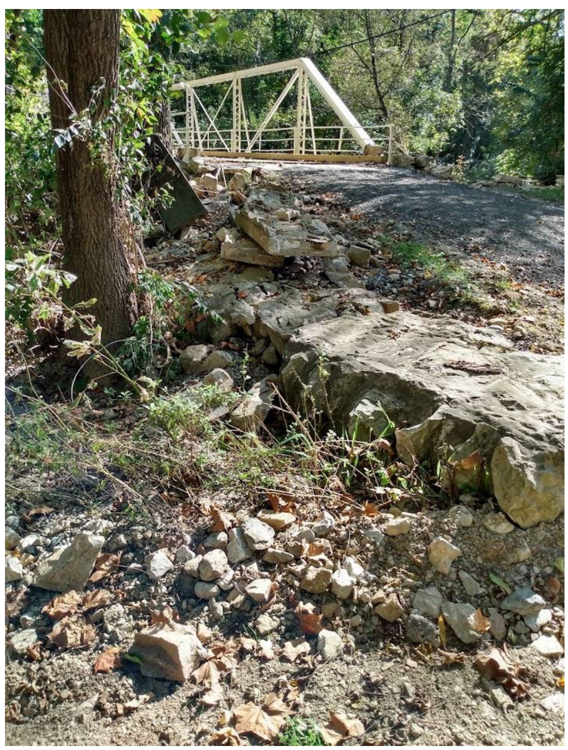

Figure 6.16. Wilson Rd Bridge Abutment and Wingwall Damage Downstream Side (40.082212, -75.456375).

Figure 6.17. Pugh Rd Bridge Damage view from Downstream (40.063619, -75.427464).

Figure 6.18. Scour at Wissahickon Trails Bridge Abutment (40.150445, -75.228859).

Figure 6.19. Scour at Wissahickon Trails Bridge Foundation for Stairs (40.150445, -75.228859).

Figure 6.20. River Rd Segment 300 Bridge Scour and Undermining view from upstream (40.323972, -74.9275).

Figure 6.21. River Rd Segment 300 Bridge Scour and Undermining view from through bridge (40.323972, -74.9275).

Figure 6.22. River Rd Segment 300 Bridge Scour and Undermining view from downstream (40.323972, -74.9275).

Figure 6.23. River Rd Segment 500 Bridge Washout and Slope Instability (40.413111, -75.047389).

Figure 6.24. River Rd Segment 500 Bridge Roadway View with rock slide materials (40.413111, -75.047389).

Figure 6.25. River Rd Segment 500 Bridge View above Roadway of Rock Slide (40.413111, -75.047389).

Figure 6.26. River Rd Segment 500 Bridge Washout and Slope Instability with view of Delaware River in Background (40.413111, -75.047389).

Figure 6.27. River Rd Segment 500 Bridge Washout and Slope Instability on Downstream side (40.413111, -75.047389).

Figure 6.28. Alternative View of River Rd Segment 500 Bridge Washout and Slope Instability on Downstream side (40.413111, -75.047389).

Figure 6.29. River Rd Segment 500 Bridge Abutment Damage (40.413111, -75.047389).

Figure 6.30. Fleecy Dale Rd Erosion behind Soldier Pile Wall (40.397806, -75.05525).

Figure 6.31. Alternative View of Fleecy Dale Rd Erosion behind Soldier Pile Wall (40.397806, -75.05525).

Figure 6.32. Location of Drainage Holes in Wall (40.397806, -75.05525).

Figure 6.33. View of Paunnacussing Creek with Soldier Pile Wall (40.397806, -75.05525).

Figure 6.34. View of Streambank Erosion on Bank Opposite of Solider Pile Wall (40.397806, -75.05525).

Figure 6.35. Roadway Erosion Behind Wall. Note steep slope above the roadway (40.397806, -75.05525).

Figure 6.36. Erosion Behind Solider Pile Wall with Lost Support of Guide Rail (40.397806, -75.05525).

Figure 6.37. Erosion and Washout leading to Lost Support of Guide Rail (40.397806, -75.05525).

Figure 6.38. View of Soldier Pile Wall looking Downstream (40.397806, -75.05525).

Figure 6.39. View of Soldier Pile Wall looking Upstream. Note the discoloration at the bottom of the wall showing potential scour depth as well exposed drainage pipes (40.397806, -75.05525).

Figure 6.40. Roadway Washout Upstream of Soldier Pile Wall on Fleecy Dale Rd (40.396747, -75.056316).

Figure 6.41. Roadway Washout and Slope Instability Upstream of Solder Pile Wall on Fleecy Dale Rd. Note exposed rock above roadway (40.393912, -75.057270).

Figure 6.42. Swamp Creek Rd Bridge Roadway Washout (40.334567, -75.449707).

Figure 6.43. Swamp Creek Rd Bridge Asphalt Pavement Washout and Exposed Geosynthetic (40.334567, -75.449707).

Figure 6.44. Price Rd Bridge Damage (40.357866, -75.426465).

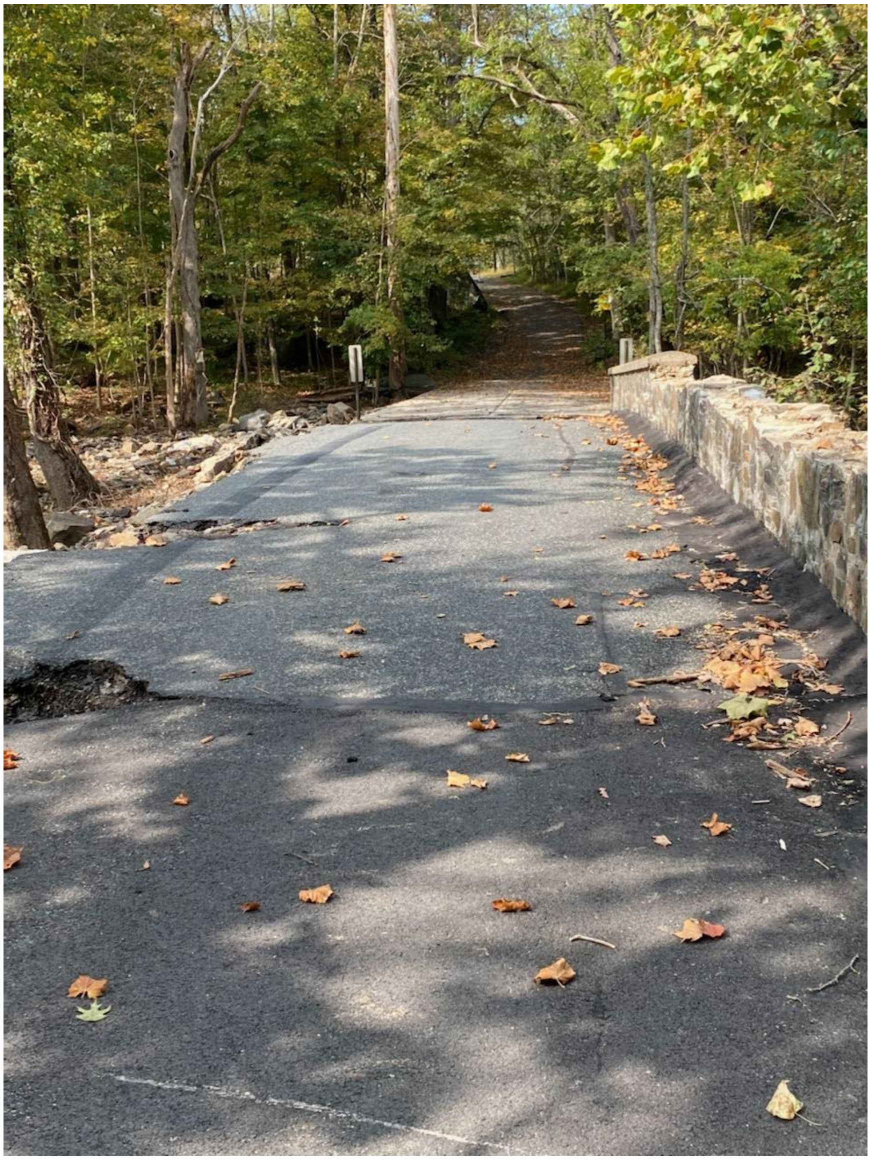

Figure 6.45. Price Rd Bridge View of Roadway and Damage (40.357866, -75.426465).

Figure 6.46. Price Rd Bridge View of Section of Bridge Wall Carried Downstream (40.357866, -75.426465).

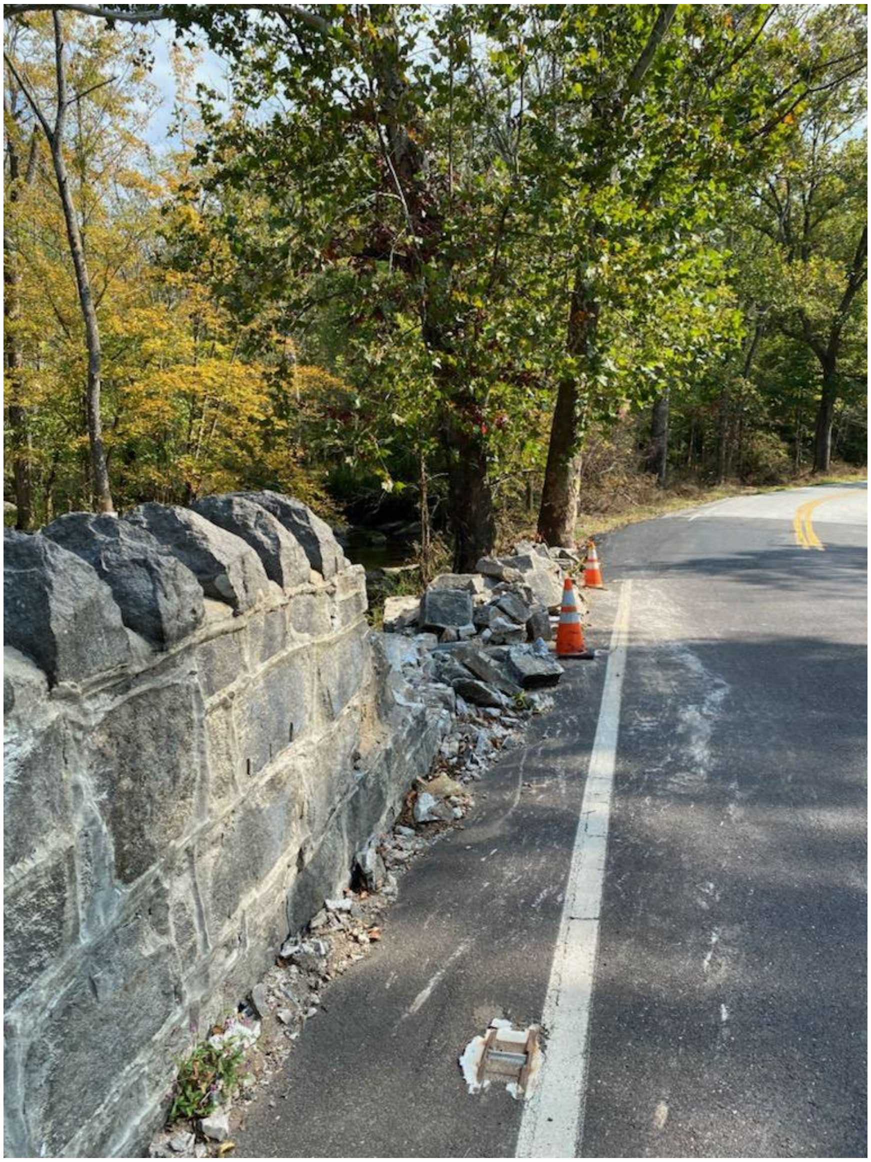

Figure 6.47. Swamp Creek Rd Bridge 2 Damage to Parapet Wall (40.367853, -75.422698).

6.5 Storm Impact in New York City Region

An unusual high-risk area for extreme rainfall and flash flooding covered much of the Northeast U.S. on Wednesday (Figure 6.48) as the remnants of Hurricane Ida joined forces with a frontal zone. Ida was a post tropical cyclone as of 11 a.m. EDT Wednesday, September 1 (NYC, 2021).

It can be mentioned that many parts of the Northeast were already soaked by tropical cyclones Fred and Henri over the last several weeks, heightening the risk of flash flooding with Ida. In New York City, Central Park recorded 24.03 inches of rain from June through August, making it the city's second wettest meteorological summer in 153 years of recordkeeping; the 9.06 inches from August 16 to 30 was Central Park's second-largest total on record for the last half of August.

On the nights of Wednesday, September 1, 2021, Hurricane Ida reached the city being technically downgraded to a 'post tropical cyclone'. Though Ida originated thousands of miles away, the 'remnants' of storm was so ferocious and dangerous for the New York City. The National Weather Service (NWS) declared a flash flood emergency for the first time ever in the history of New York City (Table 6.3). The storm shattered the record single hour rainfall in NYC, set only two weeks prior by another extreme storm Hurricane Henri. For many New Yorkers, it remined them of the 'once-in-a-lifetime' storm, Hurricane Sandy which devastated the entire Northeast less than a decade ago.

When Hurricane Ida was anticipated to strike the Gulf Coast, New York City Emergency Management (NYCEM) began tracking it on Thursday, August 26. NYCEM's Watch Command consulted the NWS multiple times per day to monitor the storm.

Beginning September 1, NWS also pushed five Wireless Emergency Alerts (WEA) to all cell phones in NYC in both English and Spanish. Table 6.3 details these warnings.

Table 6.3. Timing of the Wireless Emergency Alerts (NYC, 2021)

9/1/2021	7:34 PM	WEA	Flash Flood Warning (Considerable) for all of SI
9/1/2021	8:41 PM	WEA	Flash Flood Emergency (Catastrophic) Warning for all of SI
9/1/2021	8:59 PM	WEA	Flash Flood Warning (Considerable) for all of BK, BX, MN, QN
9/1/2021	9:06 PM	WEA	Tornado Warning for the BX & Northern MN
9/1/2021	9:28 PM	WEA	Flash Flood Emergency Warning (Catastrophic) for all of BK, BX, MN, QN

SI: Staten Island, BX: Bronx, QN: Queens, MN: Manhattan, BK: Brooklyn

6.6 NYC Experience

NYC experienced record flooding due to the remnants of Ida which took lives of 13 individuals. (Bloomberg, 2021) Flooding extended to the major roadways and into the public transit system including subway. Locations of significant flooding are shown in Figure 6.48, and observed damage are shown in Figures 6.49-6.55. As of September 16, NYC received more than 4,000 reports of single-family house damages from Federal Emergency Management Agency (FEMA) and estimated the initial damages to New York City to be approximately $38 million. This is preliminary damage without taking into the consideration the citywide infrastructure damage. The capacity of the sewer system of NYC is 1.5 to 2 inches per hour whereas the peak was recorded as 3.15 inches/hour during Ida induced rainfall. As such, heavy rainfall accumulated in the streets as it topped the sewer capacity causing major flooding. The city experienced more rainfall than it had more than a week earlier during Hurricane Henri. Henri delivered 7 inches of rainfall more evenly distributed over a period of hours. Most residential damage in single-family homes (1-4 units) is from flooding in sub or at-grade space (e.g., basements, ground floors). The damaged properties belong to mostly lower-income and immigrant communities concentrated in Queens, Brooklyn, the Bronx, and Staten Island (NYC, 2021). Impacts of Ida were notably felt inland rather than in the coastal areas (which happened during Hurricane Sandy). As such, the flooding was caused by rainfall rather than storm surge. During Hurricane Sandy, significant infrastructure damage was reported whereas during Ida, only flooding events were recorded. New York State Department of Transportation (NYSDOT) reported only one 20 ft. long drilled shaft failure in Yonkers, NY.

Broken rainfall records, devastation across communities, and tragic loss of life – all these impacts are reminders that our region and nation are confronting a new reality with extreme weather, both in scale and frequency. Ida has underscored the need for collaboration and planning across city and state lines, along with significant aid and resources from the State and Federal government, to prepare for these extreme events and protect the communities.

6.7 Impact on Tri-State Area

The remnants of Ida not only impacted NYC but also the tri-state area (New York, New Jersey, Connecticut). Some locations in the tri-state area experienced similar devastation to that of NYC. Destroyed homes, flooding across highways and roads, and lost lives were reported from these areas. More than 40 death was reported across New York, New Jersey, Pennsylvania, and Connecticut with more than 150,000 homes without power (NYC, 2021). Some examples of the impact included as follows:

- Ida brought 3.24 inches of rainfall in a single hour (8 PM – 9 PM) in Newark, New Jersey shattering the record of one-inch rainfall in an hour back in 2006
- Fish and other wildlife were displaced into the middle of streets in Passaic, New Jersey due to the breach of the Passaic River
- Dozens of homes were destroyed in the southern New Jersey experiencing winds of 150 miles per hour due to an EF-3 tornado emerged from the remnants of Ida

The NWS recorded a total of 3.15 inches (80 mm) of rainfall with a span of just an hour (8:51pm to 9:51pm) on September 1 (National Weather Service New York 2021a). This is the ever highest single hour rainfall event in the history of NYC. Based on the gauge station data of Central Park on September 1, it recorded a total of 7.13 inches (181 mm) rainfall over the 24-hour period of September 1, 2021. This was the fifth highest single day rainfall event recorded over last 150 years.

The rainfall effect was exacerbated by the rainfall experienced by Hurricane Henri two weeks before Hurricane Ida. On August 21, 2021, Henri dumped 1.94 inches (49 mm) of rainfall within an hour (8:00pm-9:00pm) in the Central Park. This was followed by a 4.45 inches (113 mm) rainfall in the following day over a 24-hour period (National Weather Service New York 2021b).

As such, the compound impact of these two extreme rainfall events put extra pressure on the city's drainage system. The soil and the drainage system were already saturated before Ida. The sewer and drainage system of the NYC is designed to manage approximately 1.75 inches of rainfall in an hour.

6.8 Efficacy of the measures taken after Hurricane Sandy

After the historic Hurricane Sandy hit NYC in 2012, billions of dollars were spent to build coastal flood defenses around the city (NYC, 2013). Hurricane Sandy caused major storm surges followed by massive flooding along the coastal areas, the bay, and the rivers in New York City. Some of the initiatives to protect the coast were short term beach nourishment, installing armor stone shoreline protection, raising bulkheads, completing a sea gate project, and installing an integrated flood protection system. The major difference between Sandy and Ida is that the flooding during Sandy was generated by storm surge whereas it was the downpour which caused the Ida flooding. Therefore, these coastal defenses were unable to protect the city from surface water flooding. The intense rainfall during Ida caused flooding in the subway stations, parks, roads, and properties (especially basements) throughout New York. It should be mentioned that, during Hurricane Sandy, NYC streets and subways also experienced intense flooding. Some of the initiatives to protect the tunnels, subways, streets were to include floodgates, raising tunnel entrances, installing watertight barrier, and designing water management in such a way that rainfall soaks into the ground rather flowing into the sewer system. However, none of the taken initiatives was proven effective as the amount of downpour (3.15 inches in an hour) was way beyond the capacity of the sewer and drainage system of the city.

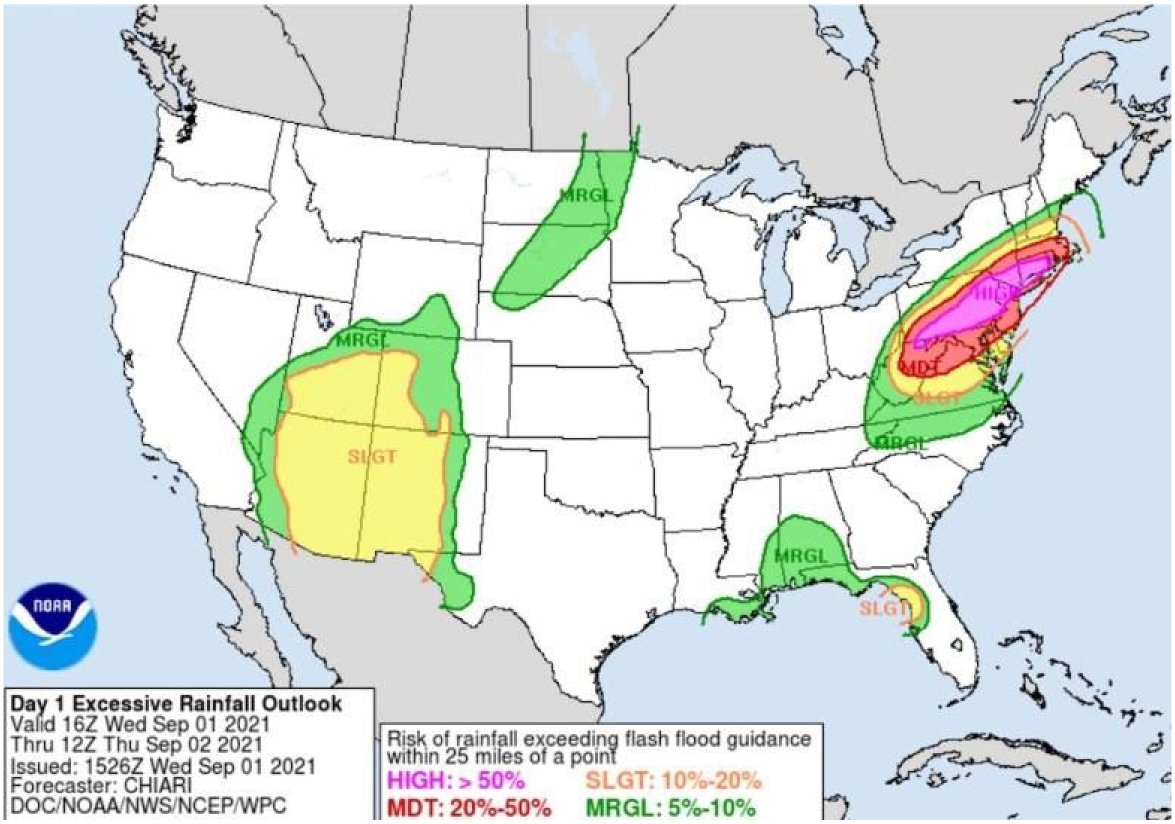

Figure 6.48. A high risk for excessive rainfall leading to flash flooding was in effect for much of the Northeast U.S., including the New York City area, through Thursday morning, September 2, 2021. (Image credit: NOAA/NWS/WPC).

Figure 6.49. Location of severe flooding in New York City (QN= Queens, Sta: Staten Island, BK:Brooklyn, BX: Bronx).

Figure 6.50. Streets flooding due to heavy rainfall in NYC (Image Courtesy: NYC, 2021).

Figure 6.51. NYCEM members visiting affected communities (Image Courtesy: NYC, 2021).

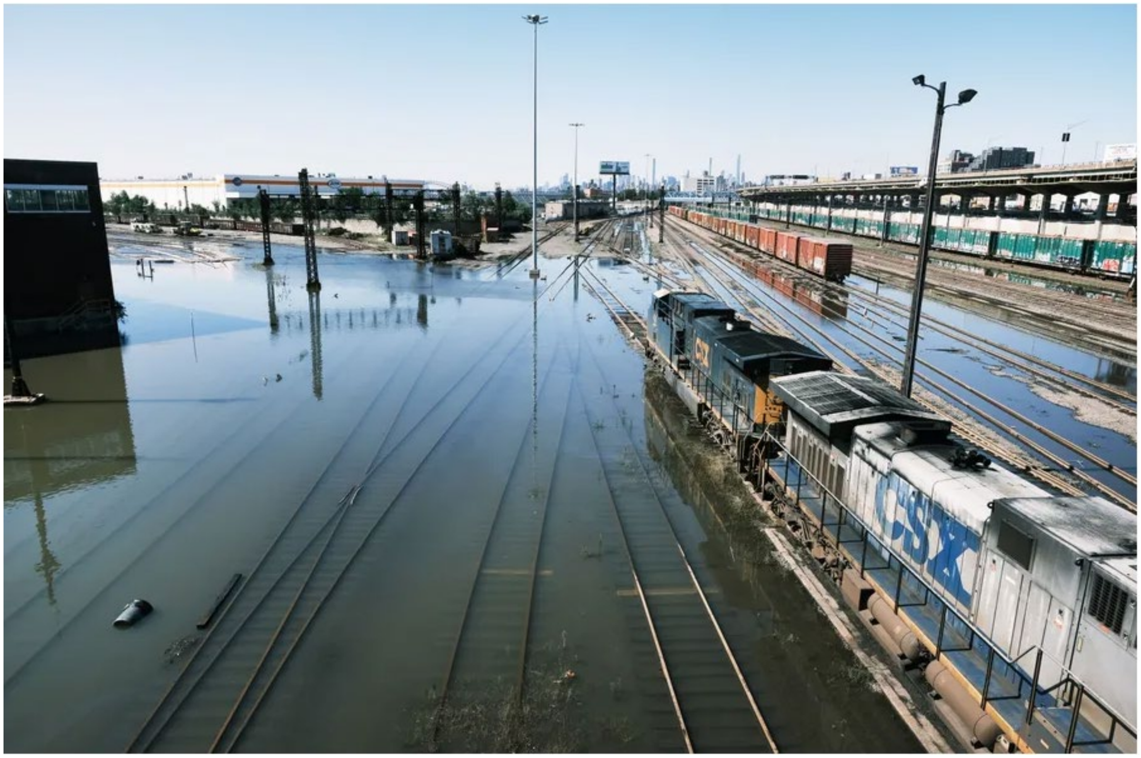

Figure 6.52. Flooded rail track in Bronx, NY (Image Courtesy: NYTimes).

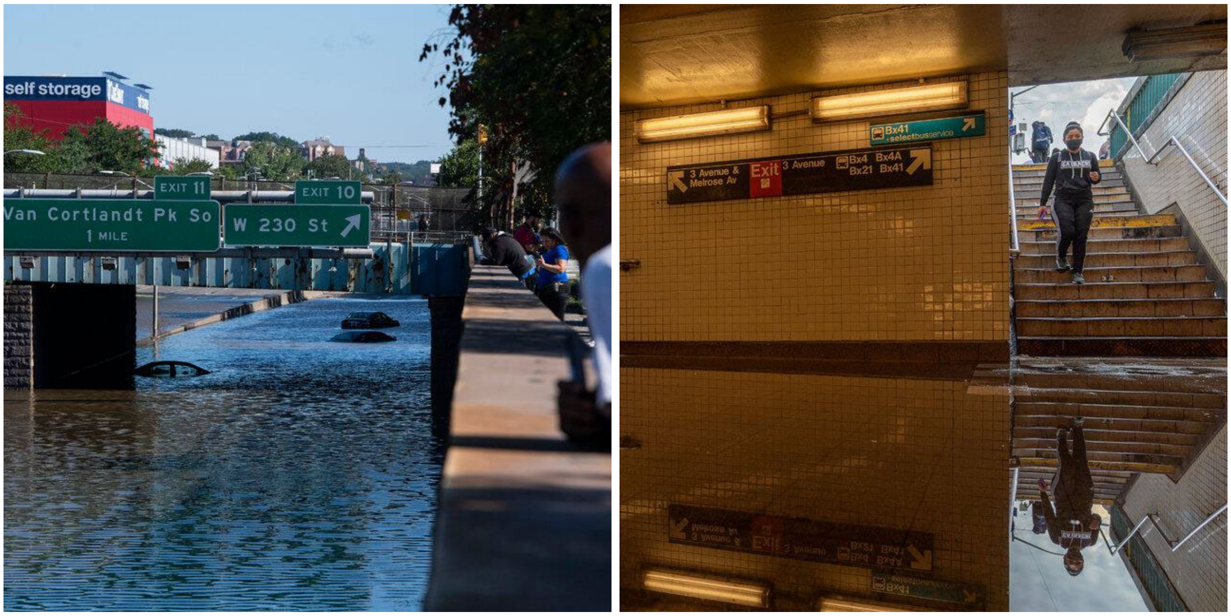

Figure 6.53. Flooded highway (left) and inundated subway (right) in NYC (Image Courtesy: NYTimes).

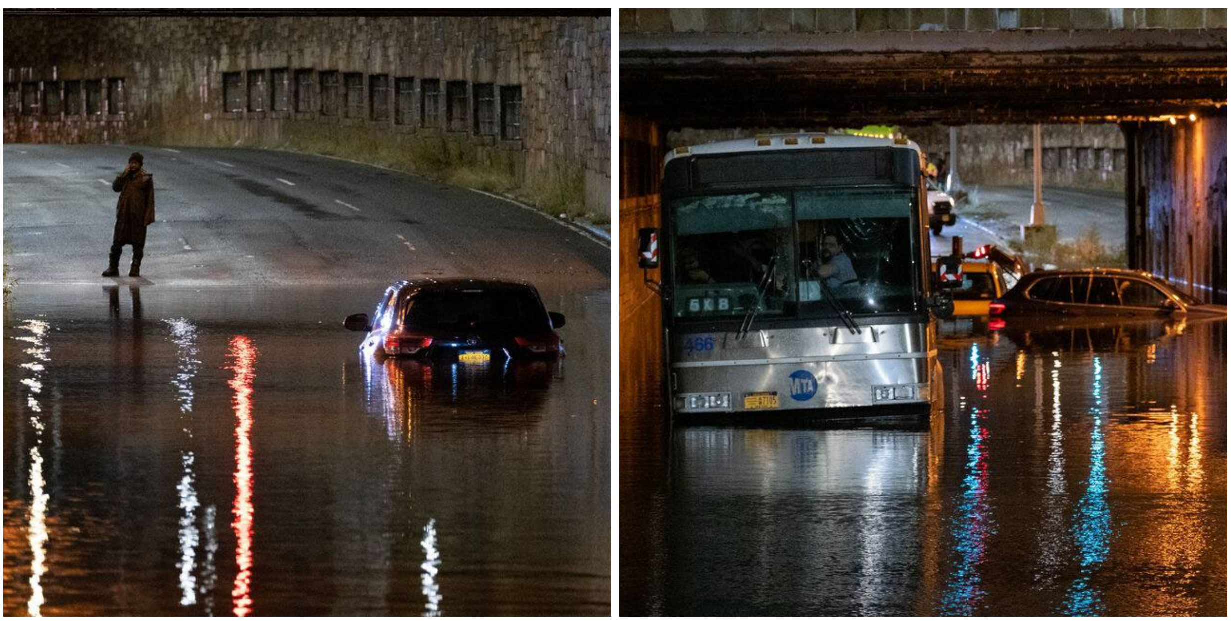

Figure 6.54. Flooded highway with stranded vehicles in NYC (Image Courtesy: Reuters).

Figure 6.55. Debris piled up at street of Queens (Image Courtesy: Reuters).

Figure 6.56. Flooded vehicles (left) and rescue operation (right) at NYC (Courtesy: nymag).

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