Geotechnical Extreme Events Reconnaissance
Turning Disaster into Knowledge
Sponsored by the National Science Foundation

Geotechnical Damage in Central and Northeastern Florida from Hurricane Irma



Team Leadership:
Team Leader: Nick Hudyma, Ph.D. P.E. (University of North Florida)
Team Co-Leader: Melissa Landon, Ph.D. (University of Maine)
Team Co-Leader: Radhey Sharma, D.Phil. (West Virginia University)

Team Members (Alphabetical Order):
Cigdem Akan, Ph.D. (University of North Florida)
Christopher J. Brown, Ph.D. P.E. (University of North Florida)
Rafael Crowley, Ph.D. P.E. (University of North Florida)
William Dally, Ph.D. P.E. (University of North Florida)
Xiaoyu Song, Ph.D. (University of Florida)

GEER Association Report No. GEER-056b
Version 1
October 2017

EXECUTIVE SUMMARY

Hurricane Irma formed in the far eastern Atlantic Ocean at 16.4 N and 30.3 W. On September 5, 2017 Irma intensified to a Category 5 on the Saffir-Simpson Hurricane Wind Scale. On September 7, 2017 the first hurricane related watches and warnings were announced for the State of Florida. Irma made landfall at Cujoe Key, Florida just after 9 AM on September 9, 2017 as a Category 4 hurricane. Later that day Irma made a second landfall at Marco Island, FL. This large storm traveled north through the central portions of Florida and was downgraded to a Category 1 Hurricane after passing the Tampa-St. Petersburg area. Eventually the storm was downgraded again to a tropical storm when it was approximately 115 km east of Tallahassee. Estimates for the damages from Hurricane Irma range from $25 to $35 billion[1] all the way up to $100 billion[2] dollars. There were numerous required evacuated zones in Florida and an estimated 6.3 million people were under evacuation orders[3]. Up to 7 million Floridians lost power during the storm[4].

Two teams from the Geotechnical Extreme Events Reconnaissance (GEER) Association, supported by the National Science Foundation, were deployed to investigate geotechnical impacts of intense rainfall, flooding, storm surge and wave forcing in Florida in response to Hurricane Irma. The teams worked collaboratively with federal, state, and local organizations in Florida. This report provides documentation of the geotechnical related damage in central and northeastern Florida. The geotechnical related damage includes erosion and scour of affecting residential structures, bridges, and retaining walls, sinkholes formed as a result of significant rainfall, damage from overwash and washover deposits, and failure of a concrete covered earth dam. It is hoped the data collected will provide guidance for planning, design, construction, and risk of assessment of infrastructure in geographically hurricane prone areas.

[1] Retrieved from http://money.cnn.com/2017/09/15/news/economy/irma-harvey-damage-who-pays/index.html
[2] Retrieved from http://time.com/money/4935684/hurricane-irma-harvey-economic-cost/
[3] Retrieved from http://www.cnn.com/2017/09/08/us/hurricane-irma-evacuation-florida/index.html
[4] Retrieved from https://www.usatoday.com/story/news/nation-now/2017/09/10/more-than-3-million-without-power-florida-hurricane-irma-makes-landfall-keys/651078001/

ACKNOWLEDGEMENTS

The work of the GEER Association is based upon work supported in part by the National Science Foundation through the Geotechnical Engineering Program under Grant No. CMMI-1266418. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF. The GEER Association is made possible by the vision and support of the NSF Geotechnical Engineering Program Directors: Dr. Richard Fragaszy and the late Dr. Cliff Astill. GEER members also donate their time, talent, and resources to collect time-sensitive field observations of the effects of extreme events. The GEER Association web site, which contains additional information, may be found at: *www.geerassociation.org*.

The authors conducted damage reconnaissance at selected sites affected by Hurricane Irma in the State of Florida two weeks after the event that occurred in September 2017. The focus of this GEER effort was to collect sinkhole damage from central Florida, beach damage along the northeast Florida coast, and bridge and hydraulic structure damage from the Jacksonville area. The authors greatly appreciate the contribution of the following persons and entities to make the GEER reconnaissance possible:

- **Florida Department of Transportation** including Binay Prakash PE, Robert S. Kosoy PE, Matt Gisondi PE, Richard Prindiville, Pablo Orozco PE, Alex Perez PE, and Brian Jimmerson, PE
- **US Army Corps of Engineers (Jacksonville District)** including Crystal Markley PE, Daniel Blades PE, and Carlos Cepero PE
- **Others** including Raymond Saliba PE (Saliba Engineering Inc.), Ben Kaimen EI (W.R. McCain & Associates, Inc.), Jacob Wirz (Project Manager, DBi Services), Richard Bonner (Soil and Water Conservation District Supervisor), Don Resio PhD (University of North Florida), Steven McCorey (Dynamic Marine Constriction), Jason Gowland PE (GSE Engineering & Consulting, Inc.), Michael Gibson, PE (Westra Construction Corp.), Earl Bright (Caila Contracting, LLC), Joshua Oglesby (University of North Florida), Angela Jacobs (WFTV Ch. 9 Eyewitness News), Doug Wernicke (resident of The Villages), Barbara Beveridge (resident of The Villages Alhambra), Dan Snyder (resident of The Villages Alhambra) and Sheila Huffman Dailey (resident of The Villages Alhambra).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

This Geotechnical Extreme Event Reconnaissance (GEER) report presents documentation of geotechnical damage from Hurricane Irma in central and northeastern Florida. A companion report has been prepared for southwest coastal Florida from Cape Coral to Key West. The purpose of these reports is to document both geotechnical damage and perishable data from this event.

1.1 Hurricane Irma

Hurricane Irma formed in the far eastern Atlantic Ocean at 16.4 N and 30.3 W. On September 5, 2017 Irma intensified to a Category 5 hurricane on the Saffir-Simpson Hurricane Wind Scale with maximum winds of 175 mph (280 km/h) with higher gusts.

On September 7, 2017 the first warnings of hurricane related watches and warnings for Florida from Irma were announced. A storm surge watch and hurricane watch were issued from Jupiter Inlet southward around the Florida peninsula to Bonita Beach, including the Florida Keys.

On September 8, 2017 the hurricane watch became a hurricane warning for Jupiter Inlet southward around the Florida peninsula to Bonita Beach. The hurricane watch and storm surge watch extended to north of Jupiter Inlet to Sebastian Inlet on the east coast and north of Bonita Beach to Anna Maria Island on the west coast of Florida.

Just after 9 AM Sunday September 10, 2017 Hurricane Irma made landfall at Cujoe Key, FL as a Category 4 hurricane with sustained winds of 209 km/hr. Later that day, at approximately 3:35 PM, Irma made a second landfall at Marco Island, FL as a Category 3 hurricane with sustained winds of 185 km/hr. The highest wind just in Florida during Hurricane Irma was recorded as approximately 225 km/hr as the Naples, FL airport.

Hurricane Irma continued traveling north along central portions of Florida. At 2:AM EST Monday September 11, 2017 Hurricane Irma was approximately 40 km northeast of the Tampa-St. Petersburg area. It was downgraded again to a Category 1 hurricane. At 11:00 AM EST Hurricane Irma was downgraded to a tropical storm and it was located approximately 115 km east of Tallahassee, FL. By approximately 5:00 EST, tropical storm Irma had left the state of Florida. The path of the hurricane/tropical storm through Florida is shown in Figure 1.

One of the most surprising aspects of Hurricane Irma was its large size and slow movement. Figure 2 shows the size of the storm with respect to Florida. Figure 2a is a composite image from data collected by the GOES-13 satellite from 8:15 AM on September 10, 2017. At this time the hurricane was passing over the Florida Keys. Figure 2b is an image extracted from a gif file of the GOES-East visual satellite image. The image was take at 2:15 AM on September 11, 2017. It is clear from both images that Hurricane Irma was large enough to affect the whole state of Florida. The greatest impacts were across the eastern portion of the state along the I-75 corridor. An estimated 6.5 million people were without power in Florida[5]. Significant rainfall occurred throughout the state with the highest amounts along the east coast, most

[5] Retrieved from https://www.weather.gov/tae/Irma2017

notably in Jacksonville. The three-day rainfall totals, from September 9 through September 11 are shown in Figure 3

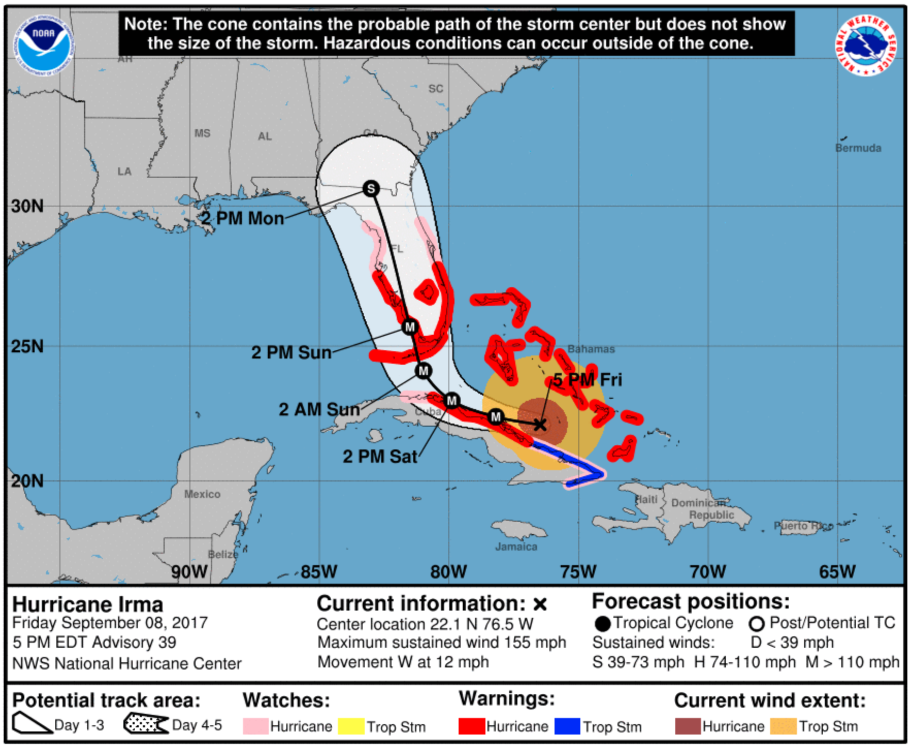


Figure 1. Path of Hurricane Irma through Florida[6]

a) Composite image from GOES-13 from September 10 at 8:15 AM[7].

b) GOES-EAST visual satellite image from Sept. 11 at 2:15 AM[8].

Figure 2. Size of Hurricane Irma.

---

[6] Retrieved from: http://www.nhc.noaa.gov/archive/2017/IRMA_graphics.php?product=3day_cone_with_line_and_wind

[7] Retrieved from: https://www.earthobservatory.nasa.gov/IOTD/view.php?id=90948

[8] Retrieved from: http://www.ospo.noaa.gov/Organization/History/imagery/Irma/index.html

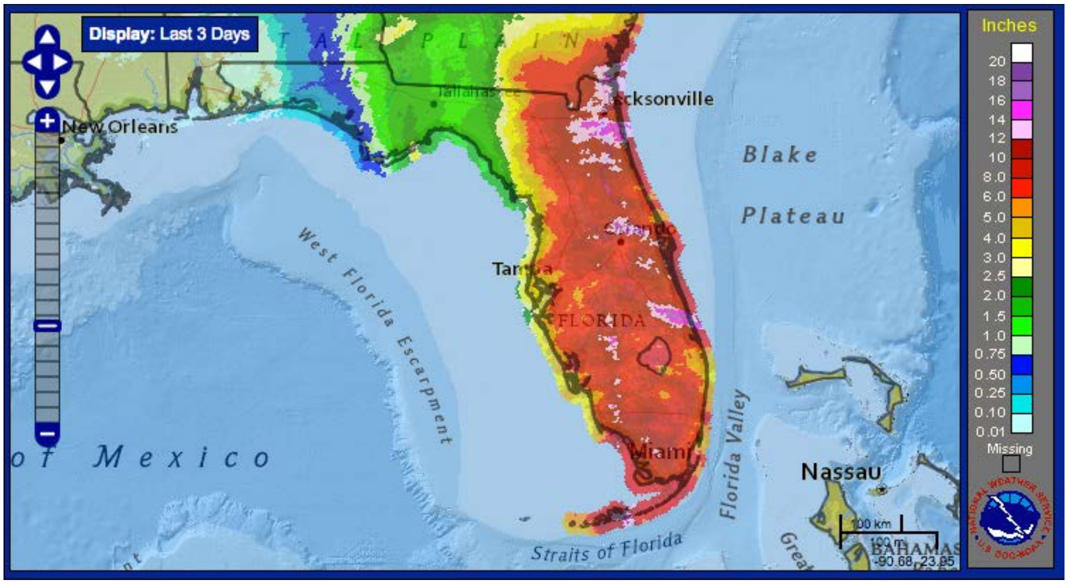


Figure 3. Rainfall totals from September 9 through 11, 2017 from Hurricane Irma[9]

1.2 GEER Team

The GEER leadership members were mobilized to Jacksonville, FL on Sunday September 24, 2017. The GEER leader, Nick Hudyma, is a professor at the University of North Florida in Jacksonville. Co-leader Melissa Landon is an associate professor at the University of Maine. Co-leader Radhey Sharma is a professor at West Virginia University. Jacksonville was the home base for the leadership team throughout the reconnaissance efforts.

The GEER team consisted of five additional members. A large team was organized because of the diverse geotechnical related damages associated with Hurricane Irma in the central and northeastern portions of Florida. Xiaoyu Song is an assistant professor from the University of Florida with an interest in sinkholes. He was part of the team for the central Florida reconnaissance on sinkhole damage.

Cigdem Akan and Rafael Crowley are assistant professors and William Dally is an associate professor at the University of North Florida in coastal engineering. William Dally organized the reconnaissance trip along the northeastern coast of Florida to document geotechnical damage.

Christopher J. Brown is an associate professor at the University of North Florida. He is a water resources engineer. He assisted the leadership team in documented geo-hydrological damage in the Jacksonville Florida areas.

1.3 Reconnaissance Areas

The GEER team documented geotechnical damage in three reconnaissance areas: Central Florida, northeast (NE) Florida Beaches, and Jacksonville. Within each of the reconnaissance areas there were a

---

[9] Retrieved from: http://www.cleveland.com/weather/blog/index.ssf/2017/09/how_does_irma_compare_to_harve.html

number of reconnaissance locations. Some reconnaissance locations were divided into reconnaissance sites. The reconnaissance areas are shown in Figure 4.

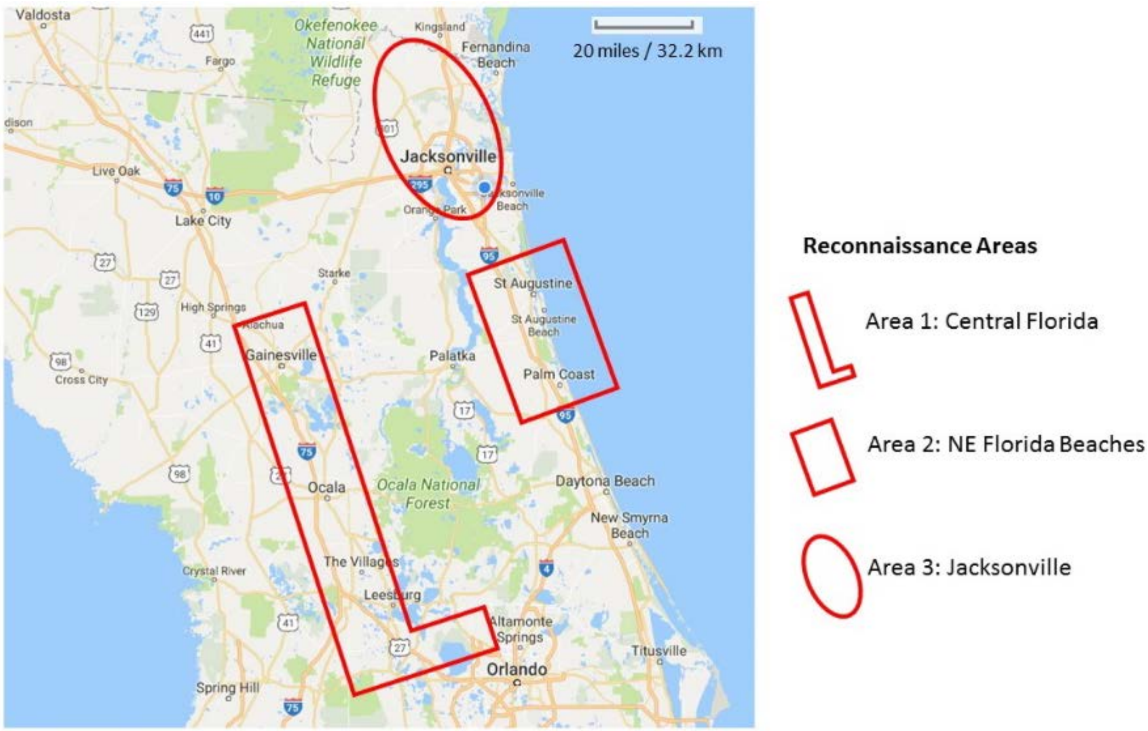


Figure 4. Reconnaissance areas for damage reconnaissance (from Google Maps, 2017).

On Monday September 25, 2017 the reconnaissance team visited Area 1 to document sinkhole damage. Area 1 covers a portion of the I-75 corridor in central Florida from approximately Gainesville to Orlando. The first stop in Area 1 was Gainesville where two locations were documented. The team then progressed south to Ocala for the second reconnaissance location. The third and fourth reconnaissance areas were in The Villages. The final reconnaissance area, located east of the I-75 corridor, was the city of Apopka.

On Tuesday September 26, 2017 the reconnaissance team visited Area 2 to document coastal damage on the beaches of Northeast Florida. The team began their documentation at the southernmost location and progressed northward during their reconnaissance. Location 1 was at Beverly Beach in Flagler County. The team progressed north to Location 2, Painters Hill in Flagler County, to document damage at two sites. Location 3, Marineland, is located on the boarder of Flagler County to the south and St. Johns County to the north. Two sites were documented at Location 3. Location 4 was the St. Johns County Ocean Pier. The final location, Location 5, was Vilano Beach in St. Johns County.

On Wednesday September 27, 2017 the reconnaissance team visited Area 3 to document bridge and hydraulic structure damage. The first location was near Hilliard in Nassau County, FL which is north of Jacksonville. Location 2 was in the Jacksonville Historic District near downtown Jacksonville. Two sites were visited in Location 2. Location 3 was at the US 17 bridge over Trout River in north Jacksonville.

2 SINKHOLE FORMATION AND DAMAGE RECONNAISSANCE IN CENTRAL FLORIDA

2.1 Near Surface Geology and Sinkholes in Central Florida

The near surface geology in central Florida consists of sand and clay overlying limestone. The surface deposits are undifferentiated siliciclastic sediments of late Miocene to Plio-Pliestocene in age. They consist of quartz and carbonate sands as well as muds, marl, and organics[10,11]. This unit varies in thickness of 0 to 20 m in central Florida[11].

Beneath the surficial sands is the Hawthorn Group which is Miocene to early Plio-Pliestocene in age. The unit consists of interbedded and intermixed siliciclastics, carbonates, and varying percentages of phosphates[12]. The thickness of this unit in central Florida ranges between 0 m to 75 m[11]. This unit sits unconformably on the underlying Ocala Limestone, which is Upper Eocene in age, consists of nearly pure limestone and dolostones[10]. The top elevation of the limestone is extremely variable due to karstification caused by weathering[13]. An example of the variability of the upper surface of the Ocala limestone is shown in Figure 5, which demonstrates a series of closely spaced borings conducted in a retention pond along State Road 26 in Alachua County, Florida[14]. Within a horizontal distance of 17 meters, limestone appears at the ground surface (B-7) and does not appear within a 10 meter depth boring (B-4). An even more dramatic example is seen between borings B-7 and B-6. Within a distance of approximately 2.5 meters the bedrock surface drops approximately 6.5 meters.

The two dominant sinkhole types in central Florida are cover subsidence sinkholes and cover collapse sinkholes. The mechanisms for sinkhole formation for these types of sinkholes are shown in Figure 6. It is important to understand the subsurface features, namely a weathered limestone rock mass with a block/slot/pinnacled structure with associated enlarged vertical fractures and bedding planes, already exists in the subsurface. One of the triggering events for sinkholes is an influx of water, such as heavy rainfall.

For cover subsidence sinkholes, the influx of rain causes movement of granular materials into pre-existing enlarged vertical fractures or slots which may be connected to existing cavities. The granular material moving into the openings causes ground loss and a sinkhole is formed.

---

[10] Scott, T. M. (2001). Text to accompany the geologic map of Florida (Open File Report Number 80). Tallahassee, FL: Florida Geological Survey

[11] Kim, Y. J., Xiao, H., Choi, Y. W., & Nam, B. H. (2017). Development of sinkhole hazard mapping for central Florida. In T. L. Brandon and R. J. Valentine (Eds.), *Geotechnical Frontiers 2017: Transportation Facilities, Structures, and Site Investigation, Geotechnical Special Publication No. 277*, Orlando, FL (pp. 459-468). Reston, VA: American Society of Civil Engineers.

[12] Campbell, K, M. and Scott, T. M. (1991). Radon potential study, Alachua County Florida: near-surface stratigraphy and results of drilling (Open File Report Number 41). Tallahassee, FL: Florida Geological Survey.

[13] Randazzo, A. F. (1997). The Sedimentary Platform of Florida: Mesozoic to Cenozoic. In A. F. Randazzo and D. S. Jones (Eds.), The Geology of Florida (pp. 39-56). Gainesville: University Press of Florida.

[14] Hudyma, N., Ruelke, T., & Samakur, C. (2005). Characterization of a sinkhole prone retention pond using multiple geophysical surveys and closely spaced borings. In B. Beck (Ed.), *Proceedings of the 10th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst: Geotechnical Special Publication No. 144,* San Antonio, TX (pp. 555-561). Reston, VA: American Society of Civil Engineers.

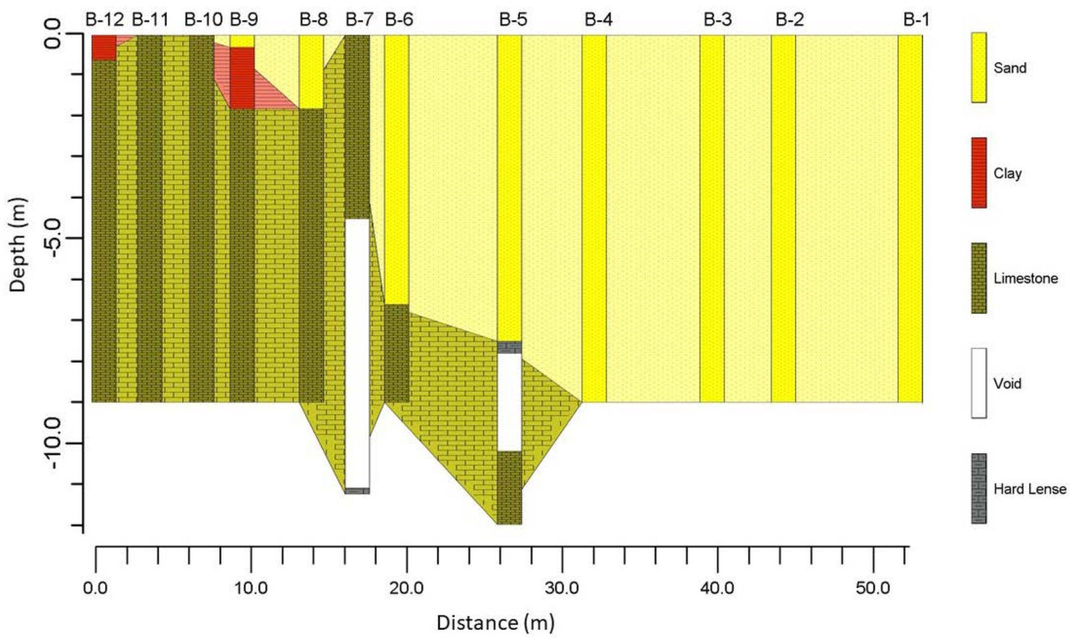


Figure 5: Example of variability of top of bedrock in Alachua County in central Florida (from Hudyma et al. 2005).

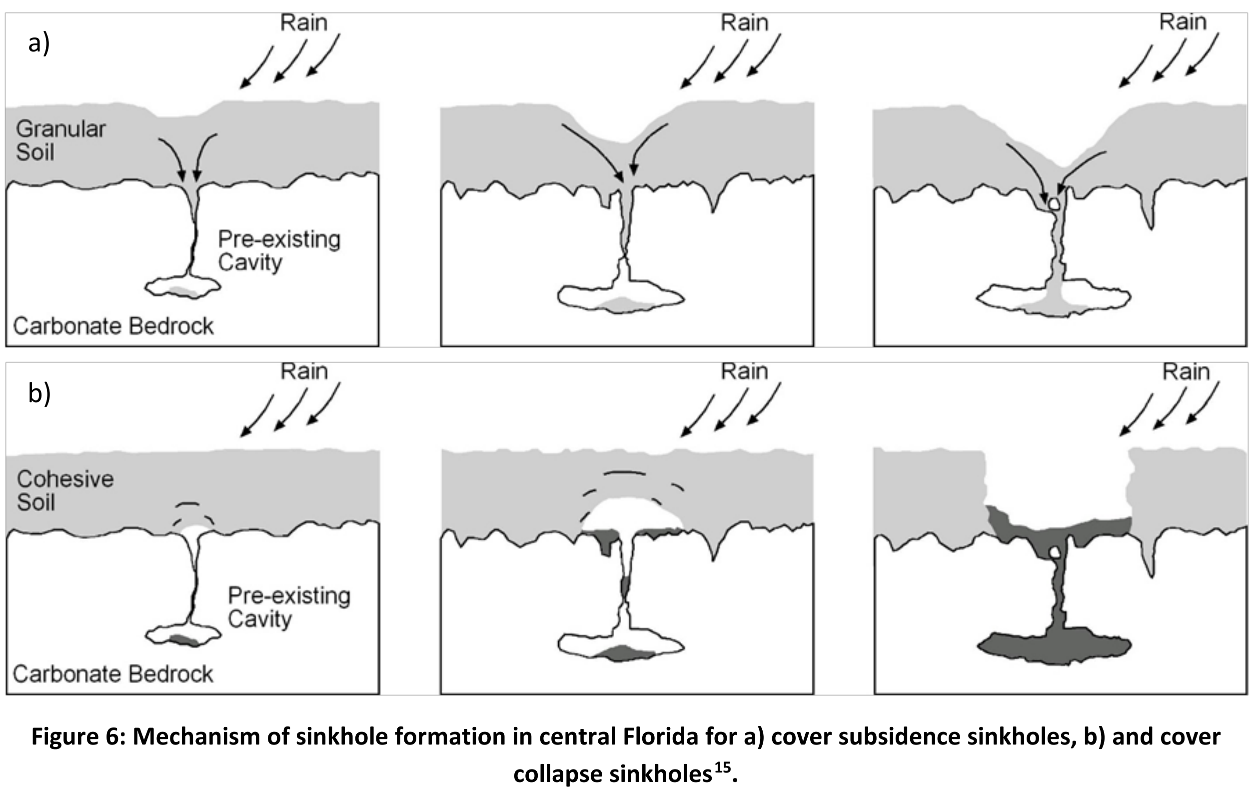


Figure 6: Mechanism of sinkhole formation in central Florida for a) cover subsidence sinkholes, b) and cover collapse sinkholes[15].

For cover collapse sinkholes, predominately plastic soils overlie weathered limestone with pre-existing enlarged vertical fractures or slots which may be connected to existing cavities. An influx of water may

[15] Hudyma, N. (2017). Lecture notes from CEG 4302/5304 Applied Engineering Geology. University of North Florida.

cause downdrag or spalling of layers beneath the surface. Tension cracks may form within the soil. Eventually the over will experience sudden collapse and a sinkhole will be formed.

Sinkhole activity in central Florida is well known and somewhat well documented. Over 2800 sinkholes have been reported in Central Florida since 1954[11].

2.2 Reconnaissance Locations

Sinkhole formation and damage reconnaissance was conducted on Monday September 26, 2017 in central Florida by GEER team members Nick Hudyma, Melissa Landon, Radhey Sharma, and Xiaoyu Song. Locations were identified through local geotechnical engineering contacts, the Florida Department of Transportation, social media, and traditional media outlets. The reconnaissance began in Gainesville, Florida where the team investigate sinkholes in and along a retention pond at Turnberry Lake subdivision (Location 1) and south of the I-75 and SR 26 interchange (Location 2). The team then drove south along I-75 to Location 3 in Ocala, FL. Here the team investigated two sites, each with sinkholes within and along retention ponds. Location 4 and 5 were in The Villages, which is southwest of Ocala. Here the team documented sinkholes in retention ponds, golf courses, between houses, beneath a house and in front of a house along a residential street. Location 7 was in the city of Apopka, which is southwest of The Villages, where the team documented a large erosional gully. The locations are shown in Figure 7.

Figure 7. Map showing locations visited for sinkhole formation and damage reconnaissance resulting from Hurricane Irma (data from Google and ESRI mapping).

2.3 Rainfall Data from Hurricane Irma

Since intense rainfall is often a triggering event for sinkhole formation in central Florida, the GEER team collected historical rainfall records from before and after the hurricane event. The data are presented in Figure 8 and Table 1. Based upon rainfall data, the six sites fall into one of two categories. The first category is significant rainfall on a single day. Sites 3, 4, and 5 received significant rainfall on only September 11, 2017. The second category is significant rainfall over two days. Sites 1, 2, 6 received significant rainfalls over both September 10 and 11, 2017.

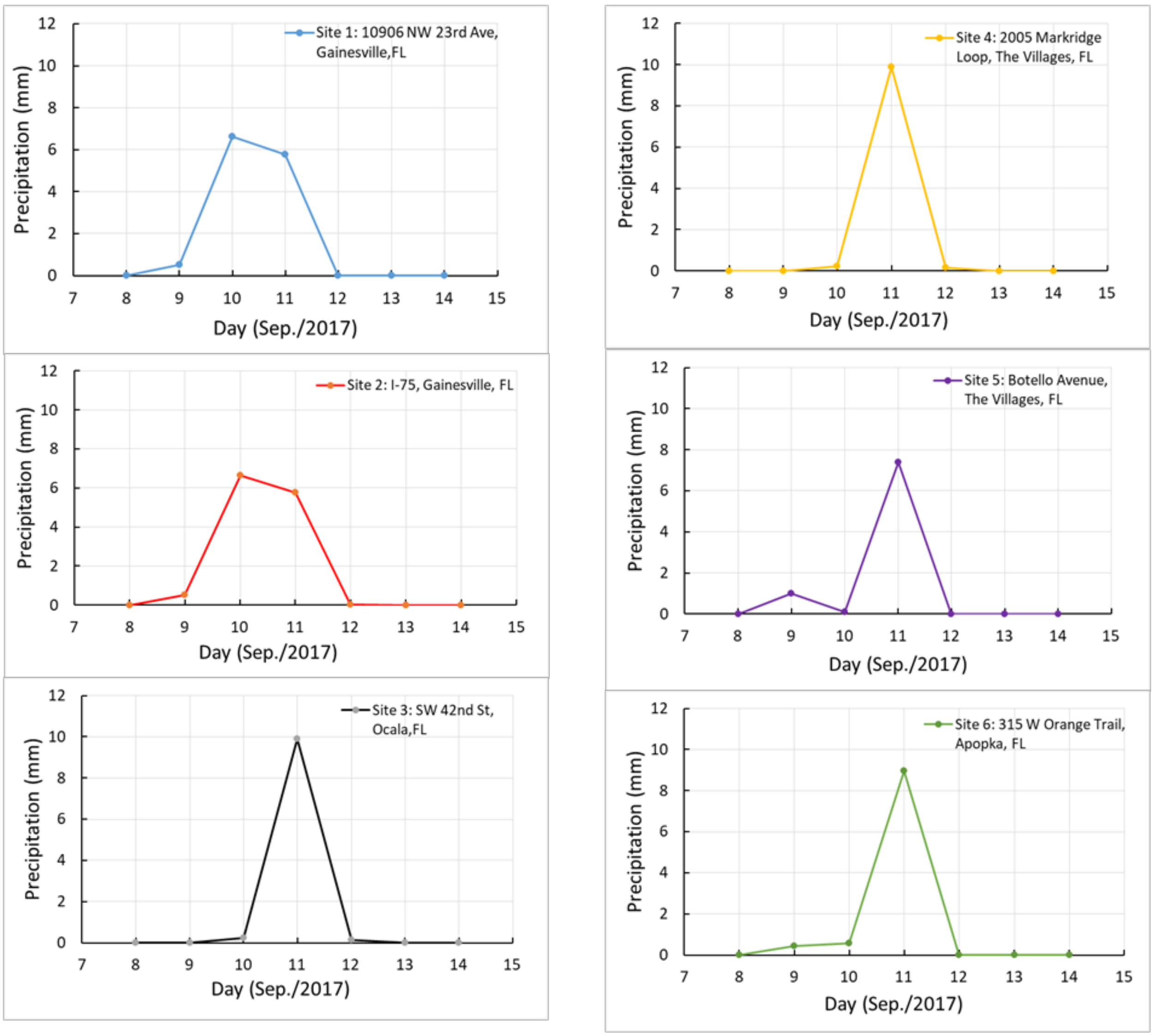


Figure 8: Rainfall before, during, and after Hurricane Irma for the six sinkhole reconnaissance sites[16].

[16] Retrieved from: https://www.cocorahs.org/Maps/ViewMap.aspx?state=FL

Table 1. Rainfall before, during, and after Hurricane Irma for the six sinkhole reconnaissance sites[17].

Sites	Coordinates	Rainfall (mm) from dates in September 2017						
		8	9	10	11	12	13	14
Site1: Turnberry Lake	29°40'35.01"N / 82°29'43.58"W	0	0.53	6.63	5.77	0.01	0	0
Site 2. I-75 and SR 26	29°39'8.00"N / 82°24'44.00"W	0	0.53	6.63	5.77	0.01	0	0
Site 3. Fore Ranch Community	29° 8'47.98"N / 82°12'31.30"W	0	0	0.22	9.90	0.15	0	0
Site 4: The Villages	28°53'0.90"N / 82° 0'1.00"W	0	1.00	0.11	7.38	0	0	0
Site 5. The Villages Alhambra	28°57'11.67"N / 81°59'30.05"W	0	0.44	0.56	8.97	0	0	0
Site 6. Apopka	28°41'7.44"N / 81°30'25.61"W	0	0.30	1.34	10.24	0	0	0

2.4 Location 1: Turnberry Lake Retention Pond

Figure 9 shows the location of five sinkholes and one depression identified within and near a retention pond associated with the Turnberry Lake community at approximately 2800 NW 143 Street, Gainesville, FL. Figure 10 and Figure 11 provide images of the sinkholes locations across the site that complement the measured geometries and featured indicated in Figure 12.

Figure 9 indicates that the location of sinkhole "B" is where a concrete drainage pipe exists to drain water from the Turnberry Lake community into the retention pond. The outfall location was previously reinforced with broken concrete, where water would run over the concrete instead onto the soil of the retention pond. During the site visit, the foreman of a work crew responsible for fencing in the location for safety that day indicated that at least one sinkhole had previously formed at the location where the reinforcing concrete was piled at the outfall.

[17] Retrieved from: https://www.cocorahs.org/Maps/ViewMap.aspx?state=FL

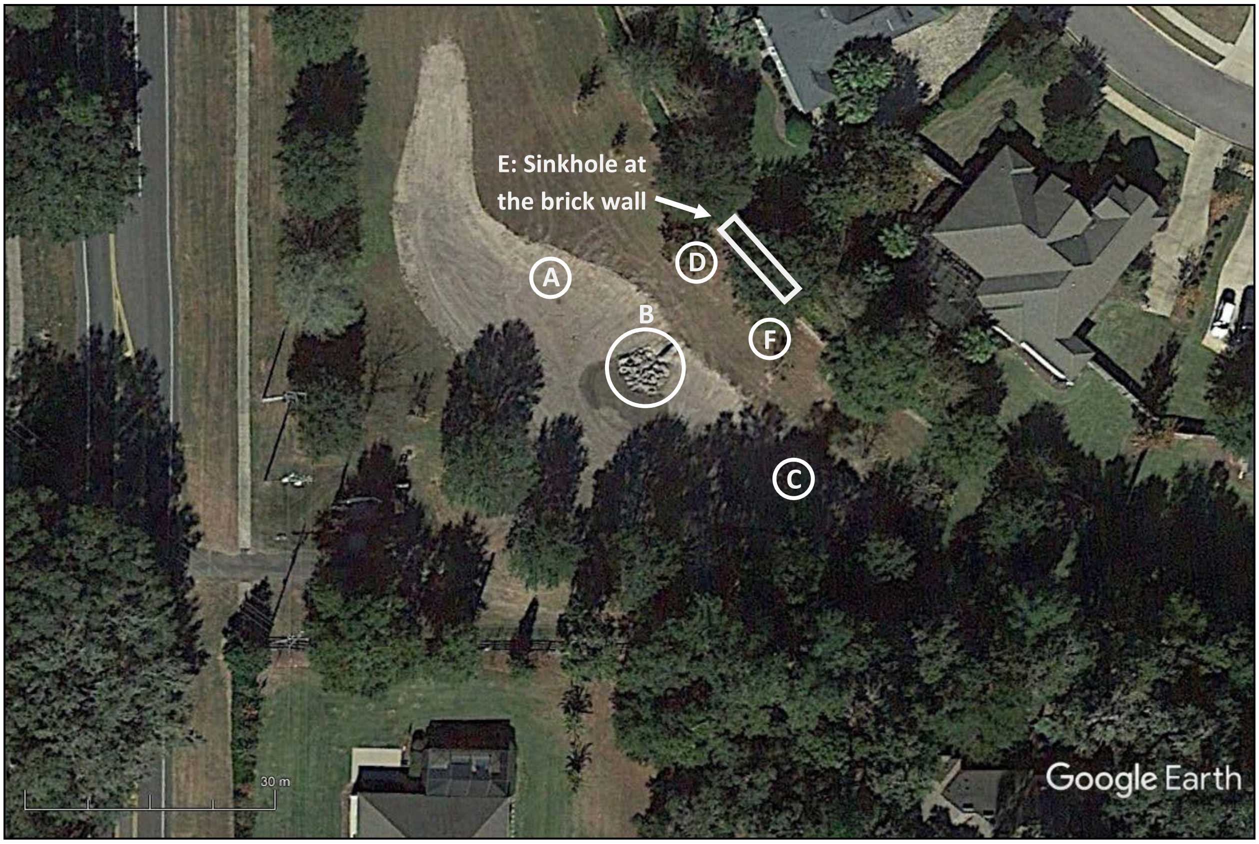


Figure 9: Approximate locations of five sinkholes (A-E) and a depression (F) within and nearby a retention pond near 2800 NW 143 Street, Gainesville, FL (Latitude: 29°40'34.84"N / Longitude: 82°29'43.31"W) (from Google Earth, 2016).

The additional four sinkholes (A, C, D, E) and depression (F) were assumed to have occurred as a result of Hurricane Irma, however it is uncertain if any had opened prior to the Hurricane (e.g., the sinkhole "E" at the brick wall). Figure 13 through Figure 17 document in image form the sinkholes, depression, and overland flow within the retention pond from location "A" to "B" that were cataloged by the GEER team.

Figure 10: Image of the retention pond showing the locations of wetted clay (left), sinkhole "A", sinkhole "B" with the drainage outfall, sinkhole "D", and sinkhole "E" under the brick wall of the community, and depression "F" (Latitude: 29°40'48.05"N / Longitude: 82°29'43.61"W).

Figure 11: Image of the retention pond showing the locations of sinkhole "B" with the drainage outfall, sinkhole "C", sinkhole "E" under the brick wall of the community, depression "F", and evidence of the of water flow into sinkhole "B" in the retention pond foreground from the storm event (Latitude: 29°40'48.05"N / Longitude: 82°29'43.61"W).

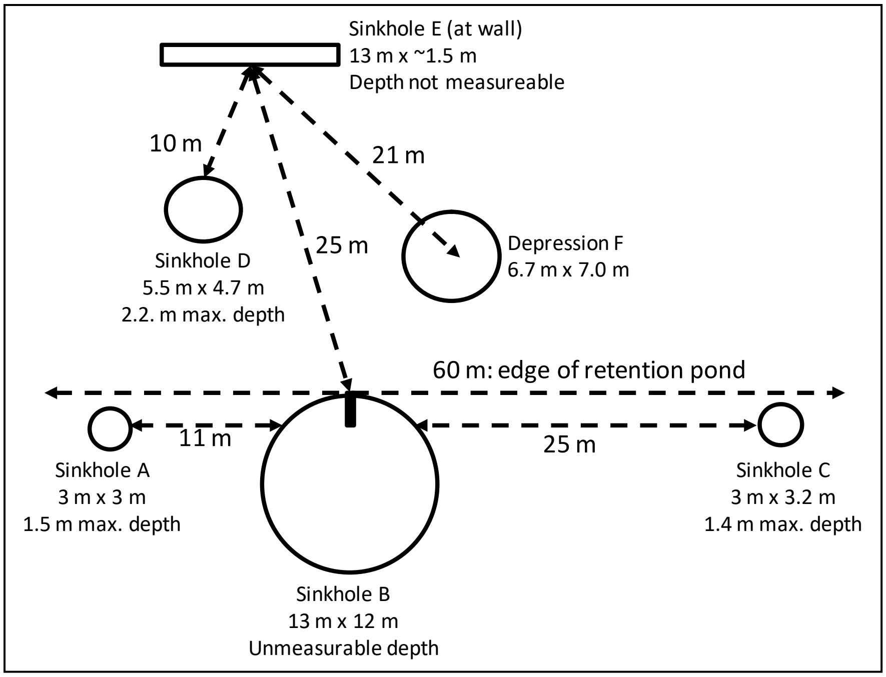


Figure 12: Approximate geometry of the five sinkholes (A-E) and depression (F) at the retention pond near 2800 NW 143 Street, Gainesville, FL (Latitude 29°40'34.84"N / Longitude 82°29'43.31"W).

Figure 13: Image of sinkhole "A" that is 3 m in diameter with a maximum depth of 1.5 m (Latitude 29°40'47.99"N / Longitude: 82°29'42.99"W).

Figure 14: Image of sinkhole "C" that has 3.2 and 3.0 m diameters and a maximum depth of 1.4 m (Latitude 29°40'47.69"N / Longitude 82°29'43.25"W).

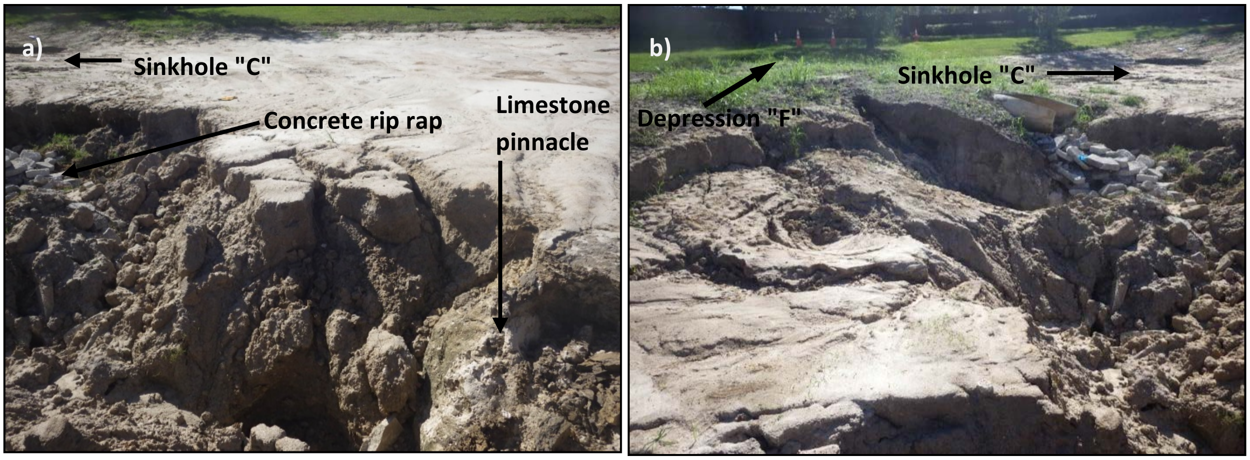


Figure 15: Sinkhole "B" showing a) limestone pinnacle (right), concrete rip rap (left), and location of sinkhole "C" (Latitude 29°40'47.57"N / Longitude: 82°29'43.37"W) and b) showing the extent of the newly developed depression behind the outfall pipe, the location of sinkhole "C", and the location of depression "F" (Latitude 29°40'47.57"N / Longitude: 82°29'43.37"W).

Figure 16: a) Erosion from overland flow within the retention area, where the direction of water flow was from sinkhole "A" toward sinkhole "B" (Latitude 29°40'48.47"N / Longitude 82°29'43.94"W), and b) toppled brick wall over a 12.5 m length at sinkhole "E" (Latitude 29°40'25.12"N / Longitude 82°29'48.35"W).

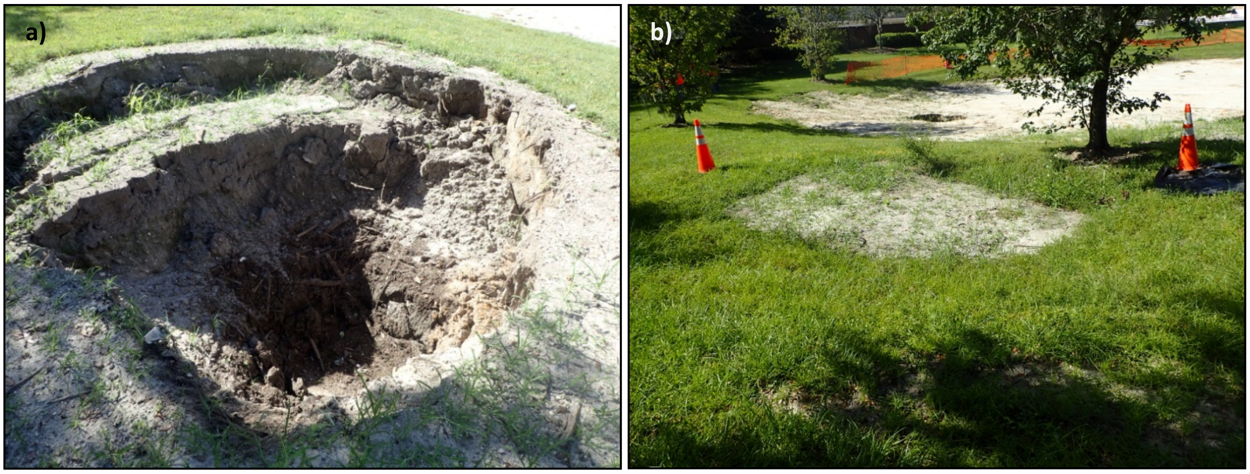


Figure 17: a) Sinkhole "D" (Latitude 29°40'48.85"N / Longitude: 82°29'43.13"W and b) newly developed depression "F" (Latitude 29°40'47.99"N / Longitude 82°29'41.99"W).

2.5 Location 2: South of the I-75 and SR 26 Roadside

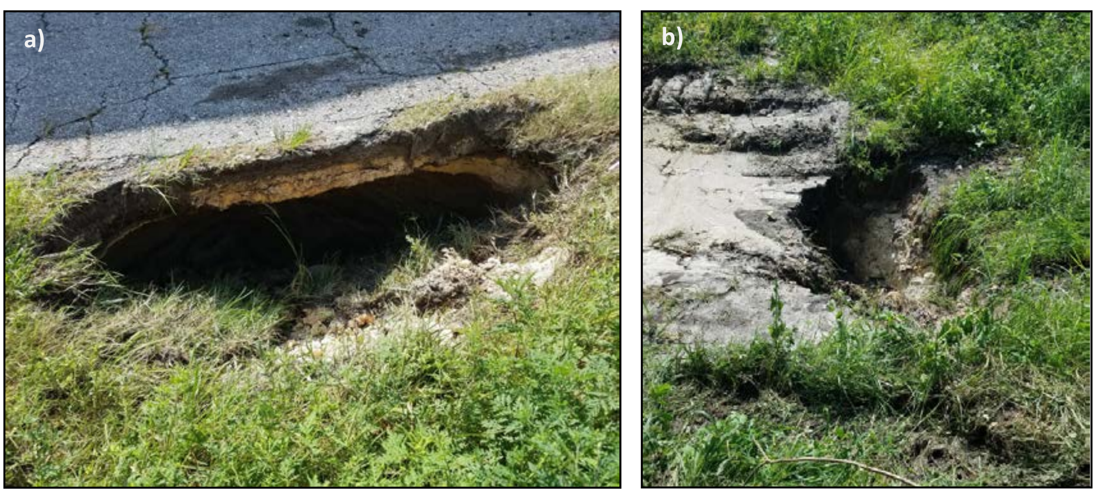
I-75 is the major north-south interstate in west and central Florida. In the Gainesville area, truck traffic is estimated at average daily traffic (AADT) 0f 13,800 to 36,600 vehicles per day[18]. The propensity of sinkhole formation in central Florida and the high traffic volumes on I-75 means that sinkhole detection and repair along I-75 is of the utmost importance. Detected open sinkholes along the I-75 right of way receive emergency treatment to arrest sinkhole growth.

The reconnaissance team visited a repaired sinkhole beneath the northbound shoulder of I-75 south of SR 26 in Gainesville, FL (Figure 18). A small sinkhole developed near the edge of the pavement, and two larger sinkholes developed on the far slope and within the of the drainage ditch. It appears that drainage and/or overland from the two residential communities and mall parking lot (Figure 18) may have contributed to sinkhole formation at this location. Mr. Binay Prakash of Florida DOT (FDOT) indicated that historically this location has had sinkholes, from as recently as June 2017, and that this location is routinely monitored for new sinkhole activity. When the sinkhole was first noticed under the shoulder of the roadway (Figure 19a), it was immediately filled with compacted soil. Two other sinkholes formed at the location, one low area of the drainage ditch (Figure 19b) and one on the back slope of the drainage ditch (Figure 19c, d). The dimensions of each of these sinkholes and their locations with respect to site features were not available to the GEER team because the sinkholes were repaired and the fill used to stabilize the sinkholes masked the locations and dimensions

[18] Florida DOT (2010). I-75 Sketch Interstate Plan Technical Memorandum. Retrieved from: http://www.fdot.gov/planning/systems/programs/sm/corridor/Sketch/I-75%20North/Freight%20Mobility_Final.pdf.

Figure 18: Location of Interstate I-75 northbound lane sinkholes in Gainesville, FL (Latitude 29°39'8.00"N / Longitude 82°24'44.00"W) (From Google Earth, 2017).

Figure 20 shows evidence of the repaired sinkhole that was encroaching on the I-75 northbound shoulder. During the site visit, the team witnessed geotechnical drilling operations whose purpose was to identify subsurface voids (Figure 21). The drilling data will be used to identify the geometry and extent of the sinkhole so that a grouting plan can be developed for the permanent repair of the sinkhole. Measurements indicate the length and width of the total distressed area are approximately 20 m by 20 m.



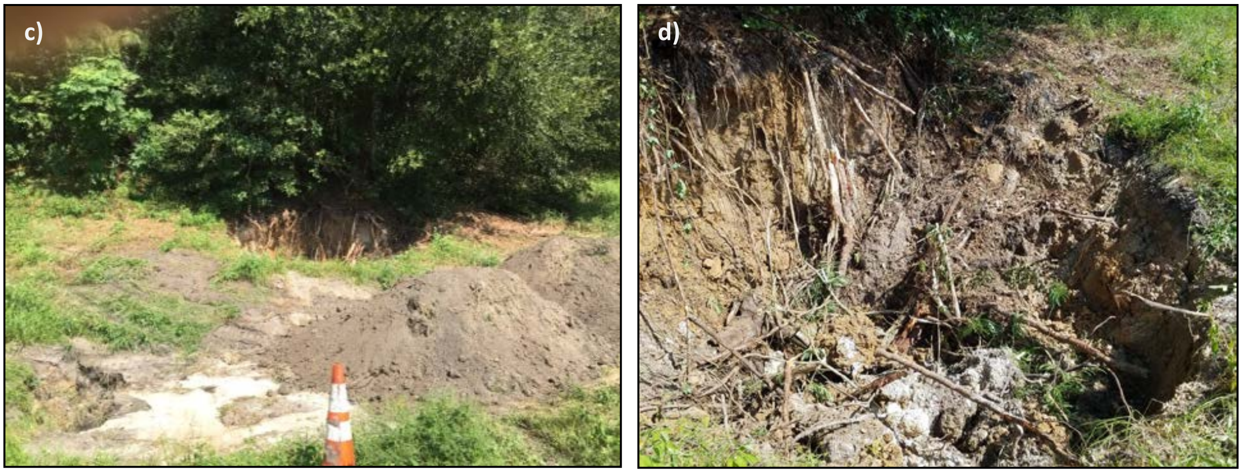


Figure 19: Images of the sinkholes that formed along I-75 northbound south of the SR 26 interchange: a) roadside sinkhole, b) drainage ditch sinkhole, c) sinkhole at the back slope of the drainage ditch, and d) contents of the back slope sinkhole (pers. comm. *Binay Prakash, FDOT).*

Figure 20: Distress from a repaired sinkhole approximately 1 m diameter at the roadway edge of the northbound lane of I-75 (Latitude 29°39'7.99"N / Longitude 82°24'44.00"W)

Figure 21: Repair activities for a sinkhole within the drainage ditch off the northbound lane of I-75 with fill and cement grout (Latitude 29°39'8.81"N / Longitude 82°24'45.00"W).

2.6 Location 3: Fore Ranch Retention Pond & Roadway

Two sites within the Fore Ranch community in Ocala, FL, both of which were at the edges of retention ponds. The locations of these sites are shown in Figure 22 with respect to the Fore Ranch community.

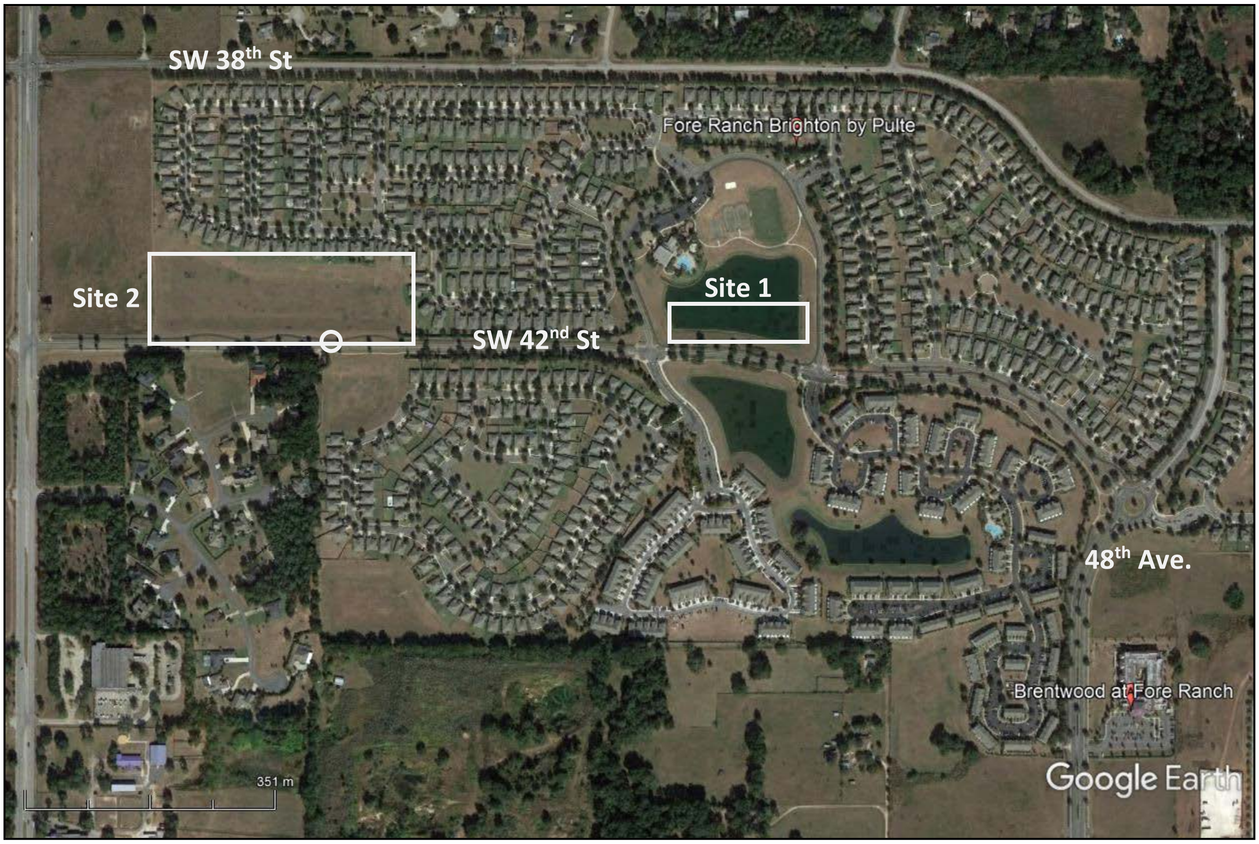


Figure 22: Location of Fore Ranch sinkhole investigation sites 1 and 2 in Ocala, FL (From Google Earth, 2017)

2.6.1 Site 1: Retention Pond at the Clubhouse

When the GEER team visited Site 1, the water in the retention pond was being pumped out onto SW 42nd St. where it entered the storm drains at the road edge and flowed in the direction of Site 2 and into the Site 2 retention ponds. Four sinkhole locations were identified on the southern side of the retention pond at Site 1, which are shown in schematic form in Figure 23 and in images in Figure 24. Sinkhole sites are numbered 1 through 4, and will be referred to as Site 1-X, where X is 1 through 4. The distance between the sinkholes is identified in Figure 23. The details for these locations are summarized below.

- Two small sinkholes were present at Site 1-1. They were approximately 1.5 m on center. The sinkhole throats were small in diameter, and depths could not be measured effectively.
- Two small sinkholes were at Site 1-2. They were approximately 2.5 m on center and had diameters of 0.7 m and 1.0 m and depths of 0.5 m and 0.1 m.
- One or more sinkholes of unknown geometry were identified at Site 1-3. When the GEER Team visited the site, the sinkhole(s) had been filled in.
- One sinkhole was present at Site 1-4. It was 1.2 m in diameter and had a depth of 0.9 m.

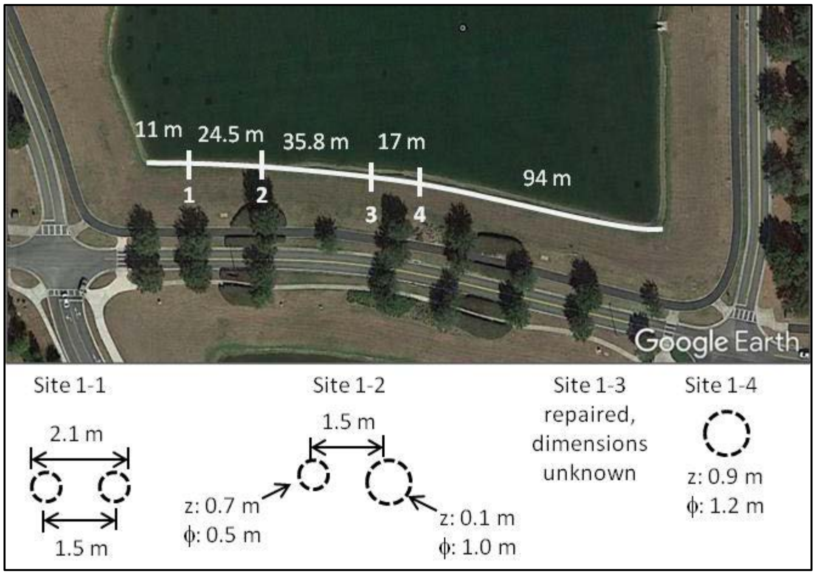


Figure 23. Schematic locations and dimensions of the sinkholes on the bank of the retention pond (from Google Earth 2017).

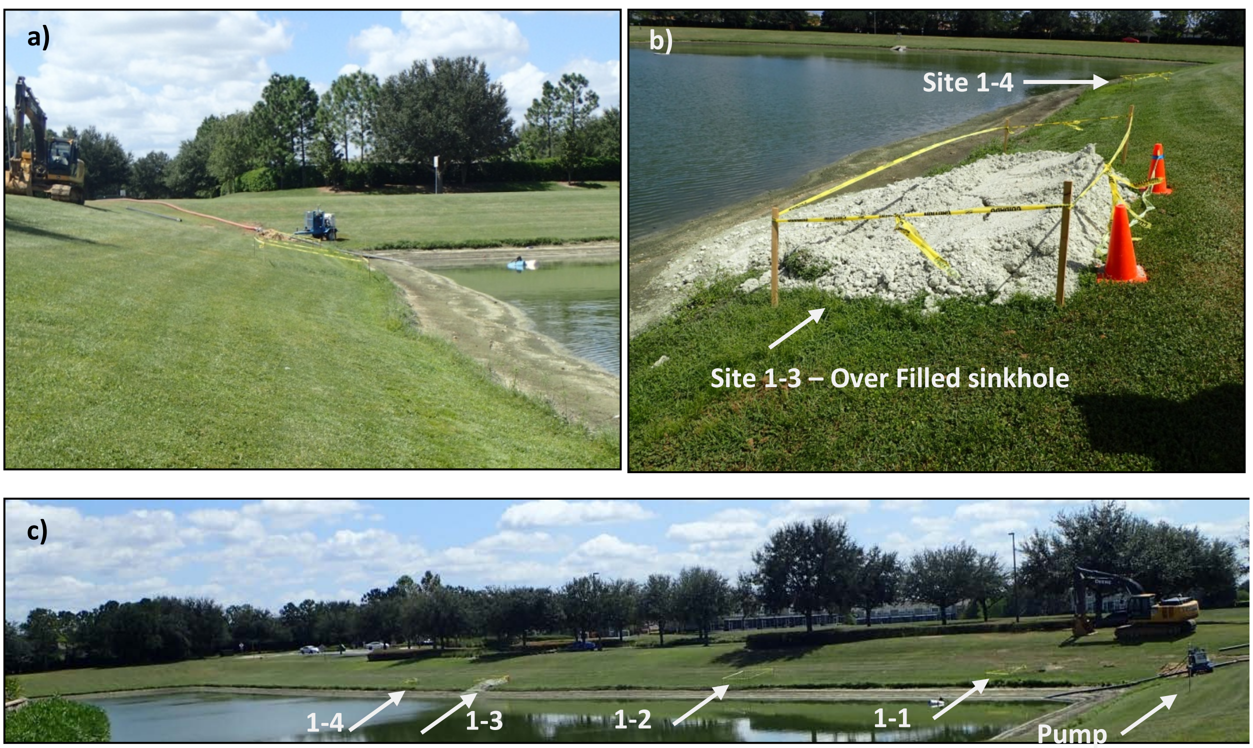


Figure 24. Images illustrating locations of the sinkholes on the bank of the retention pond (Latitude 29°8'50.99"N / Longitude 82°12'35.99"W).

The sinkholes identified at this site were relatively small and did not pose a danger to vehicles or pedestrians unless they were on the bank of the retention pond. The sinkholes, because of their small size, were most likely discovered by lawncare crews working in the community. Sinkhole 1-3 was most likely the largest sinkhole since it had been overfilled with granular soil. It is also the closest to the water level in the retention pond. The pond was most likely being drained so repairs could be made to the small sinkholes.

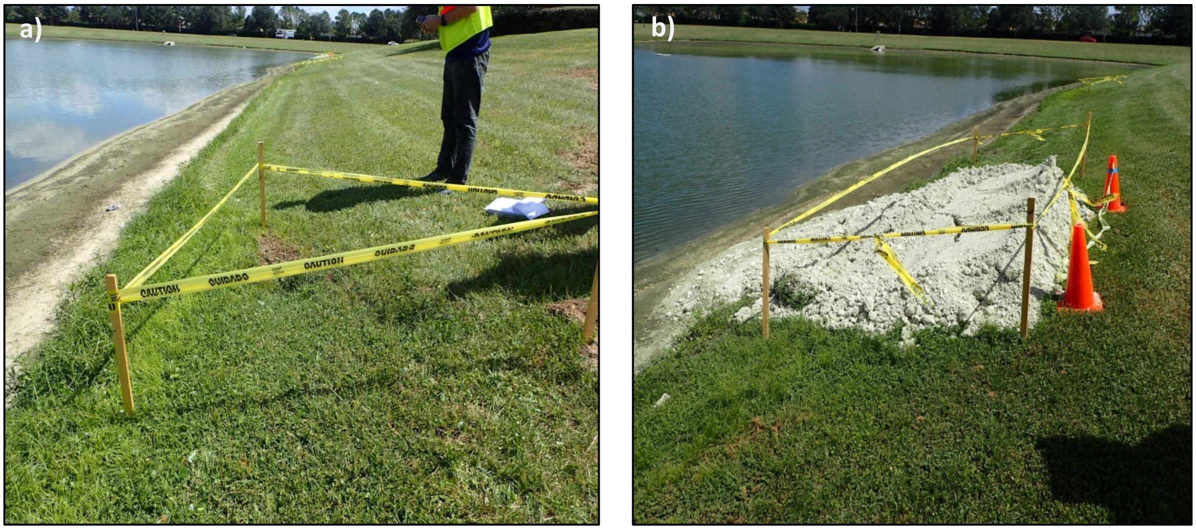


Figure 25. Sinkholes on the bank a) Site 1-1, b) Site 1-3 (Latitude 29° 8'47.98"N / Longitude 82°12'31.30"W).

2.6.2 Site 2: Retention Pond along SW 42nd Street

Site 2 was located at a retention pond along SW 42nd Street in the Fore Ranch community. Figure 26 is an aerial view from Google Earth showing the locations of the repaired and partially repaired sinkholes near the retention pond. A resident who lives on the north end of the retention pond verified that the sinkholes occurred during the hurricane.

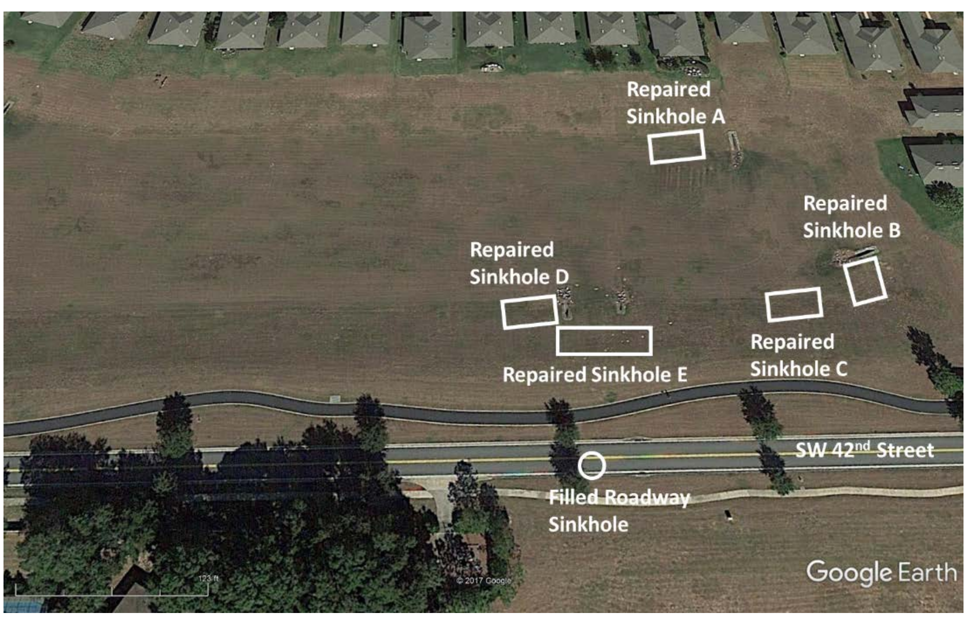


Figure 26. Fore Ranch Community Site 2 repaired and filled sinkholes (from Google Earth, 2017).

Five repaired sinkholes were present on the banks of the retention pond. The sizes of the repaired areas were not measured because they do not provide an accurate assessment of either the sinkhole size or depth. Sinkhole A was on the bank of the retention pond. Sinkhole B was on the east bank of the retention pond. Sinkholes C and D were on the south bank of the retention pond. Sinkhole E, the largest of the repaired sinkholes, was at the top of the bank of the retention pond. It is interesting to note that all of the sinkholes except sinkhole C formed near outlet structures. Figure 29 contains photographs of the repaired sinkholes. The sinkholes were repaired by filling with granular soil and compacting with equipment used to place the granular soil. The track marks on the repaired sinkholes indicate they were only recently repaired.

This site also had a sinkhole which had formed in the east bound lane of SW 42nd Street. This sinkhole had not been repaired but was overfilled with granular soil. Because of the sinkhole the street was closed to traffic. Figure 28 shows the overfilled sinkhole. Since the sinkhole is in the roadway, the repairs will need to be more sophisticated than simple fill and compaction with large equipment.

Repaired sinkhole A

Repaired sinkhole B (back) and C (front)

Repaired sinkhole D

Repaired sinkhole E

Figure 27. Repaired sinkholes on the bank of the retention pond (Latitude 29° 8'48.30"N / Longitude 82°12'52.89"W).

Sinkhole in road. Road sinkhole overfilled with granular soil.

Figure 28. Sinkhole in road (Latitude 29° 8'47.52"N / Longitude: 82°12'51.36"W).

2.7 Location 4: The Villages

The Villages is one of the largest master planned age restricted communities for residents aged 55+. Several residents informed the GEER team that approximately 44 sinkholes developed in The Villages as a result of Hurricane Irma. Figure 29 illustrates the location of three separate sinkholes that were identified following Hurricane Irma rainfall between Markridge Loop and Dove Hollow Run. These include a large sinkhole between 2005 and 2011 Markridge Loop (A), a large sinkhole and two large downed trees on the Jacaranda Nine at Cane Garden Country Club[19] (B), and a sinkhole and surface erosion at drainage pipe for a nearby retention pond and golf green (C). At least 3 smaller sinkholes and depressions were identified at the site within the area encompassed by the larger features indicated in Figure 30, however these were not cataloged in detail like the three major features that are discussed subsequently.

Figure 30a shows the sinkhole as formed between 2005 and 2011 Markridge Loop. The sinkhole formed in the early morning of September 12, 2017 and resulted in the evacuation of the two homes which were both subsequently condemned and residents prohibited from entering the homes. The sinkhole that developed extended under the slab foundation a distance of approximately 3 m laterally of 2005 Markridge Loop (pers. comm. Doug Wernicke) an into the shared yard between the two homes. Figure 30b illustrates the damage to the home at 2005 Markridge Loop, that included damage to wall-mounted utilities and cracks to the stucco block wall (assumed by the crack geometry). This prompted installation of crack gages to monitor continued deformation following stabilization of the slab and surrounding ground by backfilling (Figure 30c). The location included underground electric and water utilities that needed to be stabilized during the backfilling of the sinkhole (pers. comm. Doug Wernicke). Figure 30d additionally illustrates that ground subsidence resulting from the sinkhole extended to 2011 Markridge Loop, where a gap between the soil and slab foundation was identified.

[19] Villages News (2017). "Large sinkholes open up in Villages in wake of Hurricane Irma's brutal pounding," 11 September 2017. Retrieved from: http://www.villages-news.com/large-sinkholes-open-villages-wake-hurricane-irmas-brutal-pounding/

Figure 29: Location of three sinkholes: Markridge Loop and Dove Hollow Run, The Villages, FL (from Google Earth, 2017).

Figure 30: Documentation of a sinkhole that formed between homes at 2005 and 2011 Markridge Loop, The Villages, FL., including: a) the open sinkhole (dimensions unknown; pers. comm. Doug Wernicke); and b) cracks on the wall of 2005 Markridge Loop with crack gages; c) area between the two homes; and d) evidence of ground subsidence and an irrigation system at the wall of 2011 Markridge Loop after sinkhole backfilling. (Latitude 28°53'0.57"N / Longitude 82° 0'1.02"W).

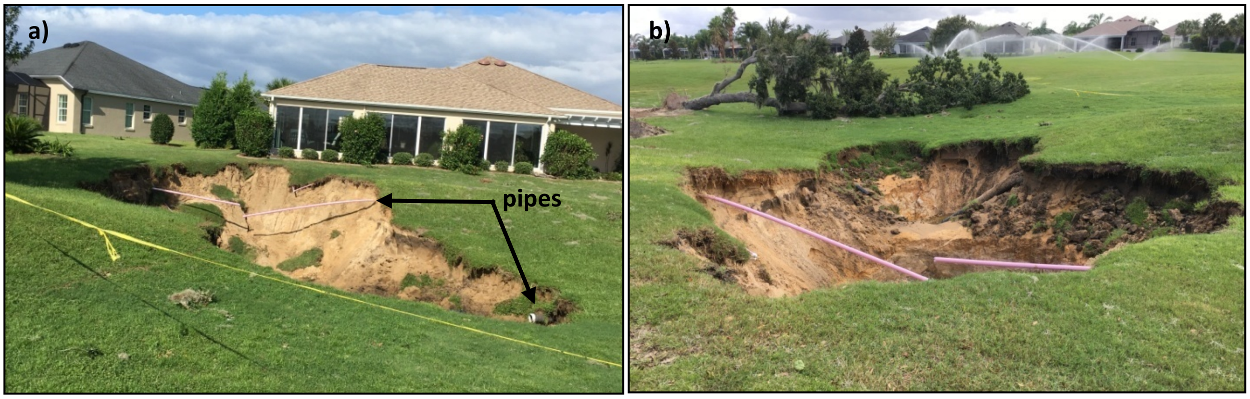


Figure 31: Images of a large sinkhole (dimensions unknown) that formed behind 2011 Markridge Loop, The Villages, FL. Note the small and large diameter pipes and large felled tree. (pers. comm. Doug Wernicke). (Latitude 28°52'59.95"N / Longitude 81°59'59.73"W).

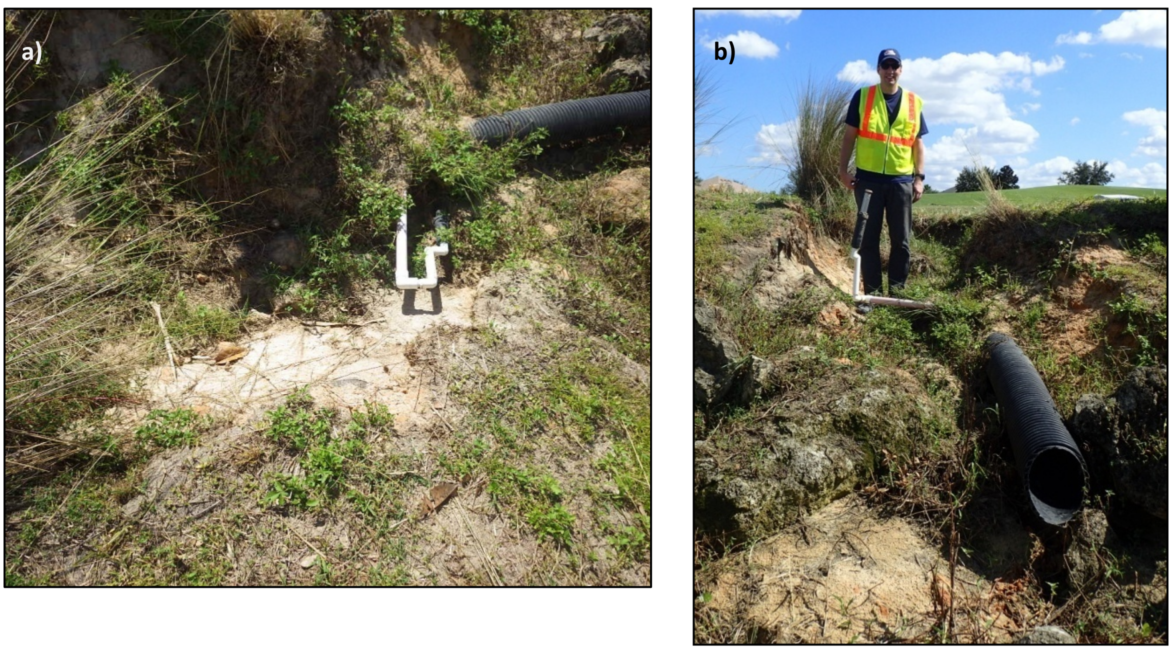


Figure 32: Documentation of a sinkhole and overland erosion that formed at edge of the golf course retention pond between Markridge Loop and Dover Hollow Run in The Villages, FL (Latitude 28°52'57.88"N / Longitude: 81°59'58.93"W).

Figure 31 indicates the sinkhole that formed behind 2011 Markridge Loop on the Jacaranda Nine at Cane Garden Country Club (see Villages News 2017). The sinkhole was at a low elevation with respect to surrounding homes. A local resident who spoke to the GEER team indicated this sinkhole was approximately 6 m wide, 6 m deep, and 20 m long (pers. comm. Doug Wernicke). The images show small diameter irrigation pipes in the near surface, as well as large diameter black corrugated plastic pipe that was assumed to be a water supply line for irrigation or the nearby retention pond. The cause of the sinkhole formation is unknown, however one potential cause large volumes of water from Hurricane Irma rains released from the black plastic corrugated drainage pipe if the pipe joint was broken. Two large trees were downed adjacent to the sinkhole (Figure 31b), providing additional evidence for soft or unsupported ground and Hurricane force winds and rains. This sinkhole was repaired with backfill and grade re-leveling at the time the GEER team visited the site.

Figure 32 illustrates the small erosional feature discovered adjacent to the retention pond with an exposed sprinkler system made of PVC pipe. It was unclear to the GEER team if this feature was a sinkhole, an erosional feature, or an unmaintained drainage area of the golf course. However it was documented as a potential location where overland flow of water into the retention pond or continued drainage from a broken irrigation system might further compromise this area and promote future sinkhole development

2.8 Location 5: The Villages - Alhambra

Figure 33 shows the location of the retention pond between Alhambra Way and Botello Ave. in The Villages Alhambra, FL where sinkholes were created on the bank, and within the basin, or the retention pond as a result of Hurricane Irma (rectangle). Figure 33 additionally shows the locations of two sinkholes that formed around houses nearby the retention pond location (circles).

Figure 33: The location of the Alhambra Retention Pond where sinkholes formed, The Villages, FL (from Google Earth, 2017).

Images provided for the retention pond sinkhole reconnaissance that show sinkholes as formed and prior to repair at the bank and basin of the pond were provided by local residents Sheila Huffman Dailey, Dan Snyder, and Barbara Beveridge as the repairs were nearly completed with the GEER Team conducted the site visit on September 27, 2017. Figure 34 demonstrates the change in the water level within the retention pond as a result of sinkhole formation. Local residents Dan Snyder and Sheila Huffman Dailey indicated that the water level was above the large diameter concrete pipes that drain water into the retention pond (there are 5 in total for the pond) on Monday, September 11, 2017. On Tuesday, September 12, the water had drained to an elevation where the water level was at the midpoint of the drainage pipe diameter. And by the morning of Wednesday, September 13, the water was fully drained from the retention pond. Figure 35 illustrates the conditions at the retention pond on the day the GEER Team visited, where the pond basin was dry, backfilling of sinkholes on the banks and within the basin was nearly completed (Figure 35a) and large mud cracks 10 mm deep and 20-50 mm wide had formed (Figure 35b).

Residents report five large sinkholes had formed on the bank of the retention pond and three large sinkholes had formed within the basin on the side nearest Botello Ave. These sinkholes are illustrated in Figure 36, which highlight sinkholes prior to repair (Figure 36a, b, c) and following repair (Figure 36d). All sinkholes had been repaired by September 27, 2017 when the GEER Team visited.

Sinkholes additionally formed along homes on Botello Ave. Figure 37 illustrates a sinkhole prior to (Villages News 2017), and after repair, that formed along the street at 2532 Botello Ave. No measurements were available for this sinkhole. Figure 38 illustrates a sinkhole that is approximately 4.5 m by 4.0 m wide and 2.5 m deep that is undercutting the slab foundation of a home and exposing damaged irrigation lines.

Figure 34. Images illustrating the retention pond a) prior to (Aug. 9 2017), and b) following (Sept. 18, 2017) Hurricane Irma and sinkhole formation where the view is from Alhambra Way. (Latitude 28°57'12.85"N / Longitude 81°59'36.36"W). Images courtesy of Dan Snyder and Sheila Huffman Dailey.

Figure 35. Retention pond between Alhambra Way and Botello Ave. (a) fully drained retention pond with fill material placed on the bank for backfilling sinkholes (Latitude 29°57'9.18"N / Longitude 81°59'31.5"W), and (b) 10 mm deep desiccation cracks in the pond bottom (Latitude 28°57'10.94"N / Longitude 81°59'36.67"W).

Figure 36. Sinkholes on the bank of, and within the retention pond between Alhambra Way and Botello Ave. (a, b, c), and under repair (d) (Latitude 28°57'11.92"N / Longitude 81°59'31.49"W) (images courtesy of local residents Sheila Huffman Dailey, Dan Snyder, and Barbara Beveridge).

Figure 37.Sinkhole formed at 2532 Botello Avenue a) prior to repair[19] and b) following repair (Latitude 28°57'10.60"N / Longitude 81°59'30.50"W).

Figure 38. Sinkhole undercutting a foundation at 2536 Botello Rd. showing multiple front views (a, b, c,) and bottom of the sinkhole (d). (Latitude 28°57'11.67"N / Longitude 81°59'30.05"W).

2.9 Location 6: Apopka Middle School

Apopka is a city in central Florida situated in Orange County. The population is approximately 43,140 according to the United States Census Bureau[20]. Apopka is located approximately 29 km northwest of Orlando. The reconnaissance site is the Apopka Middle School located at 425 N. Park Avenue, Apopka, FL. An event, initially reported as a sinkhole, occurred September 12, 2017. The event was later identified as a washout by city engineers. The damage occurred on the south end of the school property between the running track and a large school bus parking area. The school and bus parking area are separated by a short chain link fence. The fence also separates the school year from the West Orange Trail, as shown in Figure 39. When the GEER Team visited the site, the erosion feature was backfilled from near the school to the extent of the farthest edge of the track (see the dotted line in Figure 39), likely for safety reasons.

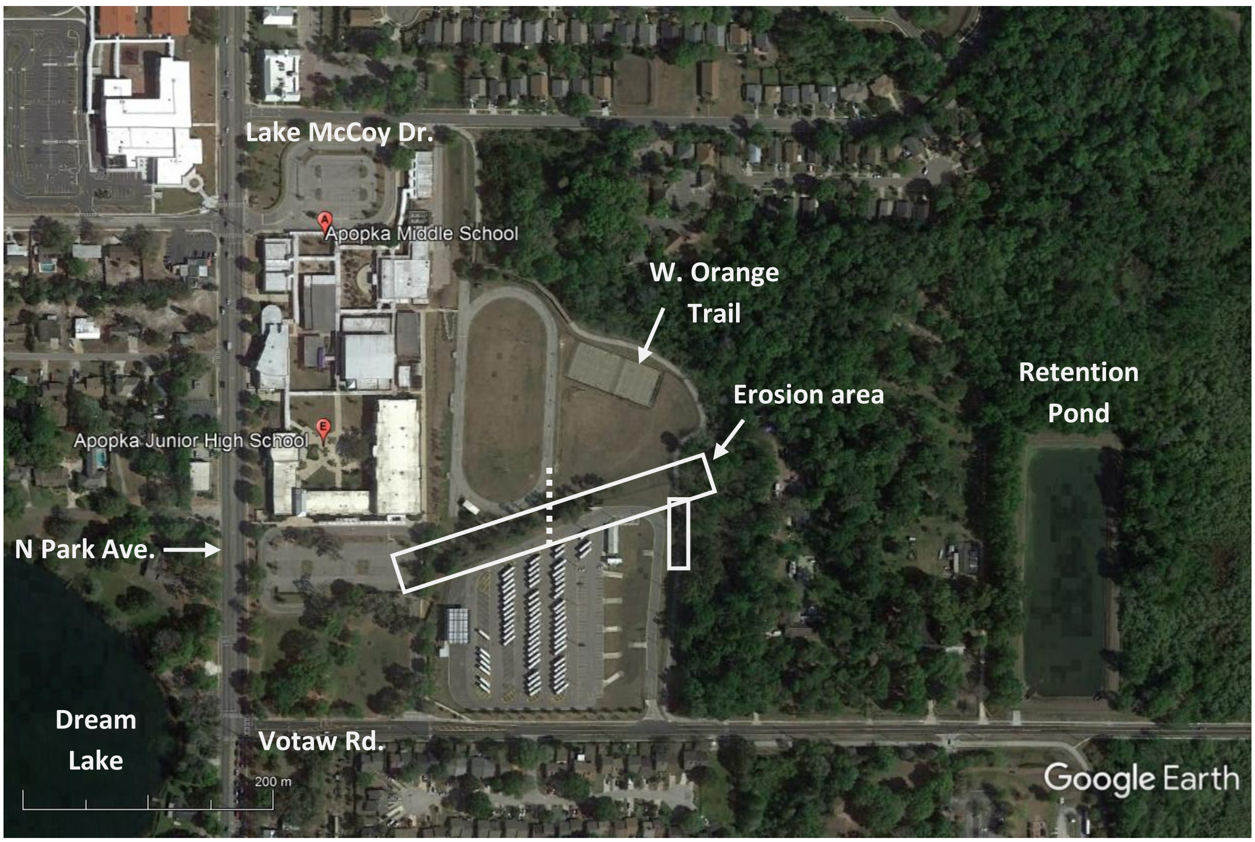


Figure 39. Reconaissance location for the massive erosional feature at Apopka Middle School (Latitude 28°41'7.44"N / Longitude 81°30'25.61"W).

[20] Statistical Atlas (2017). Population of Apopka, FL. Retrieved from: https://statisticalatlas.com/place/Florida/Apopka/Population

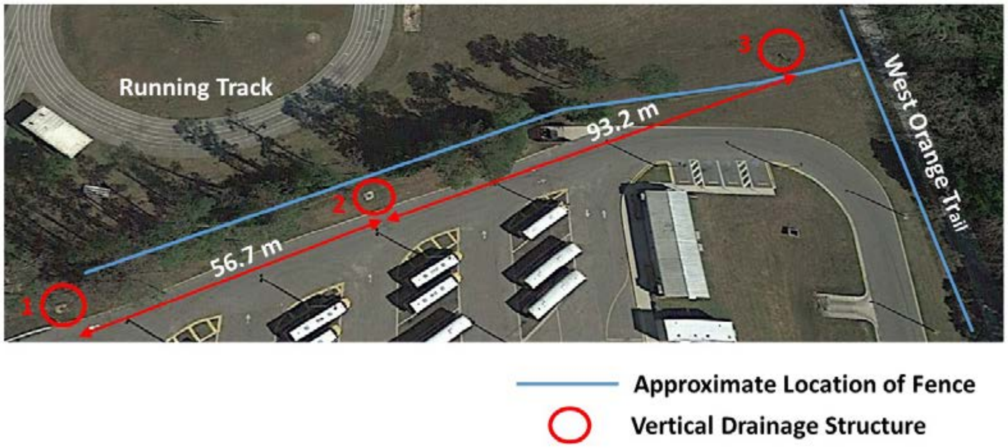


Figure 40: Location of storm drain features between the Apopka Middle School fields and bus depot (approximate location Latitude 28°41'7.77"N / Longitude 81°30'24.60"W).

There are multiple vertical storm water inlets at the site, indicated by red circles and numbers in Figure 40 that is an aerial image from before Hurricane Irma. Storm water inlet 2 is approximately 57 m northwest of storm water inlet 1 and storm water inlet 3 is approximately 93 m from storm water inlet 2. Storm water inlet 3 is on the north side of the fence, and storm water inlets 1 and 2 are on the south side of the fence, where they collect water from the large paved bus depot. There is a fourth storm water inlet that cannot be seen in Figure 40, which is hidden by the forested area beyond the paved West Orange Trail. Figure 41 is a drone aerial image obtained from local news footage. The image shows the third drainage structure has been eroded on all sides and almost to the extent of its depth. Reports indicated the erosion was approximately 23 m wide.

Figure 41: Aerial image of the Apopka erosion washout that bisected the West Orange Trail and damaged two large scale drainage structures[21] (approximate location Latitude 28°41'8.68"N / Longitude 81°30'20.97"W).

[21] Fox 35 Atlanta (2017). Sinkhole opens near Apopka middle school," September 13, 2017. Retrieved from: https://www.youtube.com/watch?v=pqDb7sNT85k.

The GEER Team investigated the washout from the head of the erosion from the western extent to the West Orange Trail by walking the banks and erosion channel. Figure 42a shows the shallow erosion channel with a west to east view from near the school near the extent of where fill had brought in to raise the elevation of the grade at the school. The washout gully increased in both width and depth from the west towards drainage structure 3. The channel is about 1 m deep and 6 m across at this location. Figure 42b shows the drainage channel with an east to west view, looking back toward the school building (not shown). At this location the channel is approximately 3 m deep and 10 m across at the original ground surface. The washout gully increased in both width and depth from the west towards drainage structure 3. Figure 43 and Figure 44 illustrate the steep banks of the erosion channel. The soil in this area was fine sand deposits, which was a likely reason so much erosion occurred.

Figure 45 and Figure 46 show the damage around drainage structure 3. The team identified that at least two drainage pipes had become separated from the drainage structure, which were still draining into the bottom of the washout at the time of the site visit. In addition to the loss of lateral support from erosion to surrounding soils, the basal support of drainage structure 3 was compromised by the erosion, as the structures was no longer vertical.

Figure 42: Images of the channel where the view is a) toward the east from the western portion of the channel (Latitude 28°41'7.87"N / Longitude 81°30'24.97"W), and b) toward the west from the channel (Latitude 28°41'8.70"N / Longitude 81°30'22.33"W).

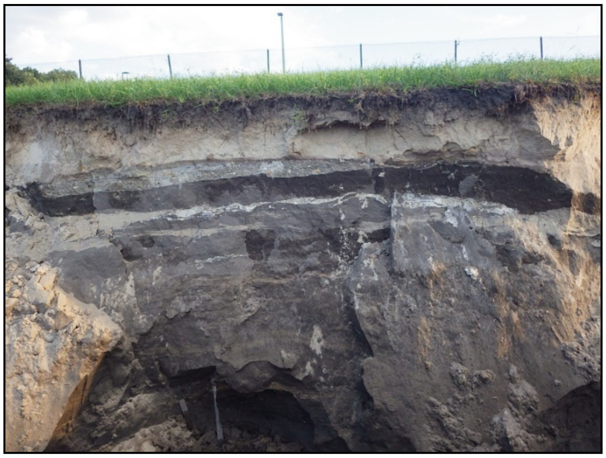


Figure 43. Interesting dark layered sand feature within washout stratigraphy (Latitude 28°41'8.54"N / Longitude 81°30'22.74"W).

Figure 44. Washout at the West Orange Trail Surface (Latitude 28°41'8.70"N / Longitude 81°30'20.79"W).

Figure 45. Damaged drainage structure 3 (Latitude 28°41'9.08"N / Longitude 81°30'22.39"W).

Figure 46. Damaged drainage structure 3, dimensioned by the investigators 2.4 m reach (Latitude 28°41'9.08"N / Longitude 81°30'22.39"W).

Figure 47. Erosion lateral to the main channel likely from failed drainage structure 3 (Latitude 28°41'9.15"N / Longitude 81°30'21.64"W).

Figure 48. Erosion lateral to the main channel likely from failed drainage structure 3 (Latitude 28°41'9.15"N / Longitude 81°30'21.64"W).

Figure 47 through Figure 49 provide images of the largest portion of the erosion and washout around drainage structure 3, includes pipes that were partially buried in the sediment at the bottom of the channel that were not likely installed at that elevation. The extent of the feature (depth, width, length) was not measured due to the challenge with site access and limited equipment.

Figure 50 illustrates a fourth drainage structure and downed trees in a pile of debris further down the channel from the West Orange Trail and fence. This area was clogged with woody debris and the team was not able to investigate this area or the further extent of the erosion, although it was clear it extended more eastward toward the wooded area and potentially the retention pond further offsite.

Lastly, as indicated in Figure 39, there was a small area of washout that was evident parallel and on the east of the West Orange Trail south of the large washout at drainage structure 3. The team could see some sediment had washed out on the far side of the trail from within the bus depot lot, but did not have access to the site to investigate further.

Figure 49. Damaged pipes, eroded West Orange Trail, and uprooted trees at drainage structure 3 area (Latitude 28°41'9.15"N / Longitude 81°30'21.64"W).

Figure 50. Fourth drainage structure buried under wooded debris east of the West Orange Trail. (Latitude 28°41'8.71"N / Longitude 81°30'20.57"W).

3 GEOTECHNICAL DAMAGE ON THE NORTHEAST FLORIDA BEACHES

3.1 Geography and Geology of Florida's Northeast Coast

The state of Florida has a coastline length of approximately 2170 km. Florida's eastern coastline is a barrier-island and tidal-inlet system. In this region there are twenty-two inlets and all but one have been significantly modified by engineering activities. The north end of this system is the southern portion of the Georgia Bight where barrier morphology in influenced by a mixed regime of tidal and wave energies. The tidal range in this area is considered microtidal, less than two meters, except during the spring when tides can be higher than two meters[22].

The shallow bedrock in Florida is predominately limestone. However most of the natural sand which forms Florida's beaches are predominately silica sands. Sediment movement likely progressed from the weathering of the Appalachian Mountains in the Carolinas and Georgia in the north and the sediments were carried south through longshore transport processes for deposition in Florida. The deposition of siliciclastic sediments began approximately 30 Ma. The transport and deposition of siliciclastic sediment ended approximately 3Ma. At this time there is virtually no transport and deposition of siliciclastic sediments by rivers or longshore transport processes[23].

3.2 Reconnaissance Locations

The GEER reconnaissance team visited five locations on Tuesday September 26, 2017 to document beach erosion, scour, and damage to geotechnical structures. For sake of clarity erosion will refer to larger scale

[22] Davies Jr., R. A. (1997). *Geology of the Florida Coast*. In Randazzo and Jones (Eds.), The Geology of Florida (pp. 155-168). Gainesville: University Press of Florida.

[23] Hine, A. C. (2013). Geologic History of Florida. Gainesville: University Press of Florida.

lowering of the ground surface whereas scour will refer to a localized loss of soil. The documentation began at the southernmost location, Beverly Beach in Flagler County, and the team progressed north to visit sites in Painters Hill (Flagler County), Marineland (on the boarder of Flagler and St. Johns County), St. Johns County Ocean Pier, and Vilano Beach (St. Johns County). The locations of the site visits are shown in Figure 51.

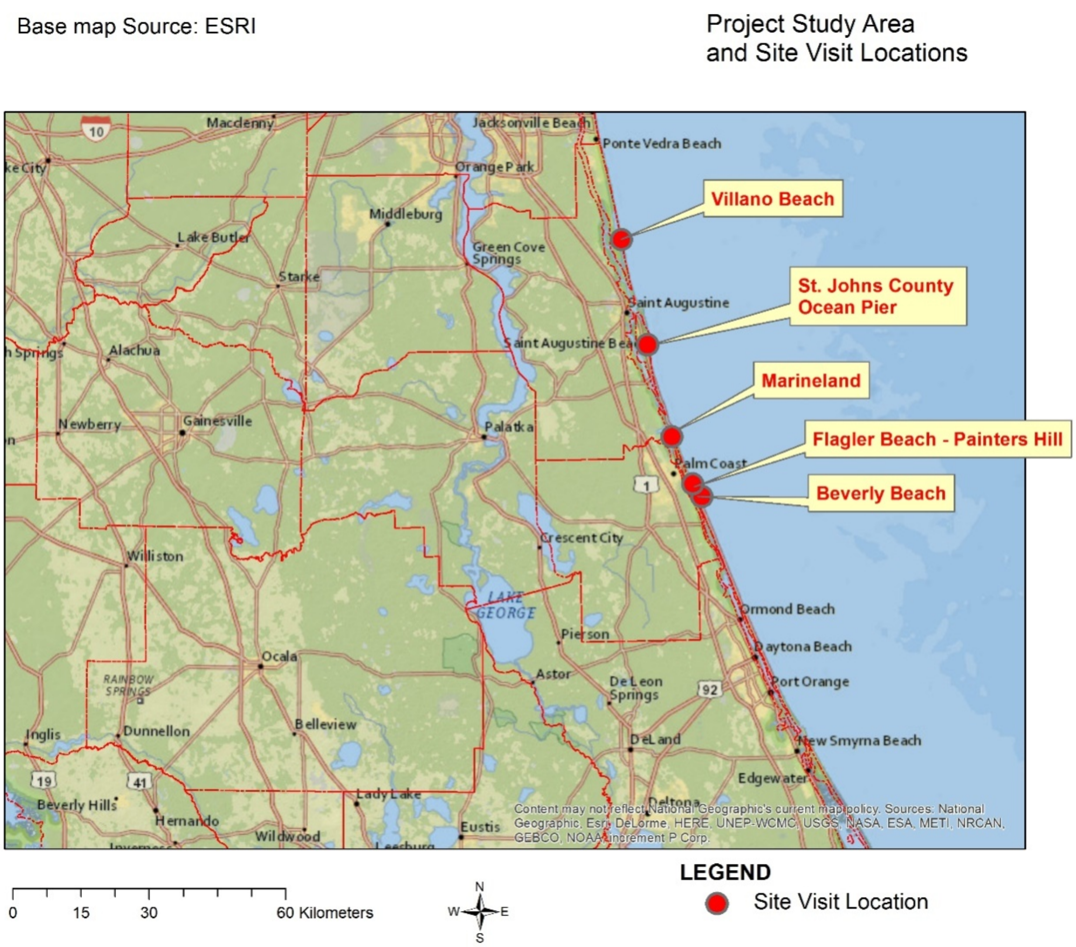


Figure 51. Location of beach damage reconnaissance locations in Northeast Florida (data from Google and ESRI mapping).

3.3 Beach Replenishment Activities

Numerous tropical storms and hurricanes have caused significant erosional events on the beaches in Northeast Florida. The Flagler County shoreline is approximately 19 miles long. Although beach erosion investigations and Storm Damage Reduction Project feasibility studies have been conducted in Flagler County by the Corps of Engineers over the past decade, a beach nourishment project has yet to be constructed. However, after Hurricane Matthew inflicted heavy erosion to its shorelines and damaged State Road A1A (a hurricane evacuation route) the County has appropriated funds to begin a dune building project, with hopes that Congress will provide the needed appropriations for the Corps to build dunes and nourish approximately 2.6 miles of beach in the southern part of the county that meet federal guidelines.

The St. Johns County shoreline is approximately 42 miles long. The Corps of Engineers examined opportunities to reduce the risk of coastal damages and improve conditions on roughly 9.8 miles of beach. The study area consisted of 3.8 miles in the South Ponte Vedra area, 3.7 miles in Vilano Beach and 2.3 in Summer Haven. Shore erosion threatens State Road A1A. The tentatively selected plan (TSP) includes beach and dune nourishment within the Vilano Beach area and a small portion of the South Ponte Vedra Beach. During the study process, the team screened out the Summer Haven area (where a breach in the barrier island occurred during Hurricane Matthew) because St. Johns County is already conducting managed retreat there. Most of the South Ponte Vedra area was screened out due to its lack of public parking and access, which is a requirement for federal beach projects.

3.4 Tide Levels

The tide levels for the all of the reconnaissance areas are not known. Tidal data was compiled using historic water level data from the NOAA website[24]. Two gage locations were identified as the closest tidal recording stations to the reconnaissance locations. This data will provide rough estimate of the tide levels at the reconnaissance locations. Tidal data was obtained from Port Canaveral Florida (gage location N 28° 14’ 56.4”, W 80° 21’ 21.6”) in the south and Fernandina Beach (gage location N 30° 24’ 10.8”, W 81° 16’ 44.4”) in the north. Figure 52 shows the locations of the NOAA tidal stations near the beach damage reconnaissance locations where are clustered around Palm Coast and St. Augustine.

Figure 54 shows the tide levels during Hurricane Irma at the Port Canaveral and Fernandina Beach gages. The predicted high tide at Port Canaveral during Hurricane Irma was approximately 1.2 m. However the measured tide was almost 2.5 meters, a difference of approximately 1.3 m. The predicted high tide on September 11 at Fernandina Beach was approximately 2 m, which is higher than the southern tides. The measured tide was approximately 3 m, a difference of approximately 1 m. The southern parts of Florida’s northeast coast received greater higher than expected tides than the northern parts of Florida’s northeast coast.

3.5 Location 1. Flagler County – Beverly Beach

The GEER team visited the Beverly Beach Camptown RV Resort in Flager County. This area is relatively sparsely populated and its population consists mostly of beach communities. The Resort is located on a barrier island bounded by the Mantanzas River on the west and the Atlantic Ocean on the east, as shown in Figure 55. The resort has a reinforced concrete seawall that runs a length of approximately 440 m parallel to the beach.

[24] Retrieved from https://tidesandcurrents.noaa.gov/stations.html?type=Historic+Water+Levels

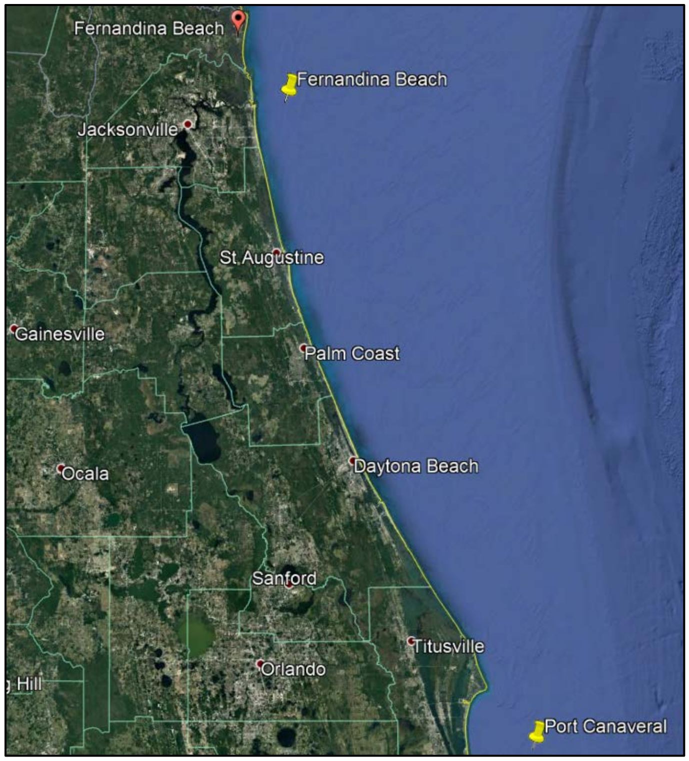


Figure 52. Location of NOAA tidal gages near the reconnaissance sites.

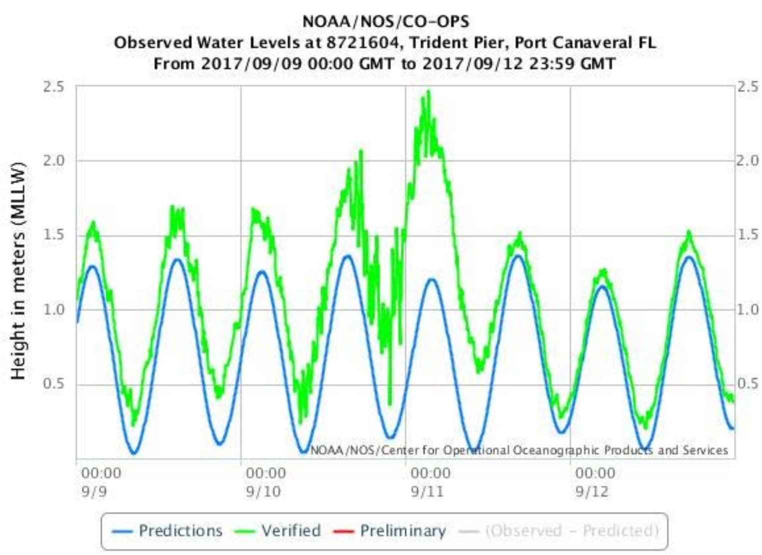


Figure 53. Tidal levels (m) during Hurricane Irma at Port Canaveral gage[25].

[25] Retrieved from: Retrieved from https://tidesandcurrents.noaa.gov/stations.html?type=Historic+Water+Levels

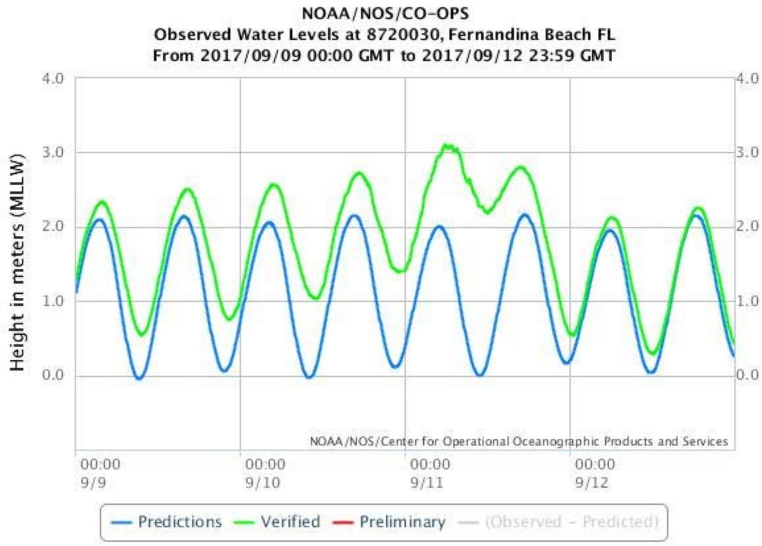


Figure 54. Tidal levels (m) during Hurricane Irma at Fernandina Beach gage[25]

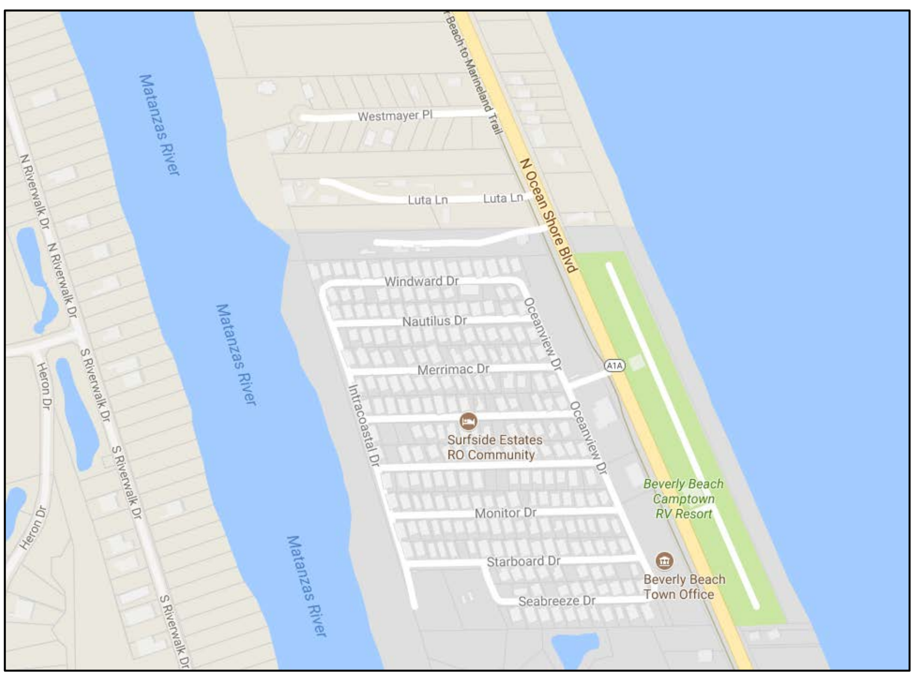


Figure 55. Location of Beverly Beach Camptown RV Resort (Latitude 29°32'36.21"N / Longitude 81° 9'30.17”W).

The documented damage at this reconnaissance site consisted of erosion along the sea wall and localized scour at timber staircases which provide access from the Resort, which is located on top of the seawall, to the beach.

a) Erosion across the face of the wall indicated by the exposed concrete (Latitude 29°31'15.29"N / Longitude 81°8'48.06"W).

b) Scour at base of timber staircase (Latitude 29°31'14.96"N / Longitude W 81°8'48.07").

c) Damage to concrete stair structure (Latitude 29°31'16.64"N / Longitude 81°8'48.78"W).

d) Scour on the north wing wall of the concrete seawall (Latitude 29°32'36.21"N / Longitude 81°9'30.17"W).

Figure 56. Documented damage at the Beverly Beach Camptown RV Resort (Latitude 29°32'36.21"N / Longitude 81° 9'30.17"W).

3.6 Location 2. Flagler Beach – Painters Hill

Reconnaissance was conducted at two sites in Painters Hill. The locations of the two sites are shown in Figure 57 below. The first site was located at 3423 N. Ocean Shore Boulevard in Flagler Beach. The second site was located at 3397 N. Ocean Shore Boulevard in Flagler Beach. There are three beach lots, two occupied by houses, between the two sites. The distance between the two sites is about 140 m.

Figure 57. The two reconnaissance sites at Location 2 in Painters Hill, Flagler Beach, FL.

3.6.1 Site A. 3423 N. Ocean Shore Boulevard

Site A is located at coordinates N 29°32'36.21" and W 81° 9'30.17". This site has a large dune system which has been severely eroded. Figure 58a is a photograph looking south along the eroded dune. The eroded dune face is almost vertical. Note the vertical scarp at the top of the failed dune and sloughing of the material downslope. Slope movement can be considered active and the slope will continue to fail until stabilized. Figure 58b is another photograph showing the severely eroded dune face. The height of the eroded dune face was measured to be approximately 5.5 m at this location. The photograph reiterates the active nature of the failure. Figure 58c is a close-up view of the crest of the failed dune looking south. Note the blocky nature of the crest at the failure face and the vertical scarp. A sprinkler head can be seen below the investigator’s hand in the photograph. The reconnaissance team speculated the blocky nature was due to the failure following seams within the sod which was placed on top of the slope. Figure 58d is a close up of one of the sod seams. Rainwater most likely infiltrates into the native dune soil through the seams causing a zone of weakness, which explains the blocky nature of the crest.

a) Extent of dune failure (photograph taken facing south, Latitude 29°32'35.83”N / Longitude 81°9'29.51"W).

b) Location where failed dune slope height was measured (Latidude 29°32'35.34”N / Longitude 81°9'29.59"W).

c) Close up of blocky nature of failed dune crest (Latidude 29°32'36.74”N / Longitude 81°9'29.95"W).

d). Close up of seam in sod where moisture most likely infiltrated into the dune (Latidude 29°32' 35.83”N / Longitude 81°9'29.51"W).

Figure 58. Dune failure at 3423 N. Ocean Shore Boulevard (Latitude 29°32'36.21"N / Longitude 81°9'30.17"W).

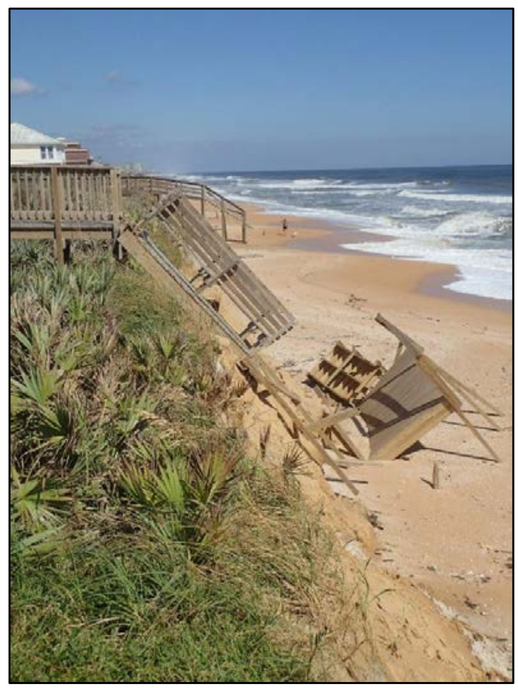
3.6.2 Site B. 3397 N. Ocean Shore Boulevard

Site B is located at coordinates N 29° 32' 32.36" and W 81° 9' 28.0". The effectiveness of a dune protection system which was constructed next to an eroded dune is clearly demonstrated. The dune protection system, a two-tiered timber sheet pile structure, is shown in Figure 59a. One of the reconnaissance team members visited this site in 2016 after Hurricane Matthew. He stated the lower tier of the timber sheet pile structure was added after hurricane Mathew in 2016. The timber sheet pile structure has successfully protected the dune structure and shoreline. However some damage was noted on the north wing wall of the structure, as shown in Figure 59b. The timber sheet pile wall was not embedded far enough into the existing dune and the erosion has exposed the end of the wall, which is covered with a black tarp.

a) Two-tiered timber sheet pile structure (Latitude 29°32'28.35"N / Longitude 81°9'27.15"W).

b) North wing wall scour of the timber sheet pile wall (Latitude 29°32'28.35"N / Longitude 81°9'27.15"W).

c) Measuring the almost vertical face of the eroded dune (Latitude 29°32'31.64"N / Longitude 81°9'27.27"W).



d) Example of collapsed timber staircase (Latitude 29°32'31.64"N / Longitude 81°9'27.27"W).

Figure 59. Reconnaissance efforts at 3397 N. Ocean Shore Boulevard (Latitude 29°32'32.36"N / Longitude 81°9'28.0"W).

To the north of the timber sheet pile wall the dune was severely eroded. The erosion produced an unstable almost vertical face which measured approximately 3 meters in height. In some locations, the crest of the eroded face was undercut making the top of the dune unstable (Figure 59c). The erosion of the dune system in this vicinity resulted in a number of beach timber staircases to be undercut and collapse. One such example is shown in Figure 59d.

The extent of the damage at this site is demonstrated in Figure 60. The eroded dune shows active sloughing of the face, undercutting of a concrete deck, and a potentially unstable timber walkover structure. This type of damage is very typical in this area with unprotected dunes. The need for continuous protection in this area is warranted.

Figure 60. Eroded dune showing active sloughing, undercutting of deck, and potentially unstable timber beach staircase (Latitude 29°32'31.04"N / Longitude 81°9'27.05"W).

3.7 Location 3. Marineland

Marineland is a marine mammal park. The park was founded in 1938 as an oceanarium where producers could film marine wildlife. Marineland is also a town on the north border of Flagler County and the south border of St. Johns County. The address of Marineland is 9600 N Ocean Shore Blvd, St Augustine, FL (29° 40' 18.47" N, 81° 12' 50.97" W). The location of Marineland and the two reconnaissance sites is shown in Figure 61. The distance between the two sites is approximately 1.36 km.

Figure 61. Location of Marineland and the two reconnaissance sites.

3.7.1 Site A. Overwash and Washover Deposits

Site A demonstrates overwash and washover deposits. Overwash is the flow of water and suspended sediment over dunes or beach crests during storm events. Washover deposits refer to the sediment deposits associated with the overwash events. The overwash damage and washover deposits were investigated over a relatively short stretch, approximately 430 m, of Highway A1A north of Marineland. This section of Highway A1A is very close to both the Atlantic Ocean and the Matanzas River.

The white rectangular area in Figure 62a shows the location of Highway A1A where the overwash and washover deposits were documented. This area is prone to overwash and subsequent washover deposits because of the proximity of the highway to the Atlantic Ocean. At this location Highway A1A is located between 45 m to 70 m from the shoreline of the Matanzas River. On the east side of Highway A1A the distance to the edge of the dunes is approximately 25 m. One common roadway protection measure that is incorporated prior to storm events is to place fill on the shoulder of the roadway to protect from scour. Figure 62b[26] is a photograph showing the placement of soil for roadway protection in Flagler County. The placed fill acts as a sacrificial dune which can be preferentially scored and eroded to protect the roadway.

[26] David Goldman (2017) Retrieved from http://www.ocregister.com/2017/09/08/hurricane-irma-slams-turks-and-caicos-on-path-to-florida/

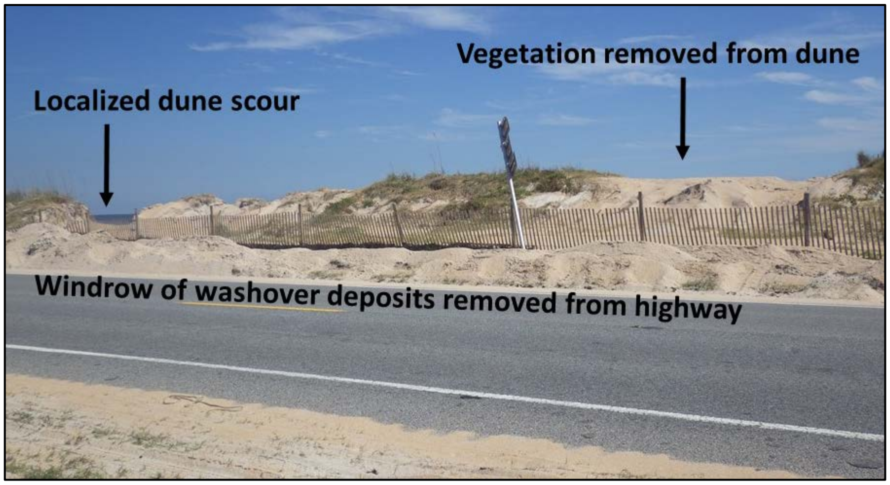
a) Location of washover and outwash deposit documentation.

b) Placing fill material to protect a roadway in Flagler County from damage [26].

Figure 62. Washover and overwash deposit location and protection scheme for roadways (Latitude 29°40' 18.47"N / Longitude 81°12'51.39"W).

The effects of overwash is seen clearly in Figure 63a. This photograph, looking east towards the Atlantic Ocean, shows damaged dunes, scoured dunes, and washover deposits that have been removed from the highway. The damage of the dunes is indicated by the removed dune vegetation. The localized scour is shown on the left hand side of the picture where there is a noticeable gap within the dunes. The washover deposits were most likely deposited on the highway. In order to make the highway useable, the deposits would have needed to be cleared and they were most likely placed in windrows also the shoulder of the highway.

Photographs from the west side of Highway A1A are shown in Figure 63b and Figure 63c. Figure 63b is a photograph looking north along Highway A1A. The figure shows a windrow of washover deposits that were removed from Highway A1A. Figure 63c shows the extent of the overwash deposits. These sediments were eroded/scoured from the dunes and deposited on the each bank of the Matanzas River. The sediments were transported distances of up to approximately 105 m.



a) Overwash damage to dunes on the east side of Highway A1A (Latitude 29°40'14.09"N / Longitude 81°12'50.37"W).

b) Windrows of washover deposits on west side of Highway A1A (Latitude 29°32'29.00"N / Longitude 81°9'25.0"W).

c). Washover deposits on the east bank of the Matanzas River (Latitude 29°40'17.59"N / Longitude 81°12'51.66"W).

Figure 63. Examples of overwash and washover deposits (Latitude 29°32'29.00"N / Longitude 81°9'25.0"W).

3.7.2 Site B. Breach

A breach, located at coordinates 29°40' 59.64" N, 81° 13' 6.204" W was documented. The breach site was located approximately 1.7 km north of the Marineland address. A breach, in terms of coastal geotechnical damage, is an erosional feature which allows salt water to move into an area of brackish or fresh water. The breach connected the Atlantic Ocean to the Matanzas River.

Figure 64 shows two views of the breach. Within the breach the water flows westward from the Atlantic Ocean to the Matanzas River. The depth of the breach is between approximately 0.3 m and 0.6 m. The deeper section of the breach is towards the western end. Figure 64a shows ripple marks at the eastern portion of the breach indicating sediment movement. Figure 64b shows the steep face of the edges of the breach. Figure 64C shows water moving westward from the Atlantic Ocean to the Matanzas River. The width of the breach was approximately 6 m.

a) Photograph looking west along the breach (Latitude 29°40'59.64"N / Longitude 81°13'6.20" W).

b) Photograph looking northwest along the breach (Latitude 29°40'59.38"N / Longitude 81°13'6.26" W).

c) Ocean water flowing west into Matanzas River (approx. location Latitude 29°40'59.64"N / Longitude 81°13'6.20"W).

Figure 64. Breach at the Marineland location (Latitude 29°40' 59.64"N / Longitude 81°13'6.204"W).

Although the breach was the emphasis at the site, there was notable structural damage and minor geotechnical damage noted along the walk from Marineland to the breach site and north of the breach site. Figure 65a is a photograph take north of the breach site. Heavy equipment was being used to remove overwash sediment deposits from the Matanzas River. The overwash sediments are clearly seen in the left hand side of the photograph. Figure 65b shows localized scour at a timber pile. The scour depth was minimal on the order of 10 centimeters and was not a contributor to structural damage. A concrete driveway was undercut by scour as shown in Figure 65c. The damage from the scour caused portions of the concrete driveway to be washed away. Figure 65d shows damage to a patio deck. The deck was constructed of brick pavers which were placed on a thin layer of cemented soil. Scour damaged a large portion of the deck.

a) Removal of overwash deposits from the Matanzas River (Latitude 29°41'6.19"N / Longitude 81°13'10.60"W).

b) Localized scour along pile foundation (Latitude 29°40'57.91"N / Longitude 81°13'5.51"W).

c) Scour at driveway (Latitude 29°40'20.18"N / Longitude 81°12'51.82"W).

d) Scour under a deck constructed of brick pavers (Latitude 29°40'38.5"N / Longitude 81°12'58.24"W).

Figure 65. Other examples of geotechnical damage at the Marineland locations.

3.8 Location 3. St. Johns County Ocean Pier

The St. Johns County Ocean Pier is located at 350 A1A Beach Boulevard. The pier and associated structures are located on Anastasia Island approximately 7.7 km southeast of downtown St. Augustine, FL. The location of the pier is shown in Figure 66.

This stretch of shoreline extending roughly 2 km to the north of the St. Johns County Municipal Pier (St. Augustine Pier) and 2 km to the south is a classic example of encroachment of development into the littoral zone as a cause' of beach erosion, as shown in Figure 67. Figure 67a portrays the typical condition of the shore in this location, with exposed seawall and revetment armoring. In 2003, the State of Florida teamed with the United States Army Corps of Engineers (USACE) to place approximately 4.5 mcy of sand on St. Augustine beaches. The USACE placed a further 2.8 mcy in 2005 as renourishment in response to severe erosion from the 2004 hurricane season. Consideration was given to a section of the project domain that historically experienced extraordinary erosion rates. The resulting nourishment design template applied additional sand at this erosional hotspot – and resulted in a protruding "elbow" in the planform design[27]. Figure 67b shows the beach after another nourishment was constructed in 2012 (note that the pier is almost landlocked by the fill). The Holiday Inn indicated in the right-hand panel was demolished in 2016, and the construction of a new hotel permitted on this protruding site. Figure 67c shows the amount of erosion that has occurred since 2012.

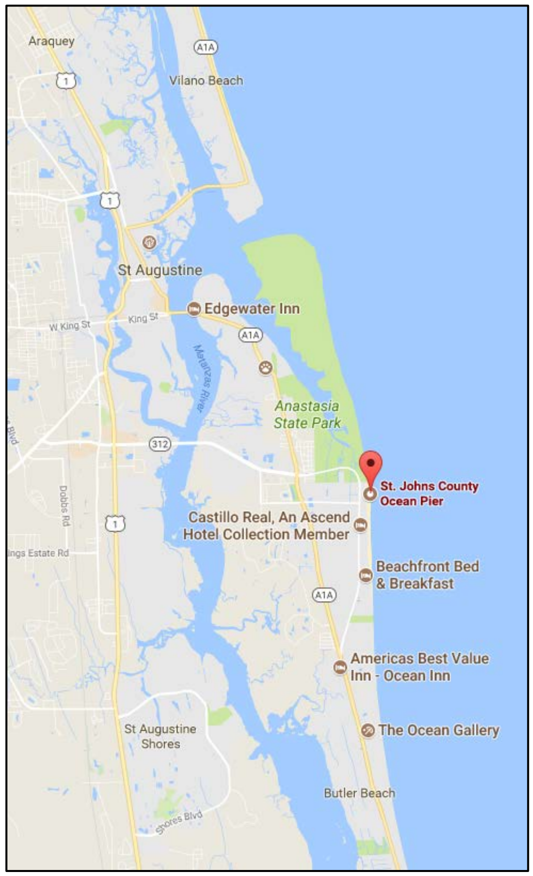


Figure 66. Location of St. Johns County Ocean Pier (Latitude 29°51'25.98"N / Longitude 81°15'55.61"W).

[27] Albada, E., Goshow, C., & Dompe, P. (2005) Effect of beach nourishment on surfing – observations from the St. Johns County shore protection project. In Proceedings of the 2007 National Conference on Beach Preservation Technology, Fort Lauderdale, FL, January 24-26, 2007. Florida: Florida Shore & Beach Preservation Association.

a) December 2011 (pre-nourishment). b) January 2013 (post nourishment). c) September 2017.

Figure 67. Google Earth images of area of chronic erosion problems (Latitude 29°51'25.98"N / Longitude 81°15'55.61"W).

Photographs in Figure 68 were taken north of the pier near the new construction indicated in Figure 67c. Figure 68a shows the new hotel under construction in the background. Figure 68b was taken looking south towards the pier, and Figure 68c was taken looking towards the north showing the condition of the beach. Figure 68d shows evidence of overwash and unraveling of the poorly constructed revetment at the north end of the property.

a) New construction (Latitude 29°51'29.30"N / Longitude 81°15'55.49"W).

b). Seawall and pier (Latitude 29°51'34.61"N / Longitude 81°15'57.22"W).

c) Beach conditions (Latitude 29°51'33.61"N / Longitude 81°15'56.29"W).

d) Overwash and unravelling of poorly constructed revetment (approximate location Latitude 29°51'34.61"N / Longitude 81°15'57.22"W).

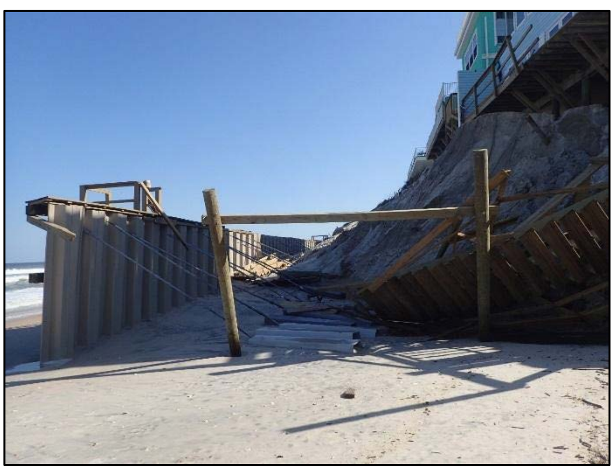
Figure 68. Photographs taken north of the St. Johns County Ocean Pier (Latitude 29°51'25.98"N / Longitude 81°15'55.61"W).

3.9 Location 5. Vilano Beach

Vilano Beach was perhaps the most damaged beach area from Hurricane Irma. Beach damage documentation at Vilano Beach began at 3920 Coastal Highway, St. Augustine, FL and progressed approximately one mile in a northeasterly direction to 4070 Coastal Highway, St. Augustine, FL. Figure 69 shows the limits of the beach damage reconnaissance.

The first significant damage noted was seawall backfill scour at 3920 Coastal Highway. The damaged occurred at the wing wall of the anchored seawall. Water action removed the granular material behind the wall exposing the anchors. The scour was significant enough to undermine the foundation of the beach house on top of the retained soil. Figure 70a shows significant erosion behind the retaining wall with anchors exposed. The northern wing wall of the retaining structure has been washed away. Note the scour beneath the structure on the right hand side of the photograph. Figure 70b shows the same retaining wall from the top of the dune.

Figure 69. Damage reconnaissance limits at Vilano Beach (from Google Maps, 2017).



a) Scour exposing anchors and north wing wall is missing (Latitude 29°56'46.05"N / Longitude 81°18'7.5"W).

b). Same damaged retaining wall photographed from the top of the dune (Latitude 29°56'46.05"N / Longitude 81°18'7.5"W).

Figure 70. Scour behind retaining wall at Vilano Beach (Latitude 29°56'46.05"N / Longitude 81°18'7.5"W).

Progressing in a northeasterly direction along the beach, the coastal bluffs were not protected by seawalls. Properties located between 3930 Coastal Highway to 4010 Coastal Highway had severe bluff erosion. The erosion caused severe undermining of foundations. The undermining did not undercut the timber pile foundations but in several instances shallow foundations supporting decks were completely undercut. Figure 71a shows severe erosion exposing timber pile foundations at 3930 Coastal Highway. Note the cross bracing that has been added to provide lateral support for the exposed piles. Figure 71b also shows severe erosion exposing timber pile foundations and undercut shallow foundations supported by micropiles which support a deck. The location of this damage is 3940 Coastal Highway. The person shown in the photograph is 1.93 meters tall. Figure 71c shows the severe erosion at 3978 Coastal Highway. Once again timber piles are exposed. Note the wooden piers supporting the deck are free hanging with no support.

a) Beach house at 3930 Coastal Highway (Latitude 29°56'46.05"N / Longitude 81°18'7.46"W).

b) Beach house at 3940 Coastal Highway (Latitude 29°56'47.00"N / Longitude 81°18'8.10"W).

c) Beach house at 3978 Coastal Highway (Latitude 29°56'50.66"N / Longitude 81°18'10.74"W).

Figure 71. Examples of erosion exposing timber pile foundations at Vilano Beach.

A beach house located at 4010 Coastal Highway, St. Augustine FL was not supported by pile foundations. Wave action associated with Hurricane Irma caused the bluff to be cut back from the ocean approximately 15 meters towards Coastal Highway (Highway A1A). Figure 72 shows aerial images of 4010 Coastal Highway. Figure 72a shows the location of the house and dune system prior to Hurricane Irma. Figure 72b is a recent image showing the severe erosion of the dune system. Note the position of the house has shifted.

a) Prior to Hurricane Irma.

b) Post Hurricane Irma.

Figure 72. Aerial image of 4010 Coastal Highway in Vilano Beach (Latitude 29°56'54.04"N / Longitude 81°18'11.00"W).

a) Picture taken facing north.

b). Picture taken facing south.

Figure 73. Collapsed house at 4010 Coastal Highway, Vilano Beach (Latitude 29°56'54.62"N / Longitude 81°18'11.03"W).

The significant erosion at the property at 4010 Coastal Highway is much more dramatic from the beach. Figure 73 shows the collapsed house at 4010 Coastal Highway. Figure 73a shows the house in a picture taken looking north. Figure 73b shows the house in a picture looking south. Both figures clearly show the significant erosion which cause the collapse of the house.

Progressing northeasterly along the beach the next three houses, 4020, 4030, and 4040 Coastal Highway, had a continuous sea wall to protect the bluffs. Once again the wing walls of the sea walls experienced damage. Figure 74 is a Google Maps aerial image of the house at 4020 Coastal Highway. Note the erosion and scour damage to the south wing wall of the retaining structure.

Figure 74. Aerial image of south wing wall damage at 4020 Coastal Highway, Vilano Beach, FL (Latitude 29°56'55.10"N / Longitude 81°18'11.25"W, from Google Earth, 2017).

The ground reconnaissance at 4020 Coastal Highway revealed significant damage. Figure 75a shows the complete southern wing wall was destroyed due to scour and wave action. Figure 75b is a photograph peering behind the wall showing significant scour which exposed anchors connecting to a deadman support and completely undermined piers supporting a deck.

a) South wing wall destroyed.

b) Damage behind the retaining structure.

Figure 75. South wing wall damage at 4020 Coastal Highway, Vilano Beach (Latitude 29°56'55.10"N / Longitude 81°18'13.49"W).

At the northern end of the seawall, there was also damage to the wing wall. However at this location (4040 Coastal Highway) the wing wall was not destroyed. However significant erosion coupled with insufficient driving depth caused the bottom of the sheet pile to be exposed, as shown in Figure 76a. Figure 76b is a close-up photograph of the exposed bottom. The close up photographs shows evidence of soil movement. The exposed bottom of the sheet pile acted as a conduit for the retained soil to escape causing significant ground loss behind the seawall. Figure 76c shows the cavity formed from escaping soil.

a) Exposed bottom of sheet pile wall (Latitude 29°56'58.35"N / Longitude 81°18'12.10"W).

b) Close up of exposed bottom of sheet pile (Latitude 29°56'58.35"N / Longitude 81°18'12.10"W).

c) Ground loss behind sheet pile (Latitude 29°56'58.16"N / Longitude 81°18'11.96**”**W).

Figure 76. Damage to retaining structure at 4040 Coastal Highway, Vilano Beach (Latitude 29°56'58.16"N / Longitude 81°18'11.96″W).

a) Wall bowing below wale and anchors (Latitude 29°57'46’1.08”N / Longitude 81°18'12.22”W).

b) Cracking and hole in sheet pile material (Latitude 29°56'44.79"N / Longitude 81°18'7.05”W).

Figure 77. Distress and damage to vinyl retaining walls at Vilano Beach, FL.

More generalized damage was noted along all of the seawalls. The seawalls are made of a vinyl (PVC) material. Many locations of the walls are bowed outwards below the timber wale (Figure 77a). The wall deformation may be due to an increase in the unit weight of the pervious material behind the wall from significant rainfall and the removal of passive resistance from the front of the wall due to scour and erosion. Other localized damage to the vinyl seawalls included cracking and punctures, as shown in Figure 77b. One important aspect that must be considered for the design of seawalls is the possibility of scour. The walls must be embedded sufficiently and the wing walls must extend sufficient distances from the front of the wall. Ideally post erosion event elevations and distances should be used for wall design.

4 BRIDGE AND HYDRAULIC STRUCTURE DAMAGE IN NORTHEAST FLORIDA

4.1 Introduction to Northeast Florida

Jacksonville Florida is located in Duval County on the northeast coast of Florida. The city was consolidated with Duval County in 1968 making it the largest city in area in the continental United States. The population of Jacksonville is approximately 850,000[28]. The Jacksonville Metropolitan Area has a population of approximately 1.4 million and includes Duval, Nassau, Clay and St. John Counties[29]. Jacksonville is home to a deep water port, numerous military facilities, an international airport, and a US Army Corps of Engineers District Office.

Downtown Jacksonville is located on the banks of the St. Johns River. The river is approximately 500 km long and drains approximately 24400 square kilometers. It flows north from a network of marshes in Indian River County in the south and enters the Atlantic Ocean in Duval County. The change in elevation between the headwaters and outlet is approximately 10 meters. The river is tidally influenced and this influence can reach as far as approximately 257 km upstream causing reverse or southerly flow. The reverse flow is influenced as much by weathering conditions as by ocean tides. Water sources for the river include rainfall, runoff, aquifers, and springs[30].

Another major waterway in Jacksonville is the Intracoastal Waterway (ICW). The Atlantic Intracoastal Waterway extends more than 1700 km from Norfolk, VA to Key West, FL. The US Army Corps of Engineers is responsible for maintaining the waterway[31]. In Duval County the Intracoastal Waterway separates Jacksonville from the communities of Atlantic Beach, Neptune Beach, and Jacksonville Beach.

Seven major bridges cross the St. Johns River in Jacksonville. These bridges are known by their local names (official names in parentheses) as the Main Street (John T. Alsop Jr.), Fuller Warren, Buckman (Henry Holland Buckman), Acosta (St. Elmo W. Acosta), Mathews (John E. Mathews), Dames Point (Napoleon Bonaparte Broward), and Hart (Isaiah D. Hart) bridges[32]. There are many smaller waterways that drain into the St. Johns River as well as the Intracoastal Waterway. These smaller waterways have numerous tributaries which require smaller bridges for vehicle access to different parts of the city. According to Florida Department of Transportation (FDOT) bridge inspection reports[33], there are approximately 780 bridges in Duval County.

---

[28] Retrieved from: http://www.coj.net/about-jacksonville.aspx

[29] Retrieved from: http://jacksonville.com/news/metro/2017-03-23/jacksonville-s-population-growth-speeds-third-year-row

[30] Retrieved from: http://sjrr.domains.unf.edu/st-johns-river-basin-landscape/

[31] Retrieved from: https://atlanticintracoastal.org/

[32] Retrieved from: http://jacksonville.com/discoverjacksonville/jacksonvilles-seven-bridges-are-seven-links-city

[33] Retrieved from: http://www.fdot.gov/maintenance/bridgeinfo.shtm

4.2 Reconnaissance Locations

Hydraulic and bridge structure damage reconnaissance was conducted on Wednesday September 27, 2017 in Nassau and Duval County Florida. Five locations were identified through local engineering contacts, the Florida Department of Transportation, social media, and traditional media outlets. The reconnaissance team began at Location 1, Hampton Lake, in Nassau County north of Jacksonville to document a failed concrete covered earth dam. The team then returned to Jacksonville to the historic Riverside/Avondale area (Location 2) which is located south of downtown. Here the team documented damage to two sites, a small pocket park and a large community park. Location 3 was the US 17 and Trout River bridge in north Jacksonville where the team documented significant scour at the bridge embankment. Figure 78 is a map showing the locations visited.

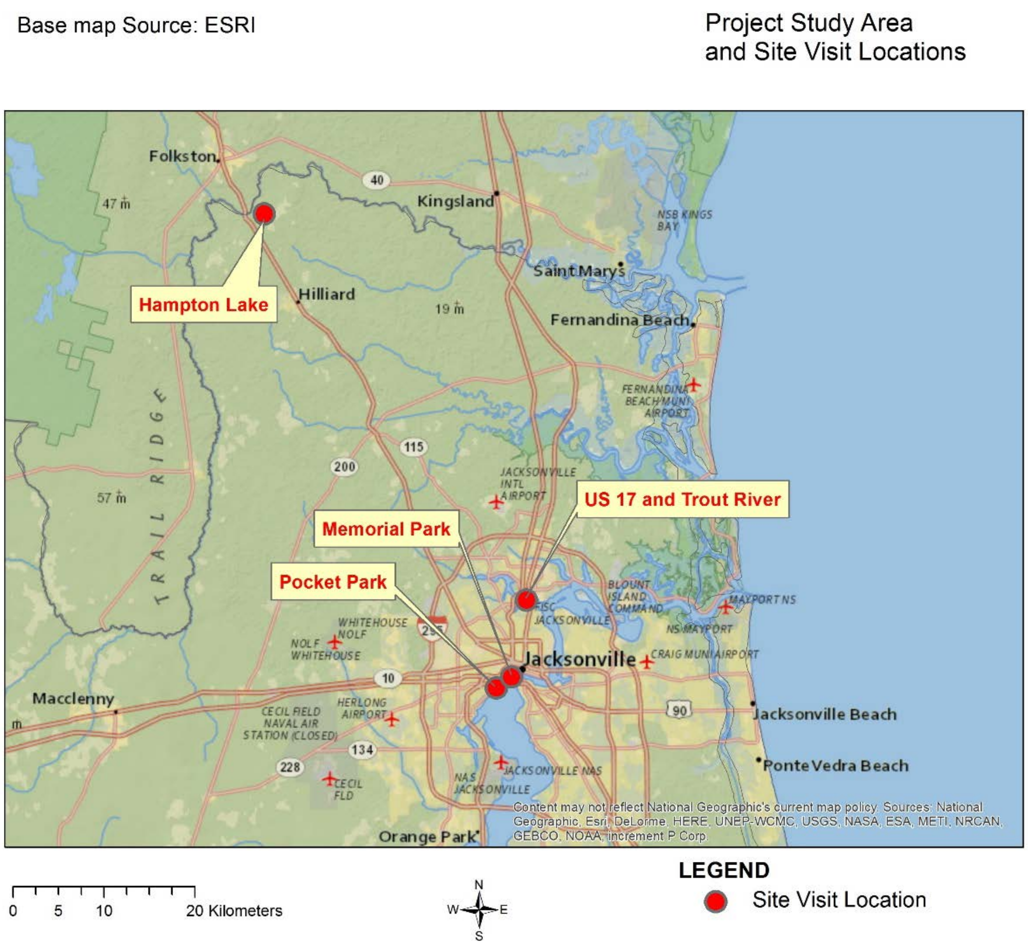


Figure 78. Google Earth map showing locations visited for bridge and hydraulic structure damage in northeast Florida (data from Google and ESRI mapping).

4.3 Water Levels in the St. Johns River during Hurricane Irma

Water levels in the St. Johns River are monitored by the USGS. Data from two water level gages, one near downtown Jacksonville and the other on the Ribault River near the Trout River are the closest to the reconnaissance sites. The downtown USGS gage, located at Latitude 30°19'20" and Longitude 81°39'56", is the closest gage to the Donald Street pocket park and Memorial Park reconnaissance sites. The distance from the gage to the two sites is approximately 3.8 km and 1.7 km respectively. The location of the gage with respect to the two reconnaissance sites is shown in Figure 79.

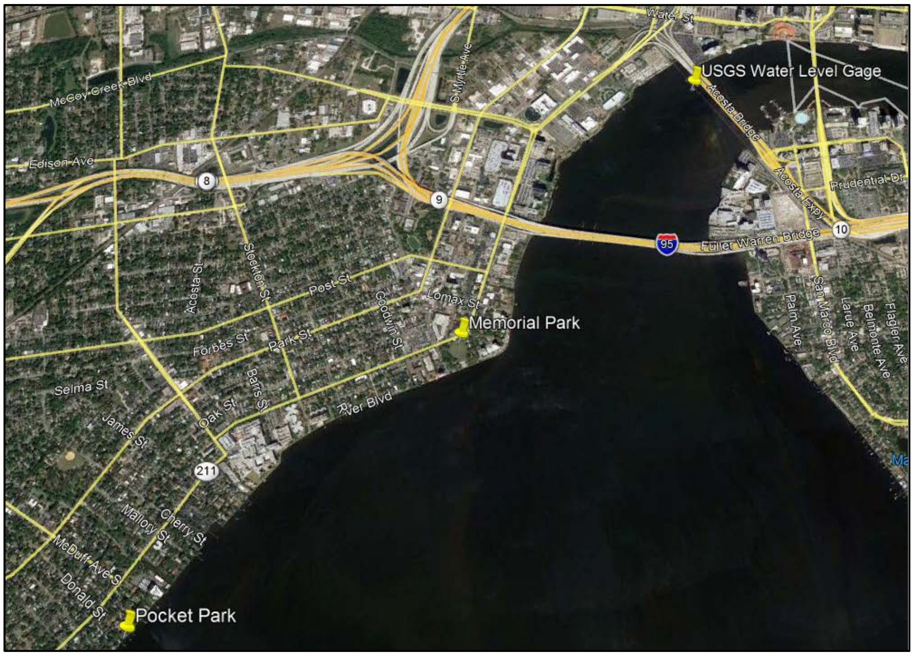


Figure 79. Google Earth view of the location of the USGS gage (Latitude 30°19'20" N / Longitude 81°39'56" W) with respect to the Donald Street pocket park (Latitude: 30°18'0.99" N / Longitude: 81°41'47.13" W) and Memorial Park (Latitude 30°18'38.44"N / Longitude 81°40'46.16" W) reconnaissance sites.

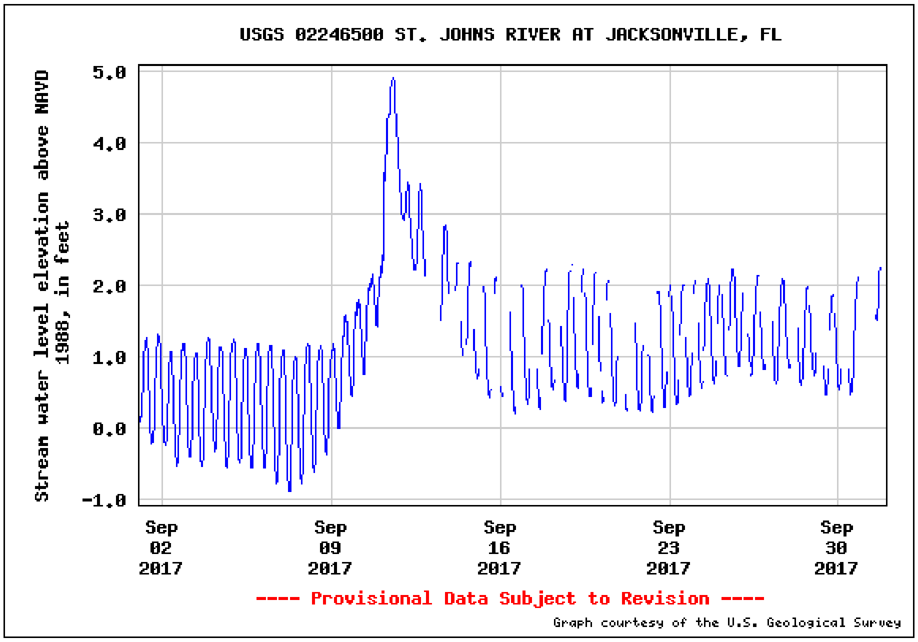


Figure 80. Water levels recorded at the USGS gage location in downtown Jacksonville[34].

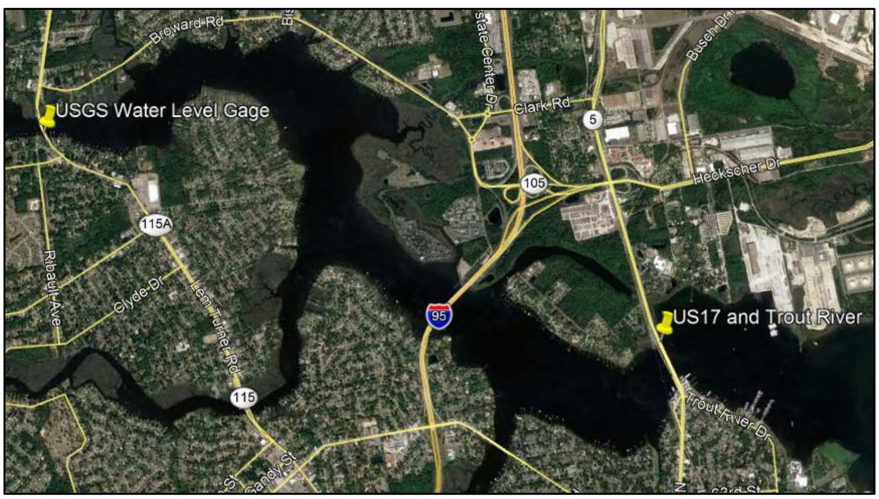


Figure 81. Google Earth view of the location of the USGS gage (Latitude 30°25'02"N / Longitude 81°41'48"W) with respect to the US17 and Trout River (Latitude 30°23'45.44"N / Longitude 81°38'53.95"W) reconnaissance site.

The water levels at the downtown Jacksonville USGS gage location are shown in Figure 80. The highest level indicated was 4.91 feet (1.49 m) NAVD 88 at 1:45 PM on September 11, 2017. This was the highest stage recorded in a seven year period. The water levels may have even been higher because no measurements were made between 11:30 AM and 1:30 PM.

The north Jacksonville USGS gage, located at Latitude 30°25'02" and Longitude 81°41'48", is the closest gage to the US17 and Trout River reconnaissance site. The distance from the gage to the site is

[34] Retrieved from: https://waterdata.usgs.gov/fl/nwis/rt

approximately 5.2 km. The location of the gage with respect to the reconnaissance site is shown in Figure 81.

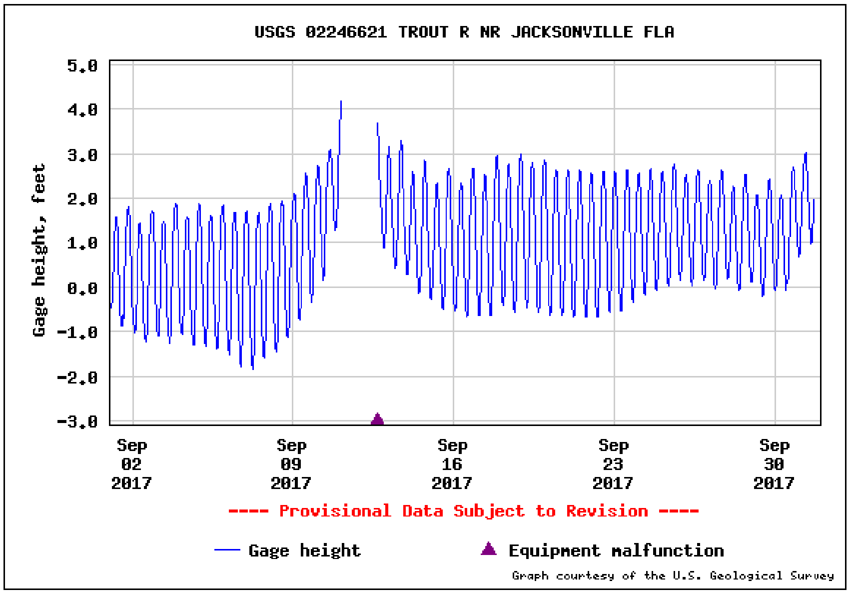


Figure 82. Water levels recorded at the USGS gage location in north Jacksonville[34].

The water levels at the north Jacksonville USGS gage location are shown in Figure 82. The highest level indicated was 4.16 feet (1.27 m) NAVD 88 at 2 PM September 11, 2017. Unfortunately there was a gage malfunction and there is missing data both before and after this reading.

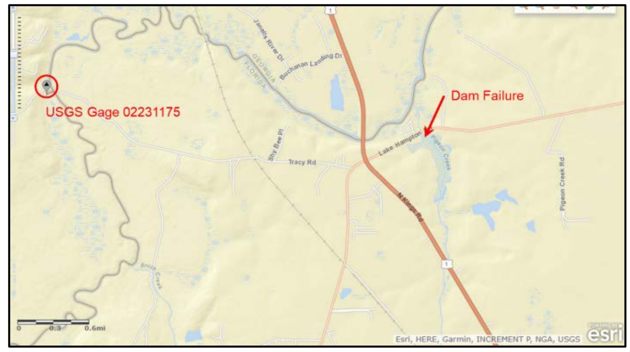
4.4 Location 1. Hampton Lake Dam

The Hampton Lake dam is located northeast of Hilliard, Florida in Nassau County. Hilliard is a small rural community with a population of approximately 3100 people[35] and is located approximately 51.6 km northwest of Jacksonville, FL (Figure 83). The reconnaissance site is the Hampton Lake Dam which is located to the east of Highway 301 along Lake Hampton Road. The coordinates of the site are Latitude 30° 46’ 38.43” N and Longitude 81° 58’ 13.09” W. Lake Hampton reservoir is part of the Pigeon Creek basin. The basin has a drainage area of approximately 2326 hectares[36]. The outlet of the dam is to a small tributary of the St. Mary's River which forms the boarder of Florida and Georgia.

The dam is a compacted earth concrete covered dam. The primary outlet control is a concrete box weir with dimensions of 1.5 m by 6.7 m. The control elevation is 5 meters and the trash rack elevation is 5.8 m. There are three 1.2 m diameter concrete pressure pipes extending through the dam. The embankment has an elevation of approximately 6.7 m (NAVD 88) and the spillway crest is at an elevation of approximately 5.2 m. The spillway has a width of approximately 15.2 m. Photographs of the dam from Google Earth are shown in Figure 84.

[35] Retrieved from: https://factfinder.census.gov/faces/nav/jsf/pages/community_facts.xhtml?src=bkmk
[36] Retrieved from: http://www.nassaucountyfl.com/DocumentCenter/Home/View/1915

a) Lake Hampton reconnaissance site (from Google Earth, 2017).



b) Location of USGS gage closest to the reconnaissance site[37].

Figure 83. Lake Hampton reconnaissance site (Latitude 30°46'38.57"N / Longitude 81°58'15.09"W).

Figure 83b shows the location of USGS gage. The gauge data from the St. Marys River are also presented in Figure 85 and Table 2.

[37] Retrieved from: https://waterdata.usgs.gov/ga/nwis/uv/?site_no=02231175&PARAmeter_cd=00065,00060,00062

a) Aerial view of Lake Hampton Dam showing both dam and concrete box weir.

b) Roadway view of Lake Hampton Dam.

Figure 84. Google Earth views of the Lake Hampton Dam (Latitude 30°46'38.57"N / Longitude 81°58'15.09"W).

The reconnaissance team was able to interview two eyewitnesses to the dam failure. One of the eyewitnesses provided a mobile phone video of the dam failure. According to the eye witnesses and the video, the dam spillway failed at approximately 7:44 AM on September 11, 2017. At that time the tail water was approximately 2.44 m NAVD 88 based on the USGS gage. The video appears to show undermining of the spillway slab and/or erosion of the embankments leading to failure because of discolored water in the video. The video clearly shows water overflowing the spillway crest indicating the height of the reservoir pool elevation of greater than 5.2 m NAVD 88. Based on the interviews and video, the failure of the dam can be approximately located on the St. Mary's River hydrograph shown in Figure 86.

Figure 87 shows the variety of geotechnical damage associated with the dam failure. Figure 87a shows the completely failed dam with the concrete weir structure still intact. Figure 87b shows the scour on the north shoulder of the Lake Hampton Road. During the event the water overflowed the spillway area and overflowed Lake Hampton Road. Figure 87c shows the embankment erosion on the east side of the former dam. Figure 87d shows the lowered water levels in the reservoir.

Table 2. Gage height at the USGS gage closest to the reconnaissance site[37]

Date (Sept. 2017)	Time	Height (m)
10	Noon	4.25
11	Noon	10.54
12	Noon	16.5
13	Noon	17.33
14	Noon	18.72
15	Noon	19.29
16	Noon	19.11

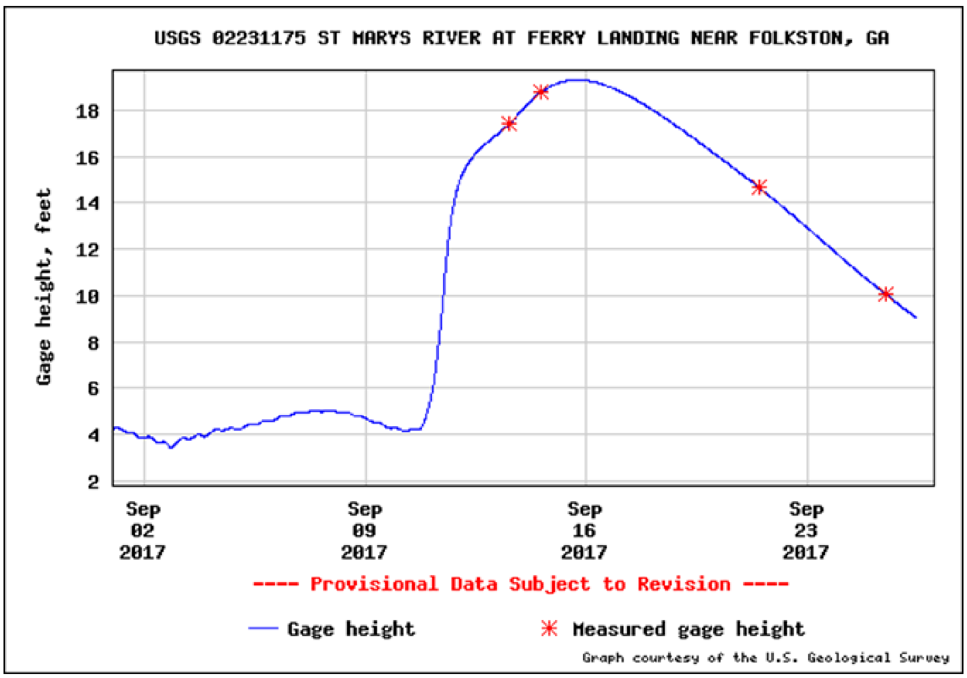


Figure 85. Gage height at the USGS gage closest to the reconnaissance site[37]

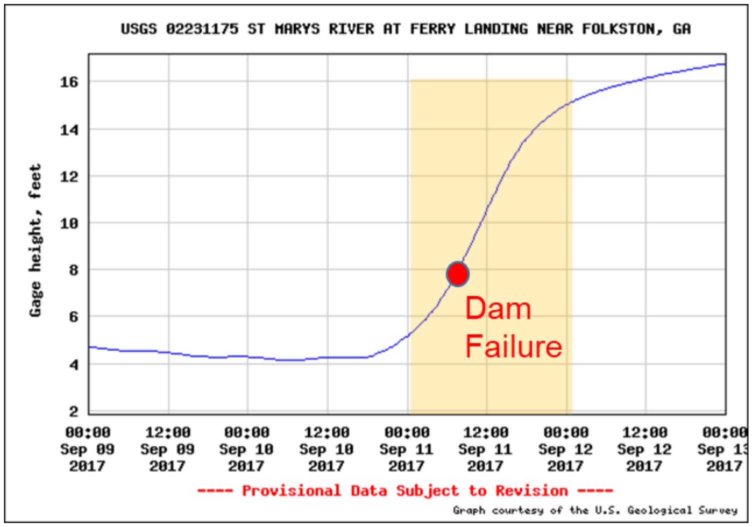


Figure 86. Dam failure and St. Mary's River hydrograph.

a) Failed dam showing concrete box weir intact (Latitude 30°46’40.1”N / Longitude 81°58’13.0”W).

b) Scour at pavement edge on north shoulder of Lake Hampton Road (Latitude 30°46’45.19”N / Longitude 81°58’24.6”W).

c) Scour of the east embankment of the dam (Latitude 30°46’33.89”N / Longitude 81°58’15.47”W).

d) Lowered water levels in Lake Hampton (Latitude 30°46’37.97”N / Longitude 81°58’14.27”W).

Figure 87. Variety of geotechnical damage at the Lake Hampton reconnaissance site (Latitude 30°46'38.57"N / Longitude 81°58'15.09"W).

4.5 Location 2. Jacksonville Historic District

The St. Johns River flows approximately northward through downtown Jacksonville. Just south of downtown Jacksonville is the Riverside/Avondale historic district. This area is roughly bounded by I-10 / I-95 to the north, SR 17 (Roosevelt Boulevard to the east), St. Johns River to the west, and Big Fishwier Creek to the south.

4.5.1 Site 1. Donald Street Pocket Park

Within the historic district along the St. Johns River there is a bulkhead which forms the western bank of the St. Johns River. Within this area avenues are oriented approximately parallel to the river and streets are oriented approximately perpendicular to the river. Where the streets terminate at the rivers, there are small pocket parks. This parks are often used by the public for recreational fishing. Figure 12 shows the location of the Donald Street pocket park as well as other similar parks in the area. There are many private boat docks in the area, as shown in the Figure 88.

Figure 88. Locations of three pocket parks, including the Donald Street pocket park, in historic Riverside/Avondale (from Google Earth, 2017).

a) Localized scour behind the river bulkhead.

b) Damage to private dock.

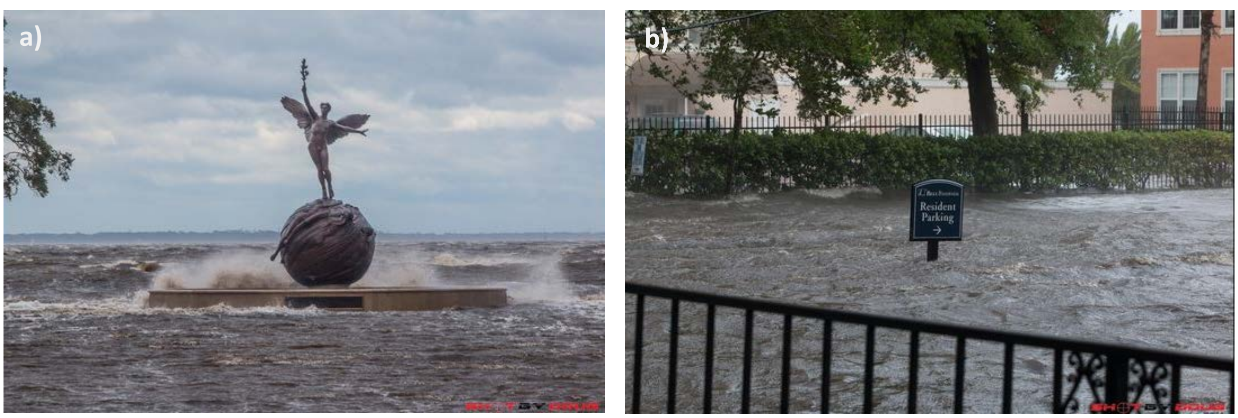
Figure 89. Damage noted at the Donald Street pocket park (Latitude 30°18'1.43"N / Longitude 81°41'7.03"W).

Localized scour from overtopping the bulkhead was noted at the Donald Street pocket park. These holes in the ground need careful repair as some of these might be extending underground up to river boundary wall. There was also considerable damage to private boat docks. Photographs of these damages are shown in Figure 89. Although the localized scour damage may not be considered significant, this type of damage occurred at a number of the pocket parks along the St. Johns River in the historic district of Jacksonville.

4.5.2 Site 2. Memorial Park

Location of Memorial Park is shown Figure 79. The river front infrastructure includes paved surface along the river adjacent to the Memorial Park. The paved surface extends to the river boundary wall. There is a decorative concrete railing along the river for safety of people using the river front for walking and fishing. The railing height is approximately 0.75 m. There is a large fountain and statue near the paved surface. The statue is a memorial to the 1200 soldiers from Florida who lost their lives[38]. Away from the river, the park has a large greenspace where people congregate for leisure activities.

During Hurricane Irma, water of St Johns River rose about 0.75 m above the ground surface due to storm surge and rainfall. From media reports and information obtained from public, it was clear that the park and the adjacent streets along the river flooded during the hurricane. This flooding is shown in Figure 90. Following the hurricane and after flood waters receded, the railing along the riverfront was damaged and in some places was washed away by the water (Figure 91). This created a safety hazard for the people and pets using riverfront and needs to be repaired as a priority.



[38] http://www.jaxhistory.org/portfolio-items/memorial-park/

Figure 90 Images from Hurricane Irma flooding at Memorial Park[39] (Latitude 30°18'38.44"N / Longitude 81°40'46.16" W).

Figure 91.Photo showing sections of the broken decorative railing. Photograph taken looking north. (Latitude 30°18’36.11”N / Longitude 81°40’44.68”W).

Localized deep scour holes were observed at a number of locations on the west or park side of the concrete walkway. Many of these holes appear to extend under the concrete walkway and towards the river. If left unattended these holes may cause localized failures of the walkway. Two examples of scour holes are shown in Figure 92.

[39] Action News Jax (CBS 47 Fox 30) (September 14, 2017). *Photos: Amazing photos of flooding in downtown Jacksonville*. Retrieved from http://www.actionnewsjax.com/news/photos/photos-amazing-photos-of-flooding-in-downtown-jacksonville/608820340

Photograph location (Latitude 30°18’35.36”N / Longitude 81°40’46.70”W).

Photograph location (Latitude 30°18’36.46”N / Longitude 81°40’44.25”W).

Figure 92. Example of scour holes at Memorial Park (Latitude 30°18'38.44"N / Longitude 81°40'46.16"W).

4.6 Location 3. Scour at US 17 Trout River Bridge Abutment.

Significant scour occurred along the embankment of the US-17/SR-5 bridge (Bridge 720011) over the Trout River in Jacksonville (Duval County) Florida (Figure 93) at approximately Latitude 30°23'45.44"N and Longitude 81°38'53.95"W on September 10, 2017.

Significant scour was observed at the north east quadrant of the bridge embankment starting from the concrete cover of the embankment and extending northward approximately 140 m (Figure 94, Figure 95). More localized scour was observed at the northwest quadrant of the bridge adjacent to the concrete cover of the embankment (Figure 95d).

The Trout River is hydraulically connected to the St. Johns River and the ocean, and is tidally influenced. The embankment soils are located above a concrete wall at the interface with the river, and this wall exists approximately 1-2 m above the elevation of the Trout River depending on the tide at this location. During Hurricane Irma, storm surge raised the elevations of the St. Johns and Trout Rivers. During the storm, elevated water levels likely overtopped the concrete wall separating the embankment from the river, subjecting the embankments near the north bridge abutment along the east and west side to erosion. The storm surge and heavy winds additionally caused several vessels to break free from their moorings, which were found washed up on the eastern embankment. These vessels cause turbulent flow which exacerbated erosion where the vessels were found.

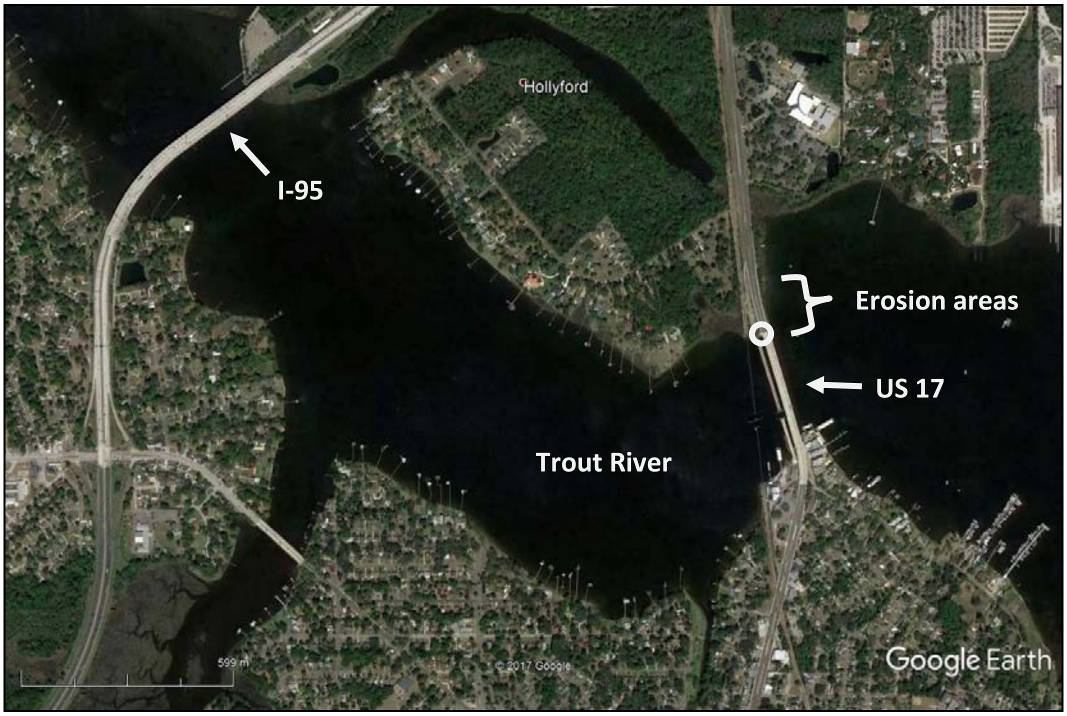


Figure 93: Location of the US 17 bridge over the Trout River within the broader regional context of northeast Florida (Latitude 30°23'45.44"N / Longitude 81°38'53.95"W).

The extent of the damage is illustrated in Figure 94 and Figure 95 over about a 140 m distance from the east side of the north abutment northward. Figure 94 illustrates the erosion below the roadway in the wooded protected area of the highway that extended south toward the unprotected area. In the area not protected by brush, the edge of the road were scoured to greater depth and width, where the road was undermined so that concrete panels became displaced and underground utilities (e.g., sewer pipe, electrical conduit, sewer access structure) were exposed. Figure 94a additionally illustrates a large boat washed ashore that led to increased amounts of erosion. Figure 95 illustrates the extent of the damage at the bridge abutment. The embankment soils adjacent to the abutment were stabilized using a concrete faced, stacked concrete sack wall. These walls were exposed at both the east and west side of the abutment. The elevated water level and volume, as well as the channel constriction caused by the bridge were the likely causes of the erosion at the hard-soft discontinuity of the concrete and embankment soils and where flow was forced on to the eastern embankment while an eddy was formed after the water flowed under the bridge.

Figure 94. Scour damage along the northeast bridge embankment of the US 17 bridge over the Trout River, (Latitude 30°23'45.44"N / Longitude 81°38'53.95"W). Scour features are presented from north to south toward the concrete cover of the embankment that demonstrate erosion of soil below the road shoulder that resulted in broken pavement and exposed buried infrastructure that included: shallow roadside scour (a); boat washed ashore and scour pattern (b); an exposed sewer access structure and sewer pipe originally located 5 feet below finished grade (c); exposed sewer pipe and conduit for electrical service to light poles (d), and; the terminus of scour (e). Scour was likely caused by eddies and turbulence around two boats washed ashore (f).

Figure 95. Scour damage along the northern bridge embankment of the US 17 bridge over the Trout River, (Latitude 30°23'44.43"N / Longitude 81°38'54.13"W). Scour features are presented from north east to north west near the concrete cover of the embankment that demonstrate erosion, which included: embankment soil erosion north of the bridge abutment (a, b), and erosion at the interface between the soil and concrete faced, stacked concrete sack wall at the east (c), and west (d) side of the north abutment.

At the site visit on September 27, 2017, two weeks after the scour damage occurred, construction crews were well into the repair. The repair included rebuilding the embankment elevation with soil after which flowable fill that was able to be excavated at a later time if necessary was trimmed into vertical trenches near the roadside to stabilize the soil under the road and the underground utilities. Figure 96 illustrates the locations of this fill. Figure 96a illustrates the flowable fill that was installed adjacent to the bridge abutment, which was approximately 5 m long, 1 m wide, and 6 m deep. Figure 96b illustrates the flowable fill that was installed adjacent to the roadway more north of the bridge, which was approximately 21 m long, 1 m wide, and 2 m deep.

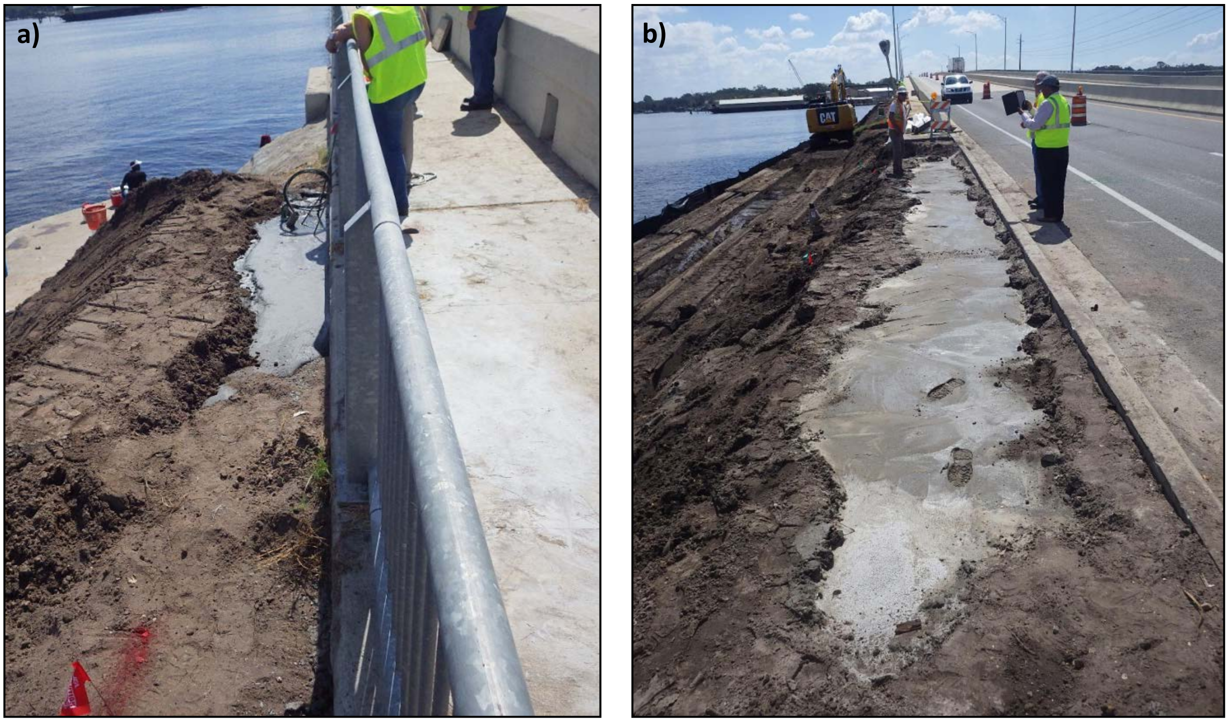


Figure 96. Repair of major scour damage along the northeastern bridge embankment of the US 17 bridge over the Trout River, (Latitude 30°23'45.44"N / Longitude 81°38'53.95"W) where the embankment was rebuilt and excavateable flowable fill trenches installed within the soil adjacent to the roadway to stabilize the roadway shoulder and underground utilities and protect against future erosion adjacent to the concrete covered stacked concrete sack wall near the northeast abutment (a) and along the eastern roadway edge to the north (b).

5 SUMMARY

This report documents the geotechnical damage attributed to Hurricane Irma in central and northeastern Florida. The GEER team leadership consisted of Nick Hudyma (University of North Florida), Melissa Landon (University of Maine), and Radhey Sharma (West Virginia University). Team members included Cigdem Akan (University of North Florida), Christopher J. Brown (University of North Florida), Rafael Crowley (University of North Florida), William Dally (University of North Florida), and Xiaoyu Song (University of Florida). The reconnaissance were conducted from September 25 through September 27, 2017. A second GEER team, led by Nina Stark (Virginia Tech), documented geotechnical damages from Hurricane Irma in southwest coastal Florida from Cape Coral to Key West. The reconnaissance was conducted at the same time as this report.

The report presents three categories of geotechnical damages which were based on the three reconnaissance areas visited. On September 25, 20017 the team documented sinkhole damage in central Florida. The team started in Gainesville, FL and travelled southwest along the I-75 corridor and then west into central Florida for their reconnaissance. Numerous sinkholes were photographed and documented. The sinkholes affected retention ponds, minor streets, freeways, golf courses, and houses. The sinkholes were located in Gainesville, Ocala, and The Villages. An extremely large erosional gully was also documented in Apopka, Florida.

Beach erosion and scour was documented at the northeast Florida beaches on September 26, 2017. Geotechnical damage that was documented included overwash and washover deposits affecting a highway, erosion affecting retaining structures, extreme scour at the wing walls of retaining structures which exposed anchoring systems, extreme scour beneath foundations exposing portions of deep foundations and completely undermining shallow foundations, significant ground loss behind a sheet pile structure from scour exposing the bottom of a sheet pile section. The most significant damage was the collapse of a beach house supported on by a shallow foundation from extreme erosion.

Damage to hydraulic and bridge structures was documented on September 27, 2017. The team documented the failure of a concrete lined earth dam in Nassau County north of Jacksonville. Other geotechnical damage included scour behind bulkheads in the historical district of Riverside/Avondale in Jacksonville and significant scour at a bridge embankment in north Jacksonville.

Although some of the documented geotechnical damage is extreme, the team was happy to notice that many infrastructure assets were not significantly damaged during the hurricane. Many bridges did not experience scour issues, not all beaches were significantly affected, and many sinkholes formed in areas where residential, commercial, and lifeline structures were not affected.

6 REFERENCES

Albada, E., Goshow, C., & Dompe, P. (2005) Effect of beach nourishment on surfing – observations from the St. Johns County shore protection project. In Proceedings of the 2007 National Conference on Beach Preservation Technology, Fort Lauderdale, FL, January 24-26, 2007. Florida: Florida Shore & Beach Preservation Association.

Campbell, K, M. and Scott, T. M. (1991). Radon potential study, Alachua County Florida: near-surface stratigraphy and results of drilling (Open File Report Number 41). Tallahassee, FL: Florida Geological Survey.

Davies Jr., R. A. (1997). *Geology of the Florida Coast*. In Randazzo and Jones (Eds.), The Geology of Florida (pp. 155-168). Gainesville: University Press of Florida.

Hine, A. C. (2013). Geologic History of Florida. Gainesville: University Press of Florida.

Hudyma, N., Ruelke, T., & Samakur, C. (2005). Characterization of a sinkhole prone retention pond using multiple geophysical surveys and closely spaced borings. In B. Beck (Ed.), *Proceedings of the 10th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst: Geotechnical Special Publication No. 144,* San Antonio, TX (pp. 555-561). Reston, VA: American Society of Civil Engineers.

Kim, Y. J., Xiao, H., Choi, Y. W., & Nam, B. H. (2017). Development of sinkhole hazard mapping for central Florida. In T. L. Brandon and R. J. Valentine (Eds.), *Geotechnical Frontiers 2017: Transportation Facilities, Structures, and Site Investigation, Geotechnical Special Publication No. 277*, Orlando, FL (pp. 459-468). Reston, VA: American Society of Civil Engineers.

Randazzo, A. F. (1997). The Sedimentary Platform of Florida: Mesozoic to Cenozoic. In A. F. Randazzo and D. S. Jones (Eds.), The Geology of Florida (pp. 39-56). Gainesville: University Press of Florida.

Scott, T. M. (2001). Text to accompany the geologic map of Florida (Open File Report Number 80). Tallahassee, FL: Florida Geological Survey.