Hurricane Irma: Consequences of Intense Rainfall and Storm Surge from a Tropical Storm in North and Central Florida

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ABSTRACT: *Hurricane Irma affected the Florida peninsula from September 9-11, 2017, with high winds, rainfall, and storm surge. Although the storm made landfall on the west coast of Florida, impacts of the rainfall and storm surge affected central and northeast Florida. A GEER team mobilized on September 23, 2017, spent three days documenting sinkhole damage in central Florida, coastal scour and erosion along the northeast coast of Florida, and infrastructure damage in northeast Florida. Numerous sites with geotechnical damage were documented but this case history focuses specifically on sinkhole damage in The Villages, erosion and scour at Vilano Beach, failure of a concrete cover earth dam at Hampton Lake, and bridge embankment damage on US-17 over the Trout River. The most notable challenges to reconnaissance were the widespread and varied nature of the damages from Hurricane Irma and the rapid repair of damaged infrastructure that required the team to work closely with local, state, and federal officials to obtain documentation of the damage prior to repair.*

KEYWORDS: reconnaissance, hurricane, sinkhole, karst, erosion, scour, beach, dam, infrastructure

SITE LOCATION: Geo-Database

INTRODUCTION

This case history describes several different impacts to infrastructure from, and geotechnical related consequences of, Hurricane Irma, which was active September 9-10, 2017, in north and central Florida (FL). A team of geotechnical and coastal engineers was deployed by the Geotechnical Extreme Events Reconnaissance (GEER) Association. The team collaborated with federal, state, and local organizations to identify sites damaged by the hurricane's intense rainfall, flooding, waves, and storm surge. The team then deployed to these sites September 25-27, 2017, before local and state agencies commenced or finalized repairs. The team cataloged geotechnical damage to infrastructure, including sinkhole damage to residential structures and roadways, storm drain capacity exceedance, storm surge and wave-induced erosion of retaining walls, bridge embankments, and a small dam failure. The hope is that information collected and described herein and by Hudyma et al. (2017) will provide guidance for future reconnaissance efforts as well as planning, design, construction, repair, and risk assessment for infrastructure in hurricane-prone areas.

NORTH AND CENTRAL FLORIDA GEER ACTIVITIES

GEER reconnaissance activities were performed by two teams in Florida following Hurricane Irma: one team for north and central Florida and one team for an area between Cape Coral in southwestern Florida to Key West. This manuscript presents the activities and findings of the GEER reconnaissance for north and central Florida. Activities were focused on cataloging geo-referenced information at locations where Hurricane Irma caused appreciable geotechnical-related damage or impacts to the natural and built environment. Information on significant and representative damage was gathered for the reconnaissance from a range of sources, including municipal leaders, state/federal agencies, and the engineering community.

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There were three main challenges associated with planning and conducting the GEER reconnaissance. Firstly, timing was critical. While the team required time to plan and conduct effective reconnaissance, state and local agencies were necessarily quick to initiate and complete repairs to important infrastructure to halt further damage and ensure continued functioning and public safety. Secondly, several types of geotechnical impacts and damage were identified, requiring a multifaceted investigation. Lastly, the damage the team identified covered a large area, spanning inland and coastal locations. Each of these challenges created time pressures and resulted in the need to create an efficiently structured yet agile reconnaissance plan.

Figure 1 identifies locations of GEER activities, which reached as far as Hilliard (near the Florida-Georgia state border) in the north, Apopka in the south, Gainesville in the west, and Vilano Beach along the Atlantic coast in the east (Hudyma et al., 2017). The primary impacts and locations presented herein are identified in yellow in Figure 1 and consist of the following: rainfall-induced sinkhole formation at The Villages, storm surge and wave-induced scour and erosion at Vilano Beach, and storm surge and rainfall-induced damage to a small dam in Hilliard and a bridge embankment in Jacksonville. At each site, the GEER team conducted an initial site walk to examine the extent of damage before collecting more detailed and specific information that included: taking GPS coordinates and photographs of the site and its features; making sketches and taking dimensions of features; writing notes; and documenting discussions with local residents or professionals in charge of repair, when possible. A report detailing the observations was subsequently created by Hudyma et al. (2017).

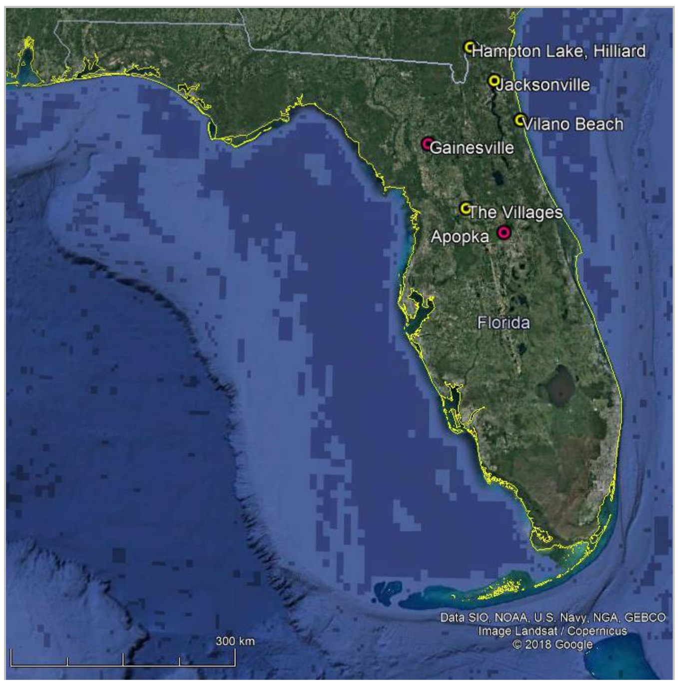

Figure 1. Locations of key north and central Florida GEER activities following Hurricane Irma (Google Earth, 2018).

Many of the locations surveyed were on public property (e.g., highway shoulders), had public access (e.g., beaches), or were on private property (e.g., residential communities). The GEER team experienced only natural and safety obstructions to accessing some sites for reconnaissance and was welcomed by landowners or municipalities. For infrastructure that experienced large-scale damage, the GEER team scheduled to meet officials or experts onsite for a tour and discussion of the damage and impacts. For smaller municipal or residential damage, the GEER team either received approval to investigate sites ahead of time or asked residents for access and permission to survey and document the damage. Every person the team interacted with was interested in the work and helpful in providing accounts of their experiences and a chronological history of events.

HURRICANE IRMA

The 2017 storm Irma formed along the coast of West Africa on August 27 and moved westward. Irma became a tropical depression over the Cabo Verde Islands by August 30, reached a hurricane strength of 741 km (400 nautical miles, nm) west of the Cabo Verde Islands on August 31, and was a Category 5 hurricane on the Saffir-Simpson Hurricane Wind Scale with a maximum wind speed of 287 km/h (155 knots) when it reached Barbuda on September 6 (Cangialosi et al., 2018). Hurricane Irma continued to move west-northwest and impacted St. Martin, the British Virgin Islands, Puerto Rico, the Dominican Republic, The Bahamas, and Cuba before it made landfall as a Category 4 storm on September 10 in the Florida Keys (Cangialosi et al., 2018). The storm decreased in intensity as it moved from the western coast toward the central inland areas of the state. On September 11, Irma was downgraded to a Category 1 hurricane at 02:00 EST approximately 40 km (22 nm) northeast of the Tampa-St. Petersburg area, was downgraded again to a tropical storm by 11:00 EST approximately 115 km (62 nm) east of Tallahassee, and had left Florida by 17:00 EST. Figure 2 shows the path of Irma as it progressed from the Florida Keys northward. This GEER team focused its effort on investigating locations along the path of the storm's eye in central Florida and along the state's northeastern coast, specifically along the eastern I-75 corridor and northeastern coastline.

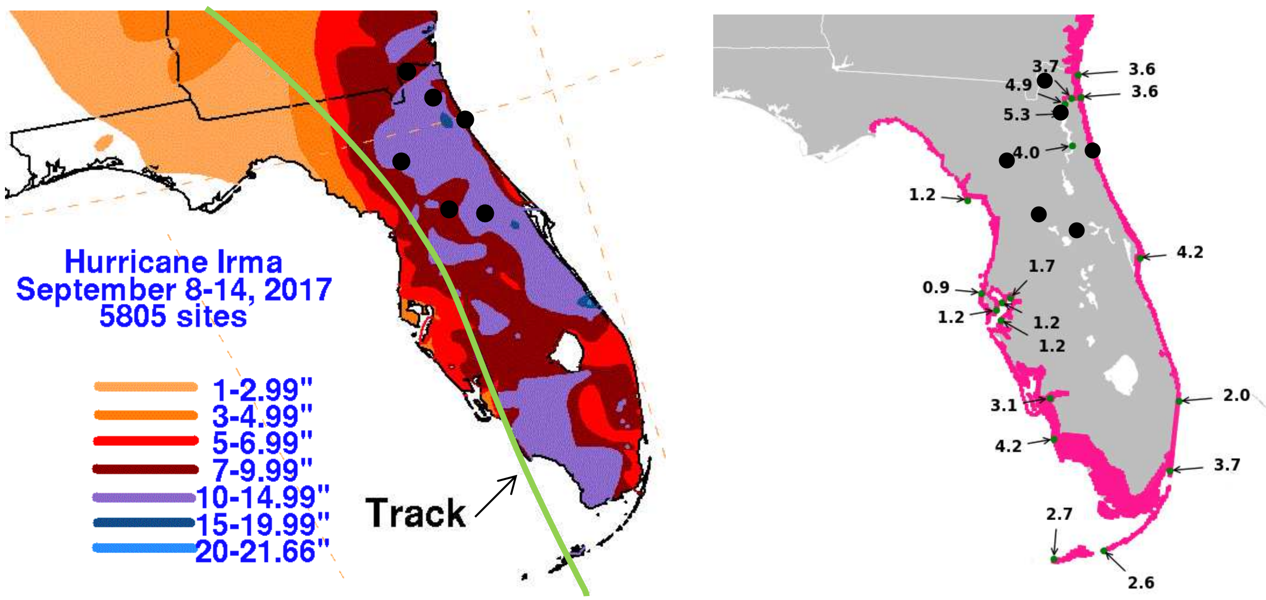

Figure 2. The track of Hurricane Irma, along with observed rainfall in inches from September 8-14, 2017 (left), maximum water levels from tide gauge measurements in feet above mean higher high water (MHHW) used to approximate inundation (right), and areas where storm surge warnings were made, in magenta (after Cangialosi et al., 2018). Black dots correspond to GEER investigation locations in Figure 1.

Water levels along the coast of Florida and in major estuaries and rivers are shown in Figure 2 (right). The data presented are tidal gage measured elevations in feet above mean higher high water (MHHW). MHHW is the Cangialosi et al. (2018) proxy for estimating the normal high-water mark, where water levels above these values indicate flooding from storm surge. Inundation is defined as the height of water over areas of normally dry ground due to the combination of both storm surge and astronomical tide. An estimated 0.9 m to 1.5 m (2.9 ft to 4.9 ft) of inundation above ground level occurred from Cape Canaveral, FL, in the south northward to the Florida-Georgia state line (Cangialosi et al., 2018). Tidal sensors reporting wave-corrected water levels above MHHW recorded values of 1.5 m (4.8 ft) in the Matanzas River just south of Vilano Beach and St. Augustine, and 1.25 m (4.1 ft) at Jacksonville Beach (Cangialosi et al., 2018), both of these being areas where GEER activities were focused. The United States Geological Survey (USGS) surveyed high water marks were reported to be 0.6 m to 1.2 m (2 ft to 4 ft) above MHHW in St. Augustine and 1 m (3.3 ft) above MHHW at Vilano Beach (Cangialosi et al., 2018). Cangialosi et al. (2018) also report that flooding in the St. Johns River in Jacksonville and the surrounding areas was significant due to both rainfall runoff and storm surge, where measured water levels were between 1.2 m and 1.6 m (4.0 ft to 5.3 ft) above MHHW.

The spatial distribution of rainfall from Irma is illustrated in Figure 2 (left). Between 0.18 m to 0.38 m (7 in to 15 in) of rainfall was recorded in north and central Florida. This heavy rainfall contributed significant amounts of water to overland flow and into natural and constructed water conveyance and storage systems (e.g., streams, culverts, retention ponds, and storm drains) and underground (e.g., through leaky underground piping and sinkhole conduits). The influx of water increased the potential for sinkhole activity. Rainfall and runoff along the coastal areas of Florida contributed to significant flooding. Many rivers in northeast Florida experienced major or record flooding. Record flooding occurred in Metropolitan Jacksonville and Hampton Lake, which were the focus of this GEER reconnaissance. The St. Johns River in Jacksonville and St. Marys River downstream of Hampton Lake (Figure 3) were likely influenced by wind-induced storm surge that retarded the flow of rainfall out of the system and led to damage at the Lake Hampton Dam in Hilliard and the US-17 bridge embankment in Jacksonville.

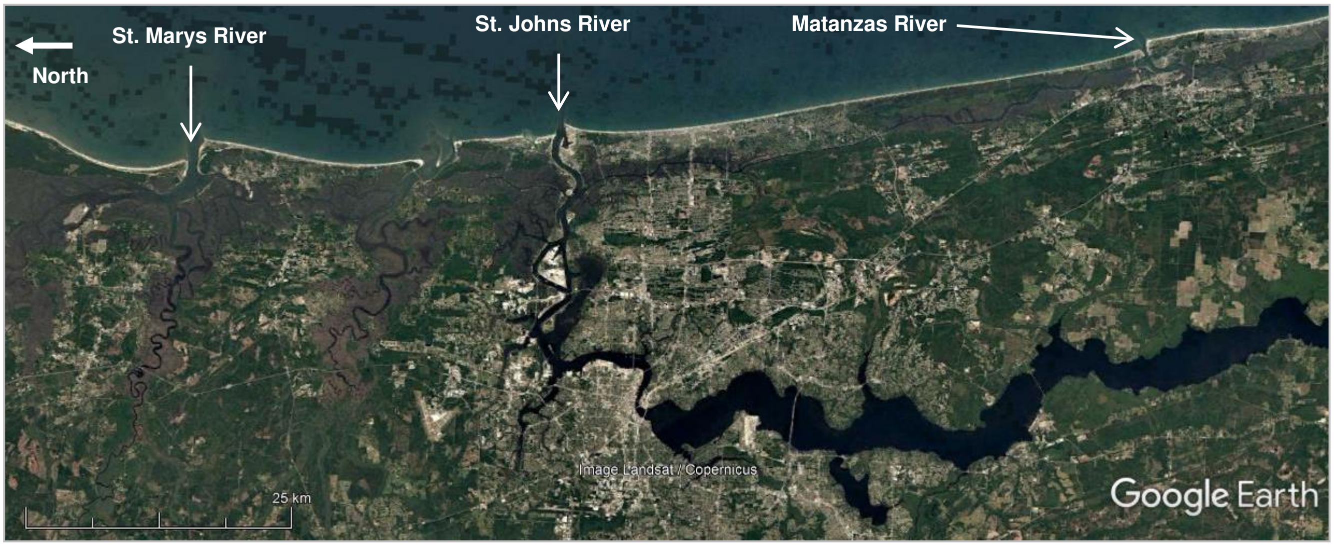

Figure 3. Northeastern rivers influenced by runoff and storm surge, including St. Marys River leading to Lake Hampton, St. Johns River leading to Jacksonville, and Matazanas River near Vilano Beach and St. Augustine (Google Earth, 2018).

SINKHOLE FORMATION AND DAMAGE

Sinkholes are common geologic hazards in Florida's central areas and its eastern panhandle. There are many anthropogenic and natural initiators for sinkhole formation, and excessive rainfall is often one of the triggers. Sinkhole reconnaissance was limitied to one day in central Florida, and this case history documents sinkhole formation at one location. The sinkhole reconnaissance was planned using information from Florida state agencies (e.g., Department of Transportation), local engineering and geology related companies, and reports by numerous news (e.g., Ruiter 2018) and social media sources. The initial itinerary considered different infrastructure types affected, sinkholes not repaired, spatial location, and necessary travel time to and between locations. During reconnaissance, the team made impromptu alterations to the itinerary as new information on sinkhole activity and locations was discovered. Each site was investigated by an initial site walk before measurements and photographs of site features were taken. The primary consideration for the reconnaissance efforts was safety as well as additional ground subsidence even in areas without visual evidence of underground instability.

Sinkholes and Central Florida Surficial Materials

The USGS classifies Florida as a humid climate karst region with two distinct zones: carbonate rock at or near the surface, and carbonate rock buried beneath approximately 91 m (300 ft) of insoluble sediments (Weary and Doctor, 2014). The shallow bedrock of the Florida peninsula consists of a series of carbonate rock formations. This includes the Ocala Limestone consisting of nearly pure limestone and dolostone, overlain by undifferentiated siliciclastic sediments which in turn consist of quartz and carbonate sands, clay muds, marl, and organics (Kim et al., 2017; Scott, 2001; Campbell and Scott, 1991). The surfaces of the carbonate formations are highly variable due to weathering-induced karstification (Randazzo, 1997). Within karst terrain, the most serious geologic hazard is sinkholes (Wilson and Beck, 1988). In central Florida, the general shallow geology of this region consists of undifferentiated Quaternary aged (Holocene and Pleistocene) surficial sediments, coarse grained sand through clay in size, unconformably overlying the Upper Eocene aged Ocala limestone. Undifferentiated sediments are typically 0.3 m to 12 m (1 ft to 39 ft) thick, and can be up to 30 m (98 ft) thick within paleo-sinkholes.

The Villages, in northeast Sumter County, Florida, is one of the largest master planned communities for residents aged 55 years and older; this area is the focus of the sinkhole observations discussed. In this area, the Crystal River Formation is the near surface limestone. This limestone is white to very pale orange, poorly to moderately indurated, variably recrystallized, and is a fine- to medium-grained packstone to wackestone (i.e., materials characterized by the percentage of mud in the rock matrix) (Campbell, 1989). The subsurface profile in this area consists of a 0.3 m to 7.6 m (1 ft to 25 ft) thick veneer of permeable overburden overlying soluble limestone bedrock with evidence of weathering features that can lead to sinkholes. Typical weathering features consist of enlarged fractures and bedding planes, large interconnected irregularly shaped pores, open cavities with arched soil caps, and block/slot/pinnacle structures (Wilson and Beck, 1988; Sowers, 1996; Hudyma et al., 2005).

Solution sinkholes are the most common sinkholes in this area. These are depressions that form when near surface bedrock is exposed to water that penetrates fracture/bedding planes and dissolves the rock. Sinkhole formation is triggered by natural or anthropogenic events, including lowering of the groundwater table, construction activities, and influxes of water. This does not preclude other types of sinkholes from forming if local geological conditions exist. Cover collapse sinkholes were also identified at neaby locations by the GEER team. Cover collapse sinkholes typically: (1) are shallow and broad, (2) occur rapidly, (3) occur where plastic soils overlie weathered limestone with pre-existing enlarged vertical fractures that may connect existing cavities, and (4) are caused by downdrag or spalling of subsurface layers following an influx of water (Sinclair and Stewart, 1985).

The Villages Alhambra Sinkholes

Several sinkholes were identified at a stormwater retention pond (Figure 4) in The Villages Alhambra, a body of water that is approximately 2 hectares (4.9 acres) in size, has six inlets, and is bounded by Privada Drive to the north and Botello Avenue to the east. The sinkholes associated with Hurricane Irma formed along the bottom, on the bank slope, and at the crest of the eastern side of the pond. Two additional sinkholes also affected residences.

Figure 4. Location of sinkholes formed in the retention pond in The Villages Alhambra, FL, at 28°57'10.68"N latitude and 81°59'33.65"W longitude (Google Earth, 2017).

Residents graciously provided the GEER team with an account of the sinkhole events and photographs taken prior to the GEER team's arrival. On September 11, the water level in the pond was above the inlet pipes. On September 12, the water level decreased to approximately the midpoint of the inlet pipes. By the morning of September 13, the pond was empty. Digital photographs from residents show five sinkholes in the retention pond basin and two sinkholes on the bank behind the house at 2536 Botello Avenue (Figure 5). During the site visit 14 days following Hurricane Irma on September 25, repair of the sinkholes within the basin and along the bank was being completed. Repair was peformed using a Caterpillar D4 bulldozer to end dump granular fill near the holes, infill them, and then compact the fill with the machine's weight. The dimensions of the sinkholes themselves could not be estimated from either the pre-repair photos or the repairs.

Sinkholes near the residential structures were easier to quantify during the site visit. The sinkhole that formed beneath the edge of the slab-on-grade foundation at 2536 Botello Avenue (Figure 6) was roughly elliptical in shape, approximately 4.0 m by 4.5 m (13 by 15 ft), with a depth of 2.5 m (8 ft), and exposed a small diameter, shallowly buried irrigation pipe that was unsupported over the hole. A repaired sinkhole with unknown dimensions was found at the edge of the road at 2532 Botello Avenue (Figure 7). There, the asphalt pavement showed no indication of distress, and it is unknown if the sinkhole extended under the road. The GEER team visited two other locations in The Villages where sinkholes formed, affecting retention ponds and a golf course irrigation infrastructure, and causing two houses to be classified as unsafe for occupancy by the local building official. The team heard anecdotal reports of dozens of other sinkholes that formed in The Villages, but were unable to visit them. Ruiter (2018) reports more than 400 sinkholes formed in north and central Florida as a result of Hurricane Irma.

Figure 5. Sinkholes on the bank of and within the retention pond between Alhambra Way and Botello Avenue at 28°57'11.92"N latitude and 81°59'31.49"W longitude (Images courtesy of Sheila Huffman Dailey, Dan Snyder, and Barbara Beveridge; from Hudyma et al., 2017).

Figure 6. Sinkhole undercutting a foundation at 2536 Botello Road at 28°57'11.67"N latitude and 81°59'30.05"W longitude (Hudyma et al., 2017).

Analysis of The Villages Alhambra Sinkholes

Several factors related to land development can influence long-term sinkhole formation, including:

- Exposure of susceptible soils and rock during land development that removes upper protective sediments;
- Retention pond storage is a continuous source of water for infiltration and potential movement of soil into enlarged fractures and potential dissolution of limestone along fractures and bedding planes (e.g., point source);

- Point source leakages from the networks of underground municiple and irrigation water distribution systems that may not be immediately identified and repaired;

- Improperly repaired sinkholes that previously developed; and

- Diffuse surface water infiltration from routine rainfall and/or lawn, golf course, and crop watering activities.

The constructed detention/retention ponds in the area used as surface water control measures may have accelerated bedrock dissolution. During the construction of a pond, the ground surface elevation is reduced along with sediment cover above the shallow weathered limestone that helps mitigate water intrusion. As rainfall is funnelled into the pond, it subsequently infiltrates, erodes, and transports the overlying soil into the limestone. Rainfall totals for The Villages Alhambra prior to, during, and after Hurricane Irma were 11.2 mm, 14.2 mm, 227.8 mm, and 0 mm (0.44 in, 0.56 in, 9.0 in, and 0 in) for September 9-12, 2017, respectively (CoCoRaHS, 2017). The predominant triggering event for sinkhole formation in The Villages is likely excessive rainfall on September 11 following a period of drought (Bodenner, 2018). However, irrigation for lawns and golf courses in the area provided sustained diffuse water infiltration and possible leakages in piping systems. Limestone dissolution and sinkhole formation may be compounded in areas having leaky underground water, sewer, stormwater, and irrigation distribution systems, and can be further accelerated by extreme rainfall events such as Irma.

Figure 7. Sinkhole at 2532 Botello Avenue at 28°57'10.60"N latitude and 81°59'30.50"W longitude: a) prior to repair (Villages News 2017), b) following repair (Hudyma et al., 2017).

Sinkhole Reconnaissance Recommendations and Challenges

Investigation duration and measurement accuracy could be significantly improved by the use of technology and a multi-team approach. A multi-team approach might include a preliminary reconnaissance team to evaluate the level of investigation, either cursory or detailed, and use drone imaging to map the widespread damage associated with sinkholes. Drone imaging could improve the quality and accuracy of information collected from each reconnaissance, including plan and depth dimensions, shape, sub-features, nearby features that might influence formation, etc. The initial survey team could be followed by a reconnsaissance team to investigate sites requiring more detailed anaysis on the ground (e.g., surveying, sampling, photography, geophysics, etc.). Measuring sinkhole dimensions by traditional surveying methods is time-consuming, dangerous, and has low accuracy. Furthermore, physical samples cannot be collected for analysis without risk. The level of detail available to future investigations using advanced tools would be far better, and reconnaissance teams would be able to better use their time and minimize risk of injury in areas of unstable ground.

While sinkholes did form in response to heavy rains from Hurricane Irma, several of these were in areas where sinkhole activity was well known, previous sinkholes had developed and been repaired, and/or subsurface conditions were such that this event triggered collapse evident at the surface. The challenge with sinkhole reconnaissance employed herein, however, is that it relies on visual evidence and any subsurface erosion created, accelerated, and/or exacerbated by Hurricane Irma that may lead to future formation of surface sinkholes would require extensive geophysical investigations to identify. Green

(2018) reported that more than 400 sinkholes developed in response to Hurricane Irma, and not all of them developed during or immediately following the storm.

Underground conduits or cavities prone to collapse could be identified by more advanced geophysical tools and LiDAR to identify surface depressions as proxies for underground cavities, or by electrical resistivity, ground penetrating radar, or seismic methods. Data from these more detailed, advanced surveys could also support subsequent reconnaissance and tracking of these underground features in sinkhole prone areas. Comparative analyses over time (e.g., more frequently, following an extreme event, and/or following multiple events) may allow for tracking sensitive areas that can be better managed, proactively addressed, or quickly identified and repaired. In emergency or time-sensitive situations, reconnaissance is likely biased by proximity to major infrastructure or clusters of sinkholes. Remote or seemingly "low impact" locations of significant sinkhole development may receive little or no attention. However, these locations could convey water underground into nearby areas where sinkhole formation may have greater impacts. Remote sensing surveys that incorporate these areas may prove useful in protecting higher impact areas.

Sinkhole reconnaissance could be aided by a centralized database for real-time reporting of sinkhole activity hosted by the Florida Department of Environmental Protection (FDEP). Links to the subsidence reporting website and sinkhole map are provided in the Appendix. FDEP indicates subsidence occurances may include sinkholes (natural or anthropogenic), but may also include causes of subsidence such as compression of organic soils, expansive soils, and/or decomposition of organics in compacted fill. Subsidence occurances are compiled and disseminated via online maps that provide spatial and GIS data. However, many of the reported occurances are not verified by either FDEP or Florida Geological Survey (FGS) professionals. This resource is invaluable for science and infrastructure planning and maintenance, and could be significantly augmented by incorporating geo-referenced images or other data uploaded to the system from cooperating state agencies, municipalities, and citizens. The database is presently limited in that it relies on voluntary reporting.

An important recommendation for FDEP is to better promote this database as a resource for the state and to educate citizens, engineering and construction firms, municipalities, and cooperating agencies to report sinkhole activity on a regular and broader basis. Providing easily accessible and simple guidance for the type and quality of information that is useful for reporting and uploading to cooporating agencies and on the website for citizens would encourage more—and more consistent—reporting. Locations of new sinkholes could thus be quickly identified and spatially analyzed for additional reconnaissance by state agencies or geoprofessionals. This is particularly important when rapid repair of sinkholes is necessary to prevent further infrastructure damage and subsurface erosion, thereby protecting public safety. For this reconnaissance, the reconnaissance team had to rely on eyewitness photographs, reports, and media information, as repairs had already been made. Without consistent documentation before repair, these locations may be lost to the broader community.

COASTAL EROSION AND SCOUR

The eastern coast of Florida is a system of barrier islands, tidal inlets, and coastal dunes. There are twenty-two inlets, and most have been modified by engineering activities. Northeast Florida is considered microtidal, meaning that tides are typically less than 2 m except for spring tides (Davies, 1997). While the shallow bedrock is predominantly carbonate, natural beach sand is predominately silica. Geologically speaking, these silica sands were most likely transported south from the weathered Appalachian Mountain landscape of North and South Carolina and Georgia by longshore transport processes and deposited along the Florida coast between 30 Ma and 3 Ma (Hine, 2013). Sand dunes are important natural coastal structures that provide habitats and protect inland areas from storm surge and overwash, as well as washover deposits. Tropical storms and hurricanes have significantly eroded beaches and dunes along much of the Florida coastline.

Erosion presents a challenge to coastal management, as beach and dune areas are desirable locations for residential, resort, commercial, and recreational facility development. Therefore, beach renourishment has been used to maintain the landscape and protect development for decades. Hudyma et al. (2017) detail several impacts from Hurricane Irma, ranging from Beverly Beach in Flagler County northward to Vilano Beach in St. Johns County. These include: low impact dune erosion and slope failures that put smaller seawalls and residences at greater risk of damage in future storms; significant impacts from overwash and washover deposits that changed beach profiles, buried coastal roadways, and destroyed or inundated the ground story of several residences; and beach and dune erosion that compromised residential seawalls and residences.

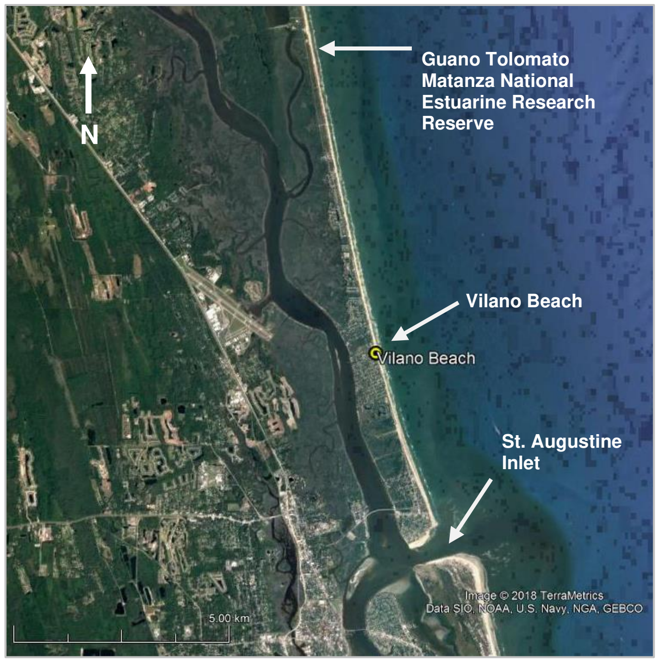

Figure 8: Location of Vilano Beach, Florida (Google Earth, 2018).

Erosion and Scour at Vilano Beach

The Vilano Beach area experienced the most significant impacts of the areas investigated by the GEER team. Vilano Beach extends from the Saint Augustine Inlet in the south to the Guano Tolomato Matanza National Estuarine Research Reserve to the north in St. Johns County (Figure 8). The GEER reconnaissance extended approximately 0.5 km (0.3 mi) between 3920 and 4070 Coastal Highway in St. Augustine and documented damage related to both scour and erosion of coastal dunes along a section of beachfront with residential homes. Herein, *erosion* refers to large-scale lowering of the ground surface and *scour* refers to localized loss of soil. It is important to note that following Hurricane Irma, the U.S. Army Corps of Engineers (USACE) announced plans for a $36.8 million beach renourishment program at Vilano Beach (News4Jax, 2018).

Vilano Beach has been experiencing consistent dune erosion during major storm events since 1994. Figure 9 illustrates how significantly and quickly the seemingly stable dune system changed because of extreme storms. The majority of erosion occurred after 2015 from both Hurricane Matthew (October 16, 2016) and Hurricane Irma (September 11, 2017). Figure 9c is annotated to show Hurricane Irma damage identified by the GEER team. To prevent erosion, seawalls of varying types were installed to protect residences from destructive wave action. The walls ranged from simply constructed walls to more complex walls with anchors. Many of the more complex systems were vinyl sheet pile walls anchored by either helical or dead man anchors connected to either pressure-treated wooden wales 100 mm (4 in) square in cross-section or cylindrical wooden piles secured at the front of the sheet piles. Several residences with more complex seawalls still experienced some damage and scour. The unprotected areas adjacent to seawalls were at greater risk of erosion and scour as the wave energy was directed around the seawalls and focused on the unprotected beach, dunes, and structures. Several residential structures with limited or no seawalls had their timber pile foundations exposed. In one extreme case, a residence supported by shallow foundations was completely undermined and toppled onto the beach.

Figure 10 provides an example of damage to a residence that had been constructed on the dunes and protected by a wooden seawall of unknown design installed a distance away from the structure on the beach. The residence and its balcony are supported by alternating deeply embedded pressure-treated timber piles and pressure-treated lumber columns supported by concrete footings, presumably at the previous ground level, and micropiles. This structure experienced substantial erosion, where foundation elements became exposed over more than 10 m (~30 ft) height and both the footprint of the balcony area and structure itself were undercut. The seawall was itself destroyed (see Figure 9c). Minor slope failures were evident on the remaining dune face (Figure 10b). Drying and loss of capillary suction in the sand during the heat of the day made the exposed slopes more prone to sloughing and put the structures at greater risk of being undermined.

Figure 9: Changes to the Vilano Beach coastline from 4020 to 3880 Coastal Highway, St. Augustine, Florida, at 29°56'49.30"N latitude and 81°18'9.37"W longitude dated: (a) November 2015, with few seawalls present; (b) March 2017, with seawalls installed following 2016 Hurricane Matthew, and; (c) October 2018, following damage from 2017 Hurricane Irma (Google Earth, 2018).

Figure 10: Erosion undercutting both the timber pile supports and micropile supported concrete footings for a beach house with continued slope failures in drying sand at 29°56'47.00"N latitude and 81°18'8.10"W longitude after Hurricane Irma.

Figure 11 shows a wooden seawall left partially intact after Hurricane Irma. The seawall was constructed from pressure-treated lumber approximately 50 mm by 150 mm (2 in. by 6 in.) in cross-section nailed to pressure-treated timber piles supporting upper levels of the residence. The lumber was either not embedded or minimally embedded into the soil. The wall itself remained intact and undamaged, likely because it was attached to the piles. While the wall may have been initially effective at preventing erosion, soil was eroded from beneath and around the sides of the wall, undercutting three rows of timber piles. Notice also the underside of the elevated structure. The GEER team was uncertain how developed the ground floor of this structure was; however, there was evidence that walls and utilities were eliminated by wind and wave activity.

Of the sites investigated, anchored vinyl sheet pile seawalls fared better than timber seawalls, but still suffered significant damage. The faces of the sheet pile walls were parallel to the beach and remained intact, showing no signs of failure or undermining from wave action. This is likely because the vinyl sheet piles were embedded to a sufficient depth. Several of the sheet pile walls had wing walls approximately parallel to the direction of wave action, and were keyed into the dunes to prevent wave action from eroding the retained soil. However, each of the wing walls observed by the reconnaissance team was compromised in one or more of the following ways: (1) the sheet pile depth was too shallow and erosion of retained sand occurred under the wall, (2) the key length into the dune was insufficient and erosion occurred into the dune around the wing wall into the retained sand, or (3) the wing wall was not completed.

Figure 11. (a) Shallowly embedded timber seawall at approximately 29°56'49.30"N latitude and 81°18'9.37"W longitude, showing significant erosion (about 2 m or 6.6 ft) below a residential structure; and (b) subsequent beach erosion and removal of the first story walls by wind and water.

Figure 12: Sheet pile retaining wall failure from undercutting at 29°56'58.16"N latitude 81°18'11.96"W longitude, showing: (a) the exposed wall base, and (b) a funnel-shaped depression following basal soil escape (Hudyma et al., 2017).

Figure 13: Failure of two residential sheet pile retaining walls from side erosion following Hurricane Irma, showing: (a) a partial sheet pile wing wall that was extended into the dune using timber piles and wooden lagging at 29°56'55.10"N latitude and 81°18'13.49"W longitude, and (b) the backside of the wall and anchors from the side where the wing wall was not yet installed at 29°56'46.05"N latitude and 81°18'7.5"W longitude (Hudyma et al., 2017).

The undercutting of shallowly embedded walls is evident in Figure 12a, which shows exposure of the base of a sheet pile wing wall that was scoured to a depth that provided a pathway for retained soil to escape from under the wall. This created a funnel-shaped depression behind the seawall at this location (Figure 12b). Figure 13a shows erosion into the dune and around a wing wall. The face and part of the wing wall were made of embedded vinyl sheet piling. However, the part of the wing wall extending into the dune was of timber pile and wooden lagging. Erosion past the sheet piling into the more open structure of the wooden lagging resulted in break-up of the wall, erosion of the retained soil, and exposure of shallow foundations previously supporting the deck (not shown). Lastly, Figure 13b illustrates the consequences of an incomplete seawall. The wing wall was a temporary timber pile and wooden lagging installed to accommodate a possible future extension of the sheet pile wall face to the neighboring property. The timber seawall was compromised by the storm. The four residences protected by the wall experienced damage, with the most damage adjacent to the temporary wing wall.

Analysis of Erosion and Scour at Vilano Beach

There appeared to be differences in the level of design and construction of the timber lagging and vinyl sheet pile seawalls. The GEER team has no knowledge of the extent of hydrodynamic analyses, designs, or construction procedures that were implemented to construct these seawalls. While some wall systems seemed to perform well with limited damage under the conditions brought by Hurricane Irma, they may not withstand demands from future storms.

The structure with face and wing walls constructed similarly with vinyl sheet pile in Figure 12 experienced some undermining damage; however, the impenetrable material of the wall (vinyl) provided excellent resistance to wave action that was likely intensified by entrained sand and debris from adjacent damaged structures. The walls that the GEER team found to be minimally damaged during Hurricane Irma had sufficient vertical embedment into the beach sands or lateral embedment back into the dune to maintain their structural integrity, even if basal or side exposure of the wing wall resulted in some erosion. The reconnaissance identified two concerns for vinyl sheet pile walls. Walls are installed with weep holes to allow water to drain from the retained sand behind the wall at the beach elevation. Following Hurricane Irma, the weep holes were approximately 0.5 m to 1 m (1.6 ft to 3.3 ft) above the new beach elevation. In many walls with soil still retained, the vinyl sheets bowed out of plumb below the weep holes. This is likely because of both the loss of basal support on the outside face of the wall and pore pressure in the confined soil from trapped water behind the wall. While the vinyl sheet piling is ductile and corrosion resistant, inspection found areas with previous cracks and repairs, possibly due to impact from wave-borne debris.

Timber pile and wooden lagging did not fare well in the extreme conditions brought on by Hurricane Irma (Figures 11 and 13). Lagging for these barriers may not have extended deep enough into the beach and retained soil was subject to basal erosion, leaving wooden walls unsupported and subject to even greater wave loading. Additionally, the impact of waves carrying entrained debris and sand likely amplified the rate of damage for these timber walls. Nearly all the wooden face seawalls installed along the beach were destroyed (Figure 9) and the wooden debris washed away. A new sand bar was evident in front of the location where the wooden seawalls were destroyed (Figure 9c). This may be a coincidence or evidence that sand in excess of equilibrium was retained prior to the storm (i.e., sand behind the wall would not be present without the wall). Cangialosi et al. (2018) report that water levels at Vilano Beach were 1.5 m above MHHW, in line with reported USGS surveyed high water marks of 1 m. These water levels indicate that water forces necessary to create scour, lower beach elevation, and erode dune slopes could have existed.

Coastal Erosion Reconnaissance Recommendations and Challenges

There were significant challenges associated with performing reconnaissance along coastal areas affected by scour and erosion from Hurricane Irma. Major challenges were locating and accessing damaged areas, as well as investigating large scale damage in a meaningful and safe manner. When writing this case history, the authors had the advantage of access to open-source aerial images to investigate the extent of the damage. However, at the time of the reconnaissance, the team relied on past knowledge of damage from 2016 Hurricane Matthew to predict newly damaged locations, in addition to media reports and word of mouth. Thus, identification of critical damage areas was highly dependent on human interaction. Once sites were identified, access to sites became a concern, from both a safety and permissions perspective. The GEER team contacted several landowners ahead of time to discuss damages and gain approval for access. In other areas, the GEER team relied on word of mouth to identify public or limited access points that at times required walking more than a mile to get to areas of interest. Once sites were selected and access secured, the limited reconnaissance time and magnitude of the damage played a large role in the information that could be gathered. Some sites had limited damage, the extent and causes of which could be simply identified. However, some sites, such as Vilano Beach and Marineland (the latter discussed by Hudyma et al., 2017), experienced more significant damage that included the beach, dunes, and foundation and wall infrastructure.

It's important to note that the large scale, limited time, and risk of injury presented by coastal damage all made human reconnaissance challenging. Infrastructure damage mapping, beach profiling, dune mapping, and similar activities that are aimed at collecting more substantial and quantitative information would have required significant time at potentially unstable and hazardous sites. The GEER team encountered many unstable areas, including partially or fully damaged seawalls, exposed foundation systems, and partial structures that were left unsupported and overhanging a significantly eroded dune or beach. Investigators recognized unsafe conditions and minimized danger when making measurements or obtaining photographs. Potential enhancements would include the use of remote sensing surveying methods (e.g., drones) for imaging and photogrammetry, satellite mapping, LiDAR, or other similar methods. However, for these methods to be productive, equipment and specialists who can capture and process the data must be part of reconnaissance planning and funding.

Lastly, reconnaissance of such large-scale coastal damage is limited to features easily identified visually. Subsurface and non-visual disturbances affect the geotechnical and structural stability of dunes and infrastructure respectively. These can result in changes to engineering properties (i.e., strength, stiffness, and compressibility) that typically cannot be investigated by initial reconnaissance but should be a focus of follow-up studies. These changes can be problematic, as redeveloped areas may retain a high risk of damage during future extreme events if soils are not adequately stabilized in place.

CIVIL INFRASTRUCTURE

While the previous discussions were focused primarily on residential areas, Hurricane Irma had a significant impact on municipal infrastructure in north and central Florida. Hudyma et al. (2017) provide reconnaissance details for several infrastructure failures and damage; however, this case history focuses specifically on the Lake Hampton Dam failure and embankment erosion at the US-17 bridge over the Trout River.

Lake Hampton Dam Reconnaissance

The Lake Hampton reservoir dam is located on Lake Hampton Road, northeast of Hilliard, in Nassau County, Florida. This reservoir, created in 2011, is on Pigeon Creek, a small tributary of St. Marys River, and is part of the approximately 2326 hectare (5748 acre) Pigeon Creek drainage basin (Ayres Associates, 2008). The dam was constructed of compacted earth with a reinforced concrete cap. The Lake Hampton dam and reservoir features included: a 1.5 m by 6.7 m (4.9 ft by 22 ft) concrete box weir inlet structure at approximately 5 m (16.4 ft) elevation, a 15.2 m (49.9 ft) wide spillway crest at approximately 5.2 m (17 ft) elevation, and a side embankment at approximately 6.7 m (22 ft) elevation (Hudyma et al., 2017). The downstream outlet consisted of three 1.2 m (3.9 ft) diameter concrete pipes at the base of the spillway allowing water to flow from the inlet structure into the spillway pool toward Lake Hampton Road, located at an elevation of 5.2 m (17 ft), where a concrete structure with four 2.1 m (6.9 ft) diameter concrete pipes passed water from the spillway pool into the downstream tributary (Hudyma et al., 2017). Figure 14 shows aerial images of the dam prior to and after the dam's failure.

Figure 15 illustrates the remains of the failed dam and surrounding infrastructure. The inlet structure remained intact and in position; the embankment and soils supporting the spillway, however, were washed away and the concrete cover was left cracked and in disarray. Figure 16 shows the significantly eroded eastern embankment and the remaining organic debris as well as the newly formed drainage path for Pigeon Creek. The post-failure erosion channel was located on the east side of the dam, while limited soil erosion was observed along the western embankment. Figure 16 shows two colors of soil in the east embankment, and we speculate the gray soil to the right may have been modified with cement or lime to minimize seepage.

Lake Hampton Road was also subject to damage, and Figure 17 illustrates the erosion that occurred downstream of the dam and road. Erosion of both pavement and road base resulted in guardrail posts becoming exposed. Figure 15b shows the road crossing from the south, where soil and infrastructure remained relatively intact. Figures 17 and 18 comparatively show the road crossing from downstream with significant erosion of embankment soils at either side of the concrete pipe culvert. The downstream floodplain (Figure 18) had low vegetation removed and/or covered with sediment; large brush was denuded to a certain elevation, and trees were destabilized and uprooted. Surface soil remaining on the downstream embankments and the denuded floodplain was dark brown and muddy; Figure 18b, however, shows areas of lighter brown soil that may indicate dried in-place soils or in-place soil mixed with eroded dam embankment soil.

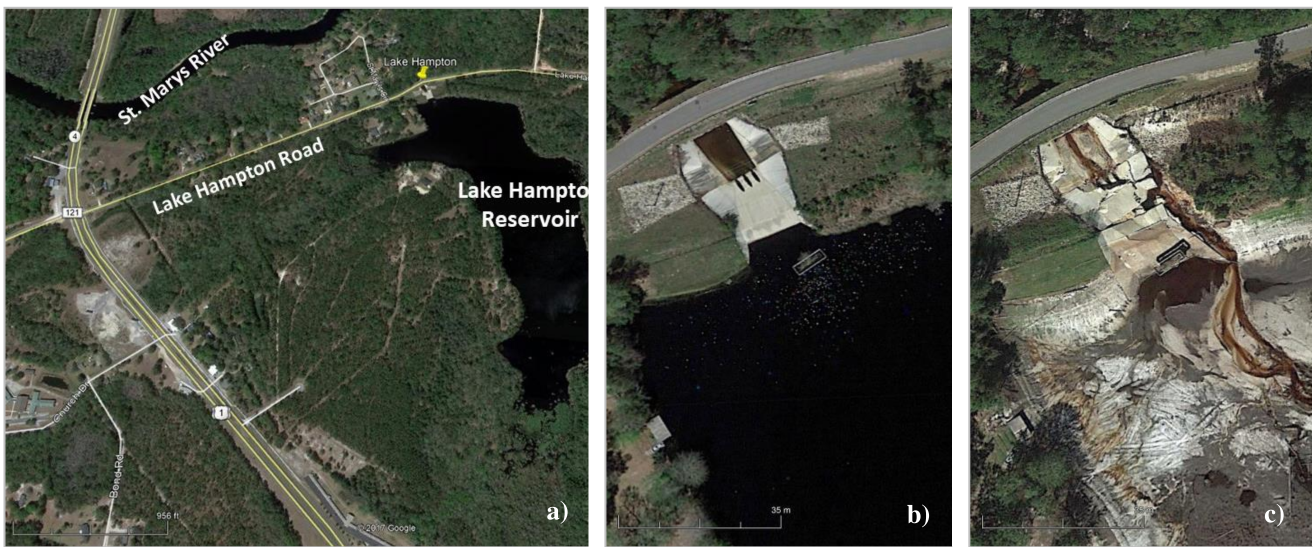

Figure 14. (a) Lake Hampton Dam reconnaissance site location with aerial photos of the dam (b) before (March 2017), and (c) after (October 2017) the failure (Google Earth 2018).

Figure 15: Failed Lake Hampton reservoir dam at 30°46’40.1"N latitude and 81°58’13.0"W longitude: (a) looking south from, and (b) looking north toward Lake Hampton Road.

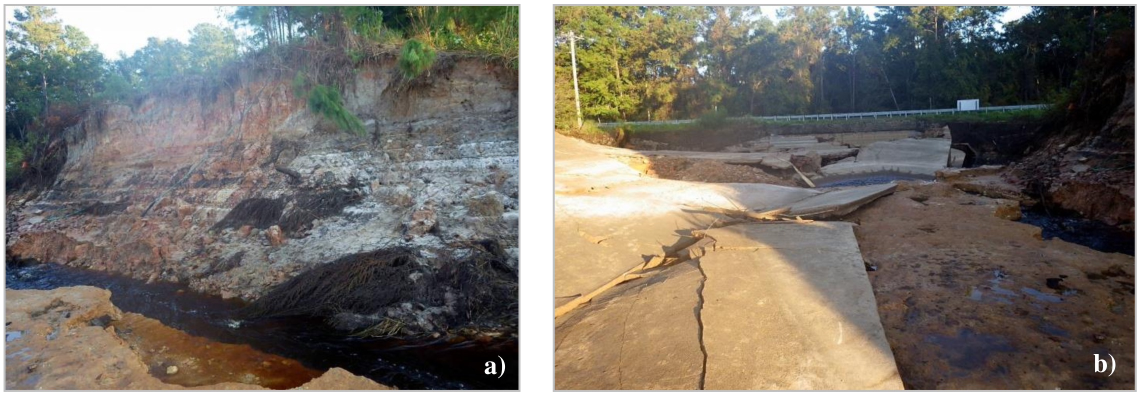

Figure 16: Erosion of the eastern natural embankment and dam soils showing: (a) eastern embankment and post failure outlet stream, and (b) eastern dam and embankment erosion south of Lake Hampton Road at 30°46'33.89"N latitude and 81°58'15.47"W longitude.

Figure 17: Erosion damage of the northern section of Lake Hampton Road at the Pigeon River crossing north of the dam near 30°46'45.19"N latitude and 81°58'24.6"W longitude.

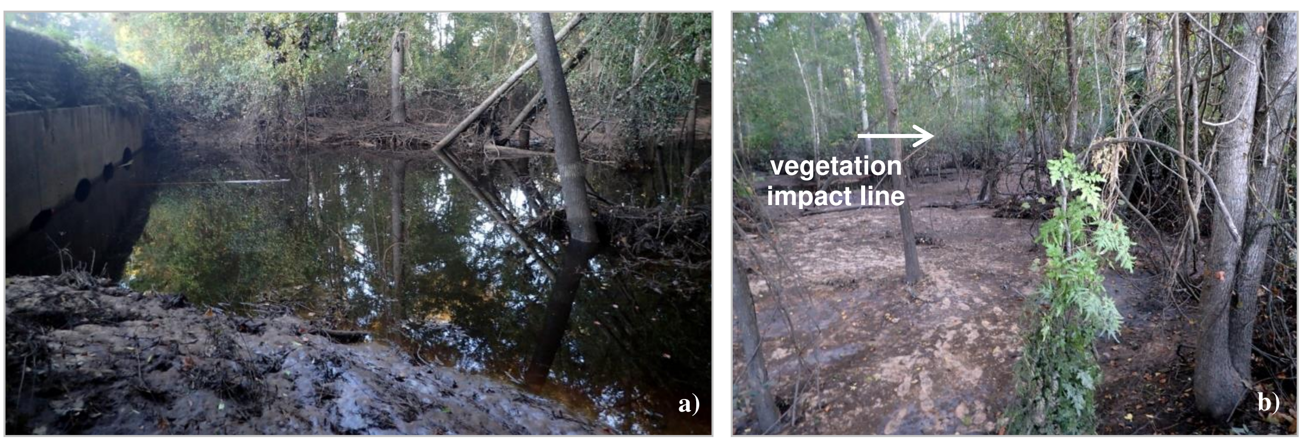

Figure 18: Downstream view of the road crossing at Pigeon Creek near 30°46'45.19"N latitude and 81°58'24.6"W longitude after the failure, illustrating: (a) the dam outlet under Hampton Road with four small diameter openings in a concrete culvert, stacked concrete sack wall stabilizing the roadway, and evidence of high water levels; and, (b) evidence of high water levels, sediment buildup, and debris within the floodplain.

Lake Hampton Dam Analysis

The GEER team interviewed two witnesses present at the time of the dam failure who provided mobile phone video and anecdotal evidence of the timeline and sequence of events. Eyewitnesses and video indicate the dam spillway failed at approximately 7:44 AM on September 11, 2017, when the USGS gage measured tail water elevation was approximately 2.44 m (8 ft) (Figure 19b). Video showed three critical conditions that led to, and/or resulted from, the dam failure: (1) water undermined the spillway slab, causing the concrete cover to collapse and expose the underlying soil to further erosion; (2) water overflowed the spillway crest, indicating the height of the reservoir pool elevation was greater than 5.2 m (17 ft), and; (3) the east side of the embankment was heavily eroded (Hudyma et al., 2017).

Cangialosi et al. (2018) report that record flooding occurred at Lake Hampton, with rainfall between 0.18 m to 0.25 m (0.6 to 0.8 ft) (Figure 2) and storm surge water levels between 1.2 m to 1.6 m (3.9 ft to 5.2 ft) above MHHW in the St. Johns River. The St. Marys River outlet to the Atlantic Ocean is approximately 35 km (21.7 mi) north of the St. Johns River outlet (Figure 3); thus, storm surge likely propagated similarly upstream in the St. Marys River. Figure 19 illustrates water level height in the St. Marys River approximately 9 km (5. 6 mi) upstream from the Pigeon Creek outlet. Water level initially increased significantly from approximately 1.3 m (4 ft) to 4.5 m (15 ft) during Hurricane Irma and continued to increase for several days thereafter. The initial rapid initial water level increase is likely from a combination of overland flow in the watershed, back up of water into the tributaries of the St. Johns River due to the flooding, and storm surge water level increases described in Cangialosi et al. (2018). The subsequent slower increase is from water entering the St. Marys River from overland flow and groundwater following infiltration.

A combination of rainfall and overland flow filling Lake Hampton upstream of the dam was likely the major cause of the dam's failure. The GEER team found significant erosion along the eastern bank of the dam (Figure 16a), which likely led to undermining of the concrete spillway and complete erosion of the soil below it. The GEER team found evidence of plant debris high up on the intact embankment at the west side, indicating a high reservoir water level. It is uncertain why the eastern embankment was preferentially eroded. However, photographic evidence shows muddier sediment to the east along the spillway and downstream floodplain, and Figure 14c shows the new breach channel across the east embankment post-failure.

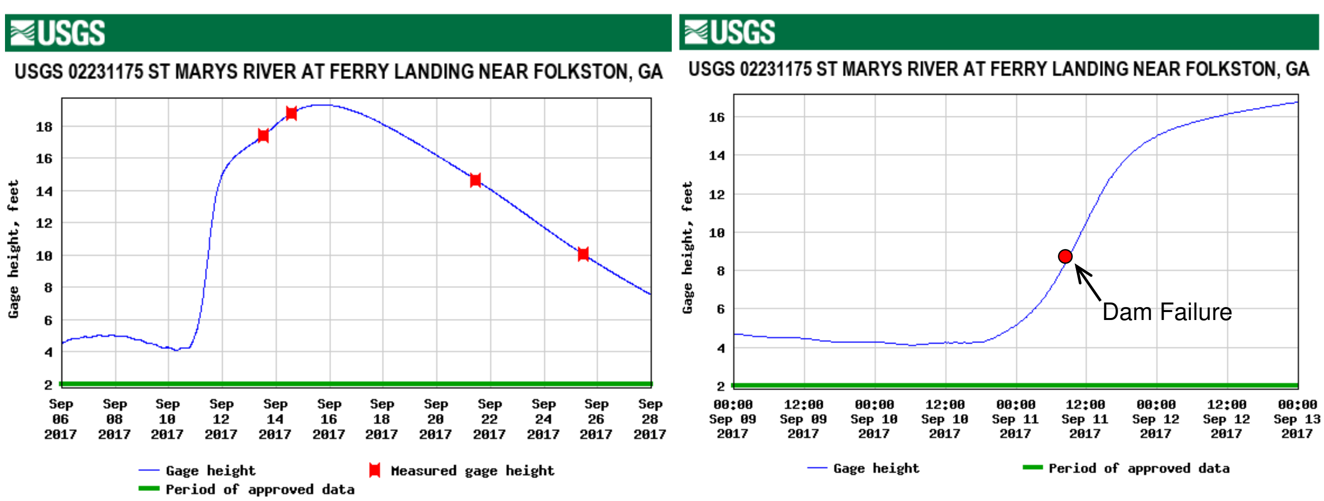

Figure 19: St. Marys River hydrograph elevations in NAVD 88 *at the USGS 02231175 St. Marys River gage at Ferry Landing near Folkston, Georgia, prior to and after Hurricane Irma (USGS 2018).*

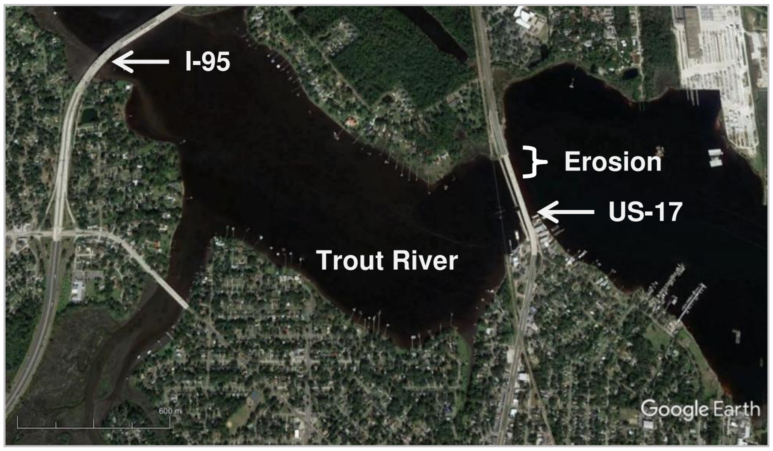

Figure 20: Location of the US 17 bridge over the Trout River in Jacksonville, Florida (Google Earth 2018).

Trout River Bridge Embankment

The US-17 bridge (structure number 720011, Figure 20) over the Trout River in Jacksonville, Duval Country, Florida, was built in 1958 and has four lanes that convey approximately 12,000 vehicles per day (City-Data, 2018). The Trout River is a tributary of the St. Johns River and thus tidally influenced. The soil embankment supporting the roadway sits atop a concrete support wall that is approximately 1 m to 2 m (3.2 to 6.6 ft) above the Trout River water level, depending on the tide. The soil embankment is stabilized along the front and sides by a concrete facing and supported at the furthest extent of the concrete where it meets the grassy embankment by a stacked concrete-sack wall. Utilities are installed in the embankment 1.5 m (4.9 ft) below the finished grade, and include sewer pipes, access structures, and electrical conduit.

Figure 21. Erosion along the northeast embankment of the US 17 bridge over the Trout River at 30°23'45.44"N latitude and 81°38'53.95"W longitude shown from the north southward, including: (a) vessel washed ashore exacerbating scour, (b) an exposed sewer pipe and access structure, (c) exposed sewer pipe and electrical conduit and failed sidewalk, and (d) the terminus of scour at the stacked concrete sack wall where embankment cover was present (Hudyma et al., 2017).

The storm surge generated by Hurricane Irma ranged from 1.2 m to 1.6 m (3.9 ft to 5.2 ft) (Cangialosi et al., 2018) in height and extended into the Trout River, elevating water levels, overtopping the embankment support wall at the river level, and subjecting the northern embankments to erosion. Significant erosion occurred along the northeast bridge embankment on September 10, 2017, extending from the concrete cover of the embankment to approximately 140 m (459 ft) north into the grass- and brush-protected area embankment. The northernmost section of the embankment was protected by woody brush and small trees, and experienced minimal scour. The grass-protected, taller section of the embankment was scoured significantly into the slope (Figure 21b, c, d) to the extent that the edge of the road was undermined, concrete sidewalk panels were dislodged, and underground utilities were exposed and unsupported. The embankment section nearest the transition between the grass and concrete cover experienced the most scour, where the concrete cover was undermined to the stacked concrete sack wall and toward the bridge abutment (Figure 21d, Figure 22a). Localized scour also occurred along the northwest embankment at, and just beyond, the transition between the grass and concrete cover (Figure 22b), likely caused by an eddy current that developed after the high winds and surge accelerated the water through the constriction in the river. During the hurricane, several vessels broke free from their moorings and washed up on the embankment (Figure 21a), which created additional erosion as turbulent water flowed around these obstacles.

The GEER team visited the site two weeks after the scour damage occurred and repairs were partially completed. Construction crews had partially rebuilt the embankment to the design elevation and placed excavatable flowable fill into vertical trenches near the roadside to stabilize soil below the road and around underground utilities. Figure 23 shows a flowable fill trench adjacent to the northeast abutment (approximately 5 m long, 1 m wide, 6 m deep, or16.4 ft by 3.3 ft by 19.7 ft) and adjacent to the northeast section of road (approximately 21 m long, 1 m wide, 2 m deep, or 69 ft by 3.3 ft by 6.6 ft).

Figure 22. Scour damage along the (a) northeastern and (b) northwestern bridge embankment of the US 17 bridge over the Trout River at 30°23'44.43"N latitude and 81°38'54.13"W longitude (Hudyma et al., 2017).

Figure 23: Repaired northeastern bridge embankment for US 17 bridge over the Trout River at 30°23'45.44"N latitude and 81°38'53.95"W longitude that includes the rebuilt soil and excavatable flowable fill trench embankment (a) adjacent to the concrete covered, stacked concrete sack wall; and (b) roadway edge (Hudyma et al., 2017).

Infrastructure Reconnaissance and Challenges

Local reconnaissance occurred almost immediately to determine the severity of damage and options for repair, while the time required to mobilize the GEER team was great enough that much of the failure was already under repair during the site visit. The GEER team relied on knowledge of local eyewitnesses, professionals, and agencies to identify reconnaissance sites and site features, articulate the extent of the damage or failure of critical infrastructure, and provide evidence of failures and damage. A complete failure occurred at Lake Hampton Dam, in that the entire structure was compromised and the lake drained following the dam's breach. As there was little threat to further damage or public safety and a full dam repair would require detailed design and permitting, repairs to the dam could not occur quickly. This allowed the GEER team to thoroughly investigate the damage. However, had the dam remained partially intact, a more rapid repair response may have been made, and the GEER team would not have witnessed the full extent of the damage at the time of reconnaissance.

For the US-17 bridge over Trout River, immediate local reconnaissance determined the damage was a major risk to critical infrastructure and public safety that required immediate attention. For the case of the Jacksonville US-17 embankment, physical evidence of the dimensional extent or key features was not systematically documented prior to starting repairs; agencies/owners/contractors had to estimate the extent of the damages requiring repair in order to project the time, materials, and cost necessary to complete the repairs. Damage estimates are a fundamental quantifier of needed repairs that agencies should systematically collect to prioritize actions, identify trends, and exchange information with other agencies to stimulate rapid response, subsequent analyses, and future planning.

CONCLUSIONS

While Hurricane Irma tracked along the west coast of Florida, extreme rainfall and storm surge caused extensive geotechnical related damage across the entire state. In central Florida, extreme rainfall coupled with geologic conditions caused the formation of numerous sinkholes that affected infrastructure. Along the northeast coast, the storm's counterclockwise rotation caused significant storm surge, which in turn caused substantial erosion and scour on beaches. In northeast Florida, extreme rainfall and storm surge resulted in river flooding, as well as damaged bridge embankments and a small dam. A GEER team spent three days documenting the geotechnical damages in these areas at sites identified through collaboration with local, state, and federal authorities, news outlets, social media, and other professional contacts.

Observations documented herein are a small portion of the damages documented by the GEER team, which are a smaller subset of the actual cumulative damage imposed by this event. In addition to identifying and investigating several noteworthy impact sites, the team faced a number of challenges. Three of the biggest challenges were: (a) covering geographically widespread damage, (b) safely investigating potentially unstable areas, and (c) documenting damage before rapid repairs to important infrastructure. In the future, reconnaissance of widespread damage could be performed by using a sub-team with drones. Documentation of potentially unstable areas can be conducted with photogrammetry or terrestrial LiDAR. In cases where critical infrastructure is damaged and rapidly repaired, GEER teams must work closely with authorities who can provide documentation and their own reconnaissance reports.

Geotechnical reconaissance and documentation are typically focused on the visible damage. The sinkholes, retaining structure failures, and dam/slope failures documented by this effort were dramatic and instantly identified. Geoprofessionals, however, must also consider that visible damage has a strong potential to influence subsequent and long-term damage and failures, in both improved and adjacent soils. For instance, dune erosion caused a decrease in stability from both oversteppening and loss of confinement, and thus makes adjacent infrastructure more prone to distress and potential failure. Similarly, soil movement from sinkhole formation could loosen adjacent soils and increase the likihood of adjacent sinkholes forming. Follow-up investigations should evaluate subsurface conditions and potential subsurface vulnerabilities (e.g., areas of erosion, spread footings, etc.) not readily accessible by reconnaissance efforts such as that of the GEER mission.

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APPENDIX – ADDITIONAL RESOURCES

FDEP Subsidence Incident Reports: <https://floridadep.gov/fgs/sinkholes/content/subsidence-incident-reports>
FDEP online sinkhole map: <https://ca.dep.state.fl.us/mapdirect/?focus=fgssinkholes>