Geotechnical Extreme Events Reconnaissance

Turning Disaster into Knowledge

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The Hydraulic and Geotechnical Aspects of the South Carolina Floods of October 1-5, 2015 Related to Offshore Hurricane Joaquin

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Executive Summary

Hurricane Joaquin was a category 4 hurricane on the Saffir–Simpson hurricane wind scale (SSHWS). Although Hurricane Joaquin ultimately tracked far to the east of the United States, a non-tropical low over the Southeast tapped into the hurricane's moisture, resulting in record-shattering rains and flooding across South Carolina. Several areas of South Carolina saw precipitation accumulations exceeding the threshold for a 1-in-1,000-year event from October 1 to 5. The subsequent floods caused inundations throughout the state with areas around Charleston and Columbia hardest-hit and killed 19 people. The damage in South Carolina alone is estimated at $12 billion. This extreme event highlights the potential long range impacts of offshore hurricanes tracking hundreds of kilometers from a coastal landfall.

A team from the Geotechnical Extreme Events Reconnaissance (GEER) Association, supported by the National Science Foundation, was mobilized to investigate the impacts of the flooding in South Carolina. The team worked collaboratively with federal, state and local organizations to augment the reconnaissance effort. This report presents the field observations of the GEER team made during the field reconnaissance from October 11 to 14, 2015 in South Carolina's Richland and Lexington Counties. The study area encompassed the greater and downtown Columbia, the Capital of South Carolina. The coverage includes the dam breaks along the Columbia Canal, the heavily devastated neighborhoods along Gills Creek in Columbia and the Twelvemile Creek in Lexington, but also includes observations along the Saluda dam spillway, the Broad river embankment breach into the Marietta quarry with a destroyed Northfolk Southern Railway bridge and the breach along Lake Elizabeth. In total 52 dams are known to have failed in the historic flooding event. The GEER team visited a dozen dams including 9 breached dams and 2 overtopped dams without a breach. All dams visited involved activation of emergency spillways. The Saluda Dam was the only dam visited by the GEER team, where the reservoir level remained below the dam crest. All other dams visited by the GEER team showed signs of water levels reaching and/or exceeding the dam crest resulting in various degrees of overtopping both in terms of overflow depths and duration. Incipient erosion on the earthen embankment dams occurred along the activated spillways mainly downstream at the transition from the concrete lining to bedrock or soil. Similar erosion was observed laterally at transitions of the sidewall lining to earthen fills. In some cases, failure by spillway and embankment overtopping induced erosion was accelerated by piping along the material interfaces. The dam breaches at the two historic 19th century dams occurred along material interfaces at the sharp transition from earthen fill to rock or brick walls. The intact Forest Lake Dam serves as example of an overtopped dam with overflow armor in the form or articulated bags, which prevented significant erosion during sustained overflow conditions.

Several lessons were learned, which may improve reconstruction efforts and future dam operations. The two dam failures along heritage dams highlight the importance of compatible materials avoiding sharp earth fill to rock wall transitions. Coordinated watershed management along with early reservoir level adjustments may provide some extra buffer during anticipated extreme rainfall events and allow to spread out the flood discharge. Ultimately emergency spillway activations are inevitable during extreme flood events. Given the apparent dam overflow situations most spillway capacities were insufficient for this extreme event. Increased spillway capacities depending on a dam's hazard classification along with erosion mitigation measures may strengthen the resiliency of dams during extreme flood events.

Acknowledgments

The work of the GEER Association, in general, 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 had the opportunity to conduct field work at selected dam sites affected by the early October 2015 South Carolina Floods. The principal purpose of the site visits was to observe and document the performance of levees and dams during and following the flood event. The authors were greatly aided by the briefings and information provided by:

Bill Argentieri (South Carolina Electric & Gas Company, SCE&G, SCANA subsidiary)
James Landreth (South Carolina Electric & Gas Company, SCE&G, SCANA subsidiary)
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James Maxwell, PG (Quality Assurance Manager – Southeast Division Martin Marietta)

Contents

List of Figures

1 Introduction

1.1 Overview

This report presents the field observations of the GEER team made during the field reconnaissance from October 11 to 14, 2015 in South Carolina's Richland and Lexington Counties encompassing the greater Columbia and Lexington metropolitan area. Hurricane Joaquin was a category 4 hurricane on the Saffir–Simpson hurricane wind scale (SSHWS) that devastated several districts of the Bahamas. On October 1 Hurricane Joaquin made landfall on Samana Cay in Bahamas as a category 3 hurricane (SSHWS). An American cargo ship, the 241 m (791 ft) *El Faro*, sank near Crooked Island with 33 crew members (28 Americans and 5 Poles) amid 6 to 10 m seas near Hurricane Joaquin's eyewall on October 1. Although Hurricane Joaquin ultimately tracked far to the east of the United States, a non-tropical low over the Southeast tapped into the hurricane's moisture. An atmospheric river developed between the two systems, resulting in record-shattering rains and flooding across South Carolina. Several areas of South Carolina saw precipitation accumulations exceeding the threshold for a 1-in-1,000-year event from October 1 to 5. The subsequent floods inundated large areas of the state with areas around Charleston and Columbia hardest-hit and killed 19 people. The damage in South Carolina alone is estimated at $12 billion. For comparison 1989 Hurricane Hugo made landfall in Charleston County, South Carolina as a category 4 hurricane (SSHWS) causing damage of $10 billion (1989 USD), which would correspond to $19 billion after inflation adjustments.

In total 52 dams are known to have failed in the historic flooding event. Out of the 52 failed dams 48 were regulated, while 4 dams were unregulated. The S.C. Department of Health and Environmental Control (S.C.-DHEC) regulates 47 of these dams and the Federal Energy Regulatory Commission (FERC) regulates the Columbia Canal. Post-flood S.C.-DHEC and the U.S. Army Corps of Engineers assessed 652 dams statewide, including all classified as High or Significant Hazard. Of the 2,370 regulated dams in South Carolina 2% failed as a result of the floods, while 3% had been issued emergency orders and 7% had been issued non-emergency repair orders. The GEER team visited a dozen dams including 9 breached dams and 2 overtopped dams without a breach.

The opinions expressed in this report are based on observations made during the field reconnaissance, a review of available information including pre- and post-storm damage photographs, a review of pre- and post-storm aerial and satellite imagery of the sites visited and surrounding areas, a review of numerous documents on Hurricane Joaquin and post-storm damage prepared by various governmental agencies, a review of videos and photographs taken during the South Carolina floods (SC-floods), and a review of general information about water resources, hydrology and hydraulics in South Carolina obtained from other research. Opinions are formed from this information, together with our professional experience gained over decade(s) as academic researchers studying the effects of flooding, hurricanes, tsunamis and natural hazards worldwide. The GEER Association web site contains additional information about the goals of GEER reconnaissance efforts (http://www.geerassociation.org/about-geer/goals).

1.2 Study Area

The study area is in the Richland and Lexington Counties, South Carolina. It essentially covered a rectangle centered on downtown Columbia and spanning 30 km (East-West) and 20 km (North-

South). The coverage includes the dam breaks along the Columbia Canal, the heavily devastated neighborhoods along Gills Creek in Columbia and the Twelvemile Creek in Lexington, but also includes observations along the Saluda dam spillway, the Broad river embankment breach into the Marietta quarry with a destroyed Northfolk Southern Railway bridge and the breach along Lake Elizabeth. The extent of the area covered in the vehicle based survey is shown by the pink GPS track on top of the overview road map in Figure 1. This study area was selected based on the hydrologic information, pre- and post-event satellite imagery, media reports of dam over toppings and dam breaks. The area is characterized by the confluence of the Saluda and Broad Rivers forming the Congaree River shown in Figure 2 and Figure 3, while most dams visited are upstream of the confluence or along tributaries.

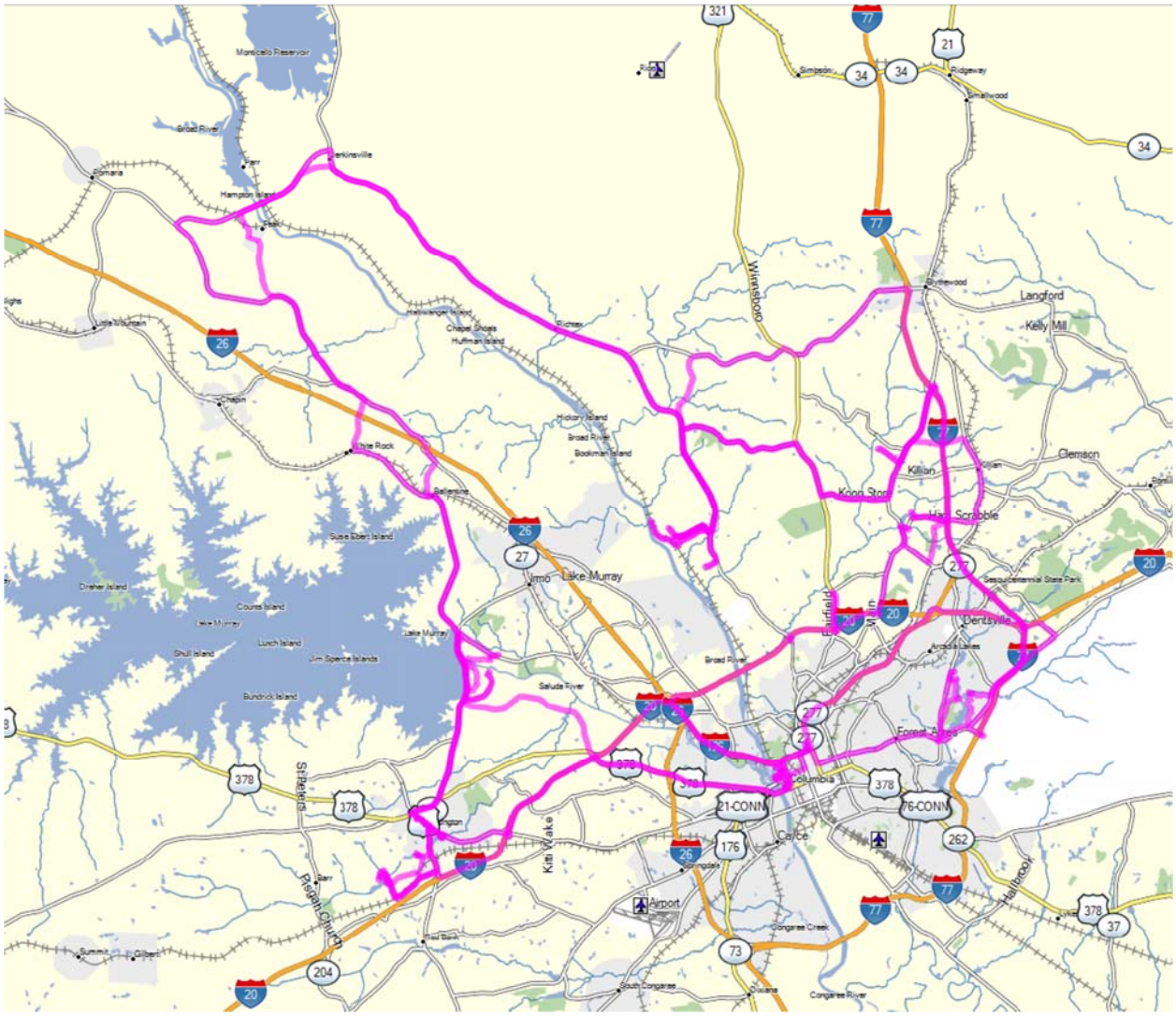


Figure 1. Roadmap of the greater Columbia metropolitan area in South Carolina's Richland and Lexington Counties with an overlaid GPS track indicating the areas covered during the GEER field survey from October 11 to 14, 2015.

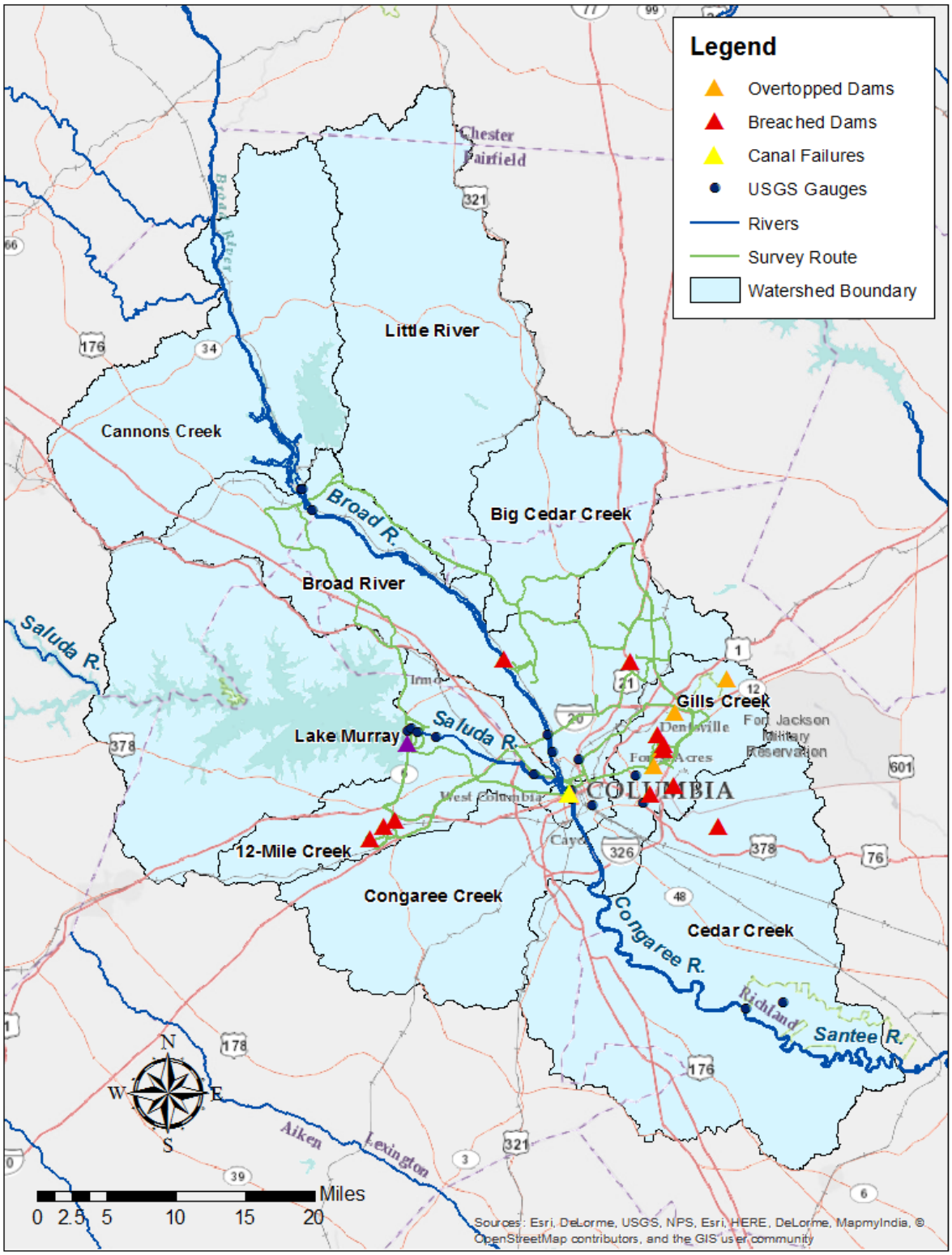


Figure 2. Overview of watershed boundaries and rivers in the greater Columbia metropolitan area in South Carolina with an overlaid GPS track indicating the distressed and breached dams covered during the GEER field survey from October 11 to 14, 2015.

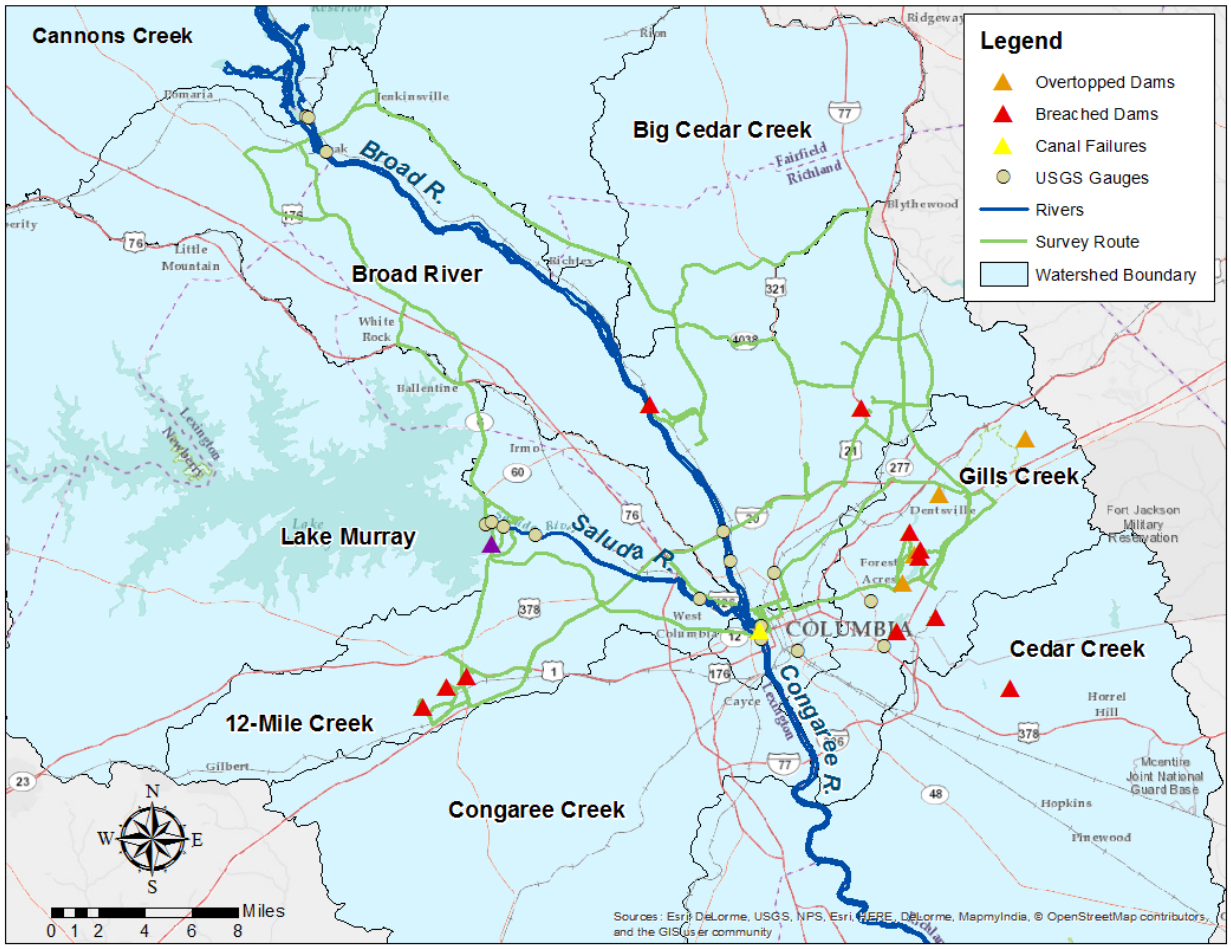


Figure 3. Detailed watershed boundaries and rivers in the greater Columbia metropolitan area in South Carolina's Lexington and Richland Counties with an overlaid GPS track indicating the distressed and breached dams covered during the GEER field survey from October 11 to 14, 2015.

2 Meteorological and Hydrological Background

2.1 Data Sources Used

For the purposes of this report, three primary sources of background information about the meteorological and oceanographic conditions in Hurricane Joaquin have been used:

- Berg, R., 2016. Tropical Cyclone Report Hurricane Joaquin 23 September – 7 October 2015. National Hurricane Center (NHC), Miami, Florida.
- Feaster, T.D., Shelton, J.M., and Robbins, J.C., 2015. Preliminary Peak Stage and Streamflow Data at Selected USGS Streamgaging Stations for the South Carolina Flood of October 2015, Open-File Report 2015-1201, U.S. Geological Survey (USGS).
- Musser, J.W., Watson, K.M., Painter, J.A., and Gotvald, A.J., 2016. Flood-Inundation Maps of Selected Areas Affected by the Flood of October 2015 in Central and Coastal South Carolina, Open-File Report 2016-1019, U.S. Geological Survey (USGS).

The NHC study provides a meteorological summary of Hurricane Joaquin, focusing primarily on the storm genesis, storm track, and storm intensity as measured by central pressures and maximum wind speeds. For this report, it has been used primarily as a source of measured wind speeds, storm surge and total rainfall amounts.

The USGS (OFR 2015-1201) peak stage at USGS gages as well as about 140 streamflow measurements at 86 locations to verify, update, or extend existing rating curves, which are used to compute streamflow from monitored river stage.

The USGS (OFR 2016-1019) provides high water marks and inundation maps. USGS personnel in collaboration with FEMA and SCDOT documented 652 high-water marks, noting the location and height of the water above land surface. Using a subset of these high-water marks, 20 flood-inundation maps of 12 communities were created.

2.2 Meteorological Characteristics with Rainfall and Hurricane Joaquin

The storm track of Hurricane Joaquin is shown in Figure 4 from the NHC report. Although Joaquin ultimately tracked far to the east of the United States, a non-tropical low over the Southeast tapped into the hurricane's moisture. Flooding rains and coastal flooding affected portions of the United States East Coast during the first several days of October while Joaquin was near the Bahamas, but the hurricane only indirectly contributed to these hazardous conditions.

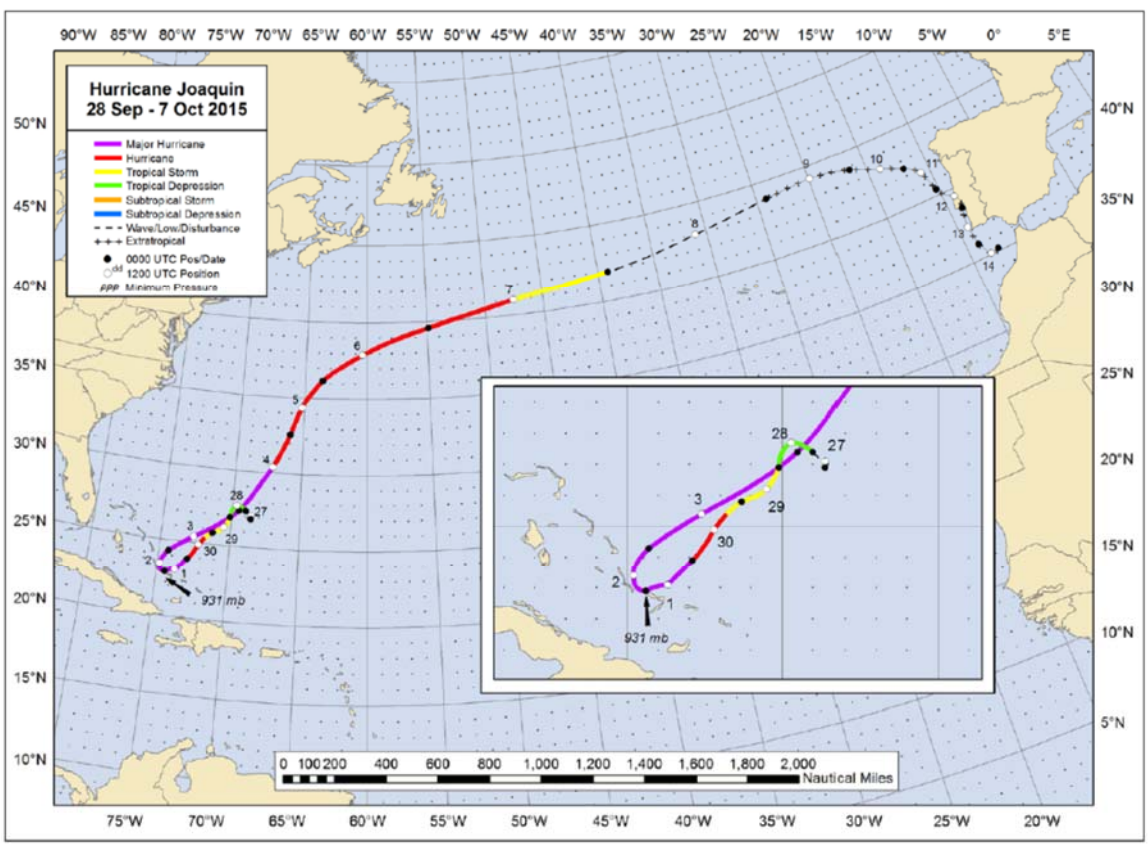


Figure 4. Best track positions for Hurricane Joaquin, 28 September – 7 October 2015, from NHC report.

An upper atmospheric low-pressure system developed over the southeastern U.S. on 1 October drew a steady plume of upper-level moisture from Joaquin northwestward into South Carolina shown in Figure 5 and Figure 6. This moisture contributed to a multi-day rainfall event that caused historic flooding in that state's two largest cities of Charleston and Columbia. The unofficial South Carolina state record for 5-day total rainfall, which has stood for 107 years, has been surpassed at more than a dozen reporting sites shown in Figure 7. Several additional rainfall records in South Carolina have been shattered including the 24-hour rainfall record at several stations. The rainfall totals over the study area encompassing the greater Columbia metropolitan area with Lexington and Richland Counties in central South Carolina is shown in Figure 8.

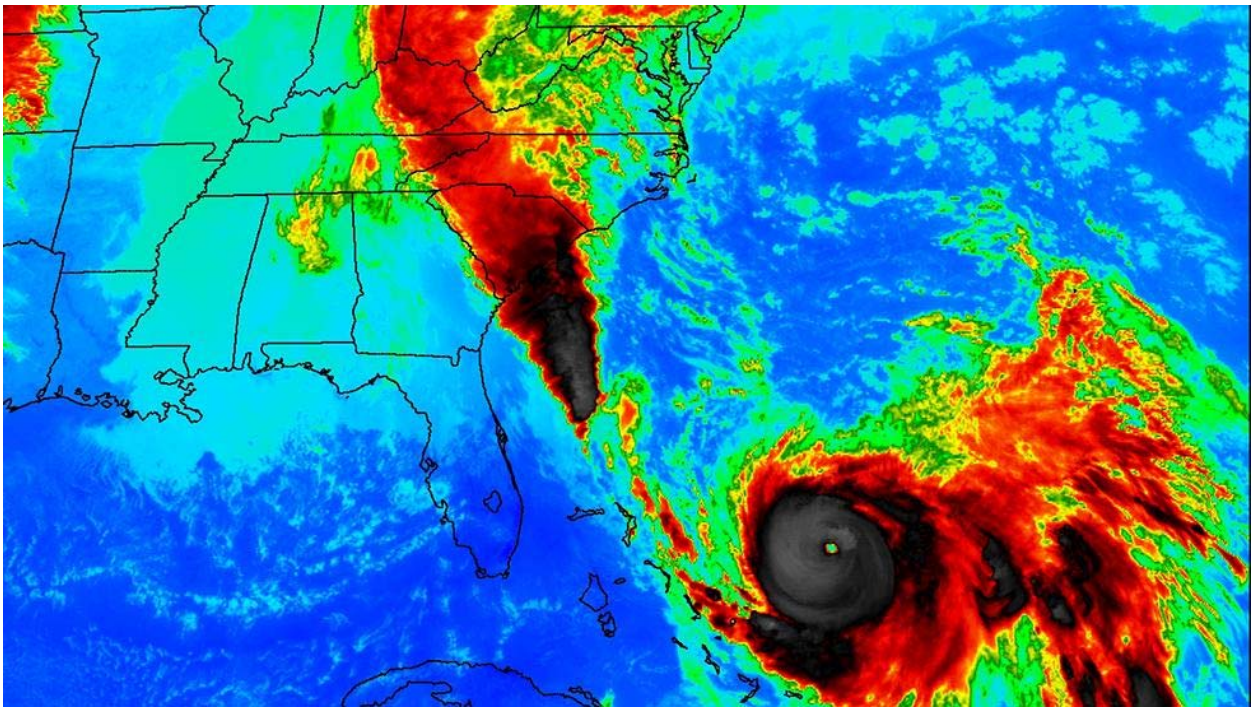


Figure 5. Infrared satellite image of the intense rainfall being funneled into South Carolina during the morning of October 3, 2015. Note the location of Hurricane Joaquin. (http://www.weather.com/news/news/stunning-meteorological-images-october-2015-flooding, NASA).

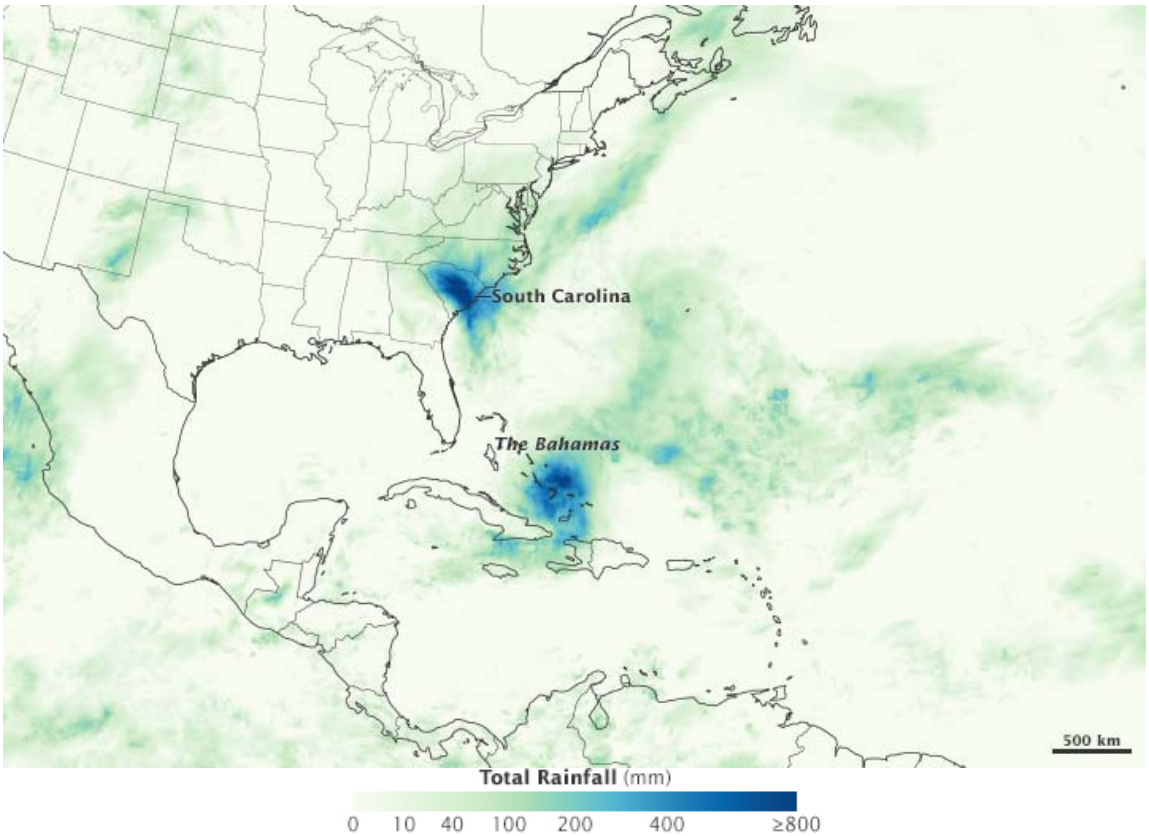


Figure 6. NASA satellite-based estimates of total rainfall in the northwestern Atlantic Ocean from October 1–5, 2015. Darkest blues represent rainfall totals approaching 800 millimeters (31.5 inches) over the five days observed. (http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=86736&eocn=image&eoci=morenh).

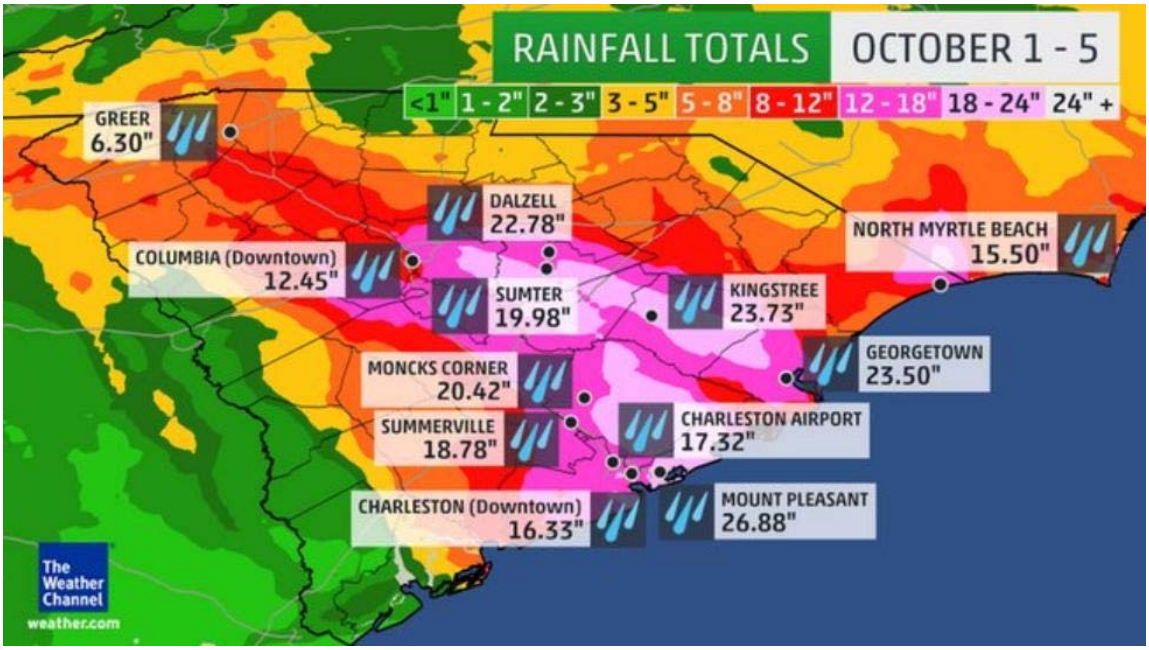


Figure 7. South Carolina rainfall totals for period of October 1-5, 2015 with satellite based contour map by NASA as background and individual values based on ground measurements by NOAA (NWS). (https://weather.com/forecast/national/news/soaking-weather-pattern-east-flooding).

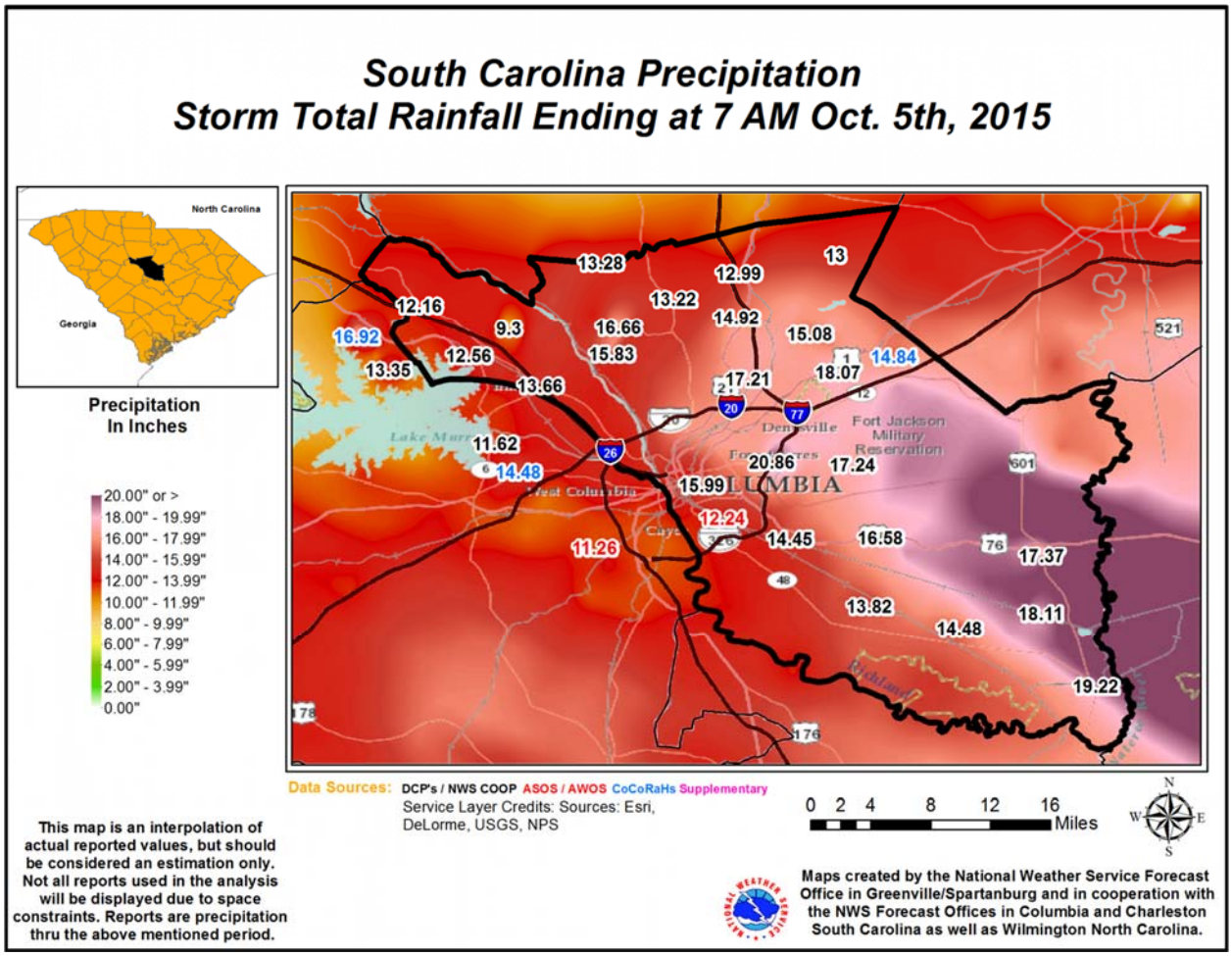


Figure 8. Richland County rainfall totals for period of October 1-5, 2015 with satellite based contour map by NASA as background and individual values based on ground measurements by NOAA (NWS). (http://noaa.maps.arcgis.com/apps/MapJournal/?appid=2d473e302db74c3799419d4b89f00d47).

Contributing to the coastal flooding was a strong pressure gradient off the New England coast behind a frontal boundary that produced a long fetch of northeasterly gales directed at the mid-Atlantic coast at the start of the month, while tides were already running higher than normal. Although the gales were not part of Joaquin's circulation, the pressure gradient increased when the hurricane moved northward from the Bahamas, and swell from Joaquin also emanated northwestward toward the U.S. East Coast. All of these factors contributed to coastal flooding along portions of the U.S. East Coast even while Joaquin remained well offshore. Selected wind, rainfall, and storm surge observations along the Southeast Coast of the United States associated with the indirect effects of Joaquin are given in Table 1 from the NHC report. The rainfall exceeded that reported of any tropical cyclone in South Carolina history. The rainfall and flooding in South Carolina associated with Hurricane Joaquin's center tracking more than 1000 km off the coast of South Carolina highlights the potential long-range implications of North-Atlantic hurricanes without a landfall on the eastern seaboard of the United States.

Table 1. Selected surface observations along the Southeast Coast of the United States due to the indirect effects of Hurricane Joaquin from the NHC report.

Location	Maximum Surface Wind Speed			Storm surge (ft)[c]	Storm tide (ft)[d]	Estimated Inundation (ft)[e]	Total rain (in)[f]
	Date/ time (UTC)[a]	Sustained (kt)[b]	Gust (kt)				
Florida							
Mayport (Bar Pilots Dock)	2/0400	22	26	2.25	3.94	2.0	
Fernandina Beach	5/1648	18	21	2.98	4.88	2.2	
Georgia							
Fort Pulaski	3/1830	24	34	2.74	5.89	2.4	
South Carolina							
Charleston	4/0030	30	37	2.79	5.15	2.5	
Oyster Landing (N Inlet Estuary)				4.19	5.07	2.7	
Springmaid Pier	3/1554	33	40	3.25	5.14	2.7	
Mount Pleasant 6 NE							26.88
Kingstree							24.75
Boone Hall Plantation 3 NNE							24.23
Shadowmoss 3 SSW							24.10
Longs							23.74
Charleston 5 SSE							23.61
Limerick 1 NNW							22.02
Folly Beach 3 SW							21.45
Huger 5 NNW							21.04
Georgetown 4 SSW							20.75
Gills Creek							20.28
Summerville 3 NW							19.47
Shaw AFB							19.32
Wateree							18.90
Kiawah Island 4 NNW							18.25
Effingham 2 W							17.95
Myrtle Beach 8 WNW							17.40
Charleston (KCHS)							17.29

Location	Maximum Surface Wind Speed			Storm surge (ft)[c]	Storm tide (ft)[d]	Estimated Inundation (ft)[e]	Total rain (in)[f]
	Date/ time (UTC)[a]	Sustained (kt)[b]	Gust (kt)				
James Island County Park 1 NNE							17.00
Little River 1 N							16.00
Garris Landing 2 NNW							15.81
Santee							14.84
Huger 3 NNE							14.68
Sangaree 2 NE							14.51
Florence 5 W							14.34
Charleston NWS							13.88
Darlington 7 SSW							13.00
Goose Creek 5 E							11.26
Columbia Metro Airport							10.77
Wando 1 SSW							8.76
North Carolina							
Wrightsville Beach	4/1854	40	54	3.40	4.90	3.1	
Wilmington				2.85		2.2	
Beaufort	5/1542	26	36	2.65		2.4	
USCG Station Hatteras	5/1548	25	34	2.28		2.6	
Oregon Inlet Marina	4/1854	27	37	1.98	2.25	1.8	
Duck	4/1700	37	42	3.19	4.65	3.2	
Smith Reynolds Airport			37				
Sunset Beach 2 WNW							18.79
Longwood 1 NNW							17.83
Longwood 1 NW							13.63
Southport 1 NE							13.42
Bayshore 1 ENE							12.74
Wilmington 4 SE							12.30
Tabor City 4 NE							12.29
Bolivia 8 SSW							11.48
Topsail Beach 1 E							10.17
Wilmington (KILM)							8.79
Lake Waccamaw 3 S							8.63

2.3 Hydrological Characteristics with Peak Flood Stages and Streamflow

Peak streamflow and stage during the October 2015 flood for 86 streamgages are listed in Feaster et al., 2015 (USGS), and their site locations are shown in Figure 9. Seventeen of the 86 streamgages had new peaks of record. Of the 61 stations with at least 20 years of record, eight had new peaks of record: 02136000, Black River at Kingstree (87 years of record); 02136361, Turkey Creek near Maryville (21 years); 02162093, Smith Branch at North Main Street at Columbia (38 years); 02167450, Little River near Silverstreet (24 years); 02167582, Bush River near Prosperity (24 years); 02168504, Saluda River below Lake Murray Dam near Columbia (26 years); 02169570, Gills Creek at Columbia (50 years); and 02175000, Edisto River near Givhans (81 years). Along with the 17 streamgages that had new peaks of record, an additional 15 streamgages recorded new peaks that ranked in the top 5 for the period of record. For stations with at least 20 years of record, 13 recorded peaks ranked in the top 5 for the period of record.

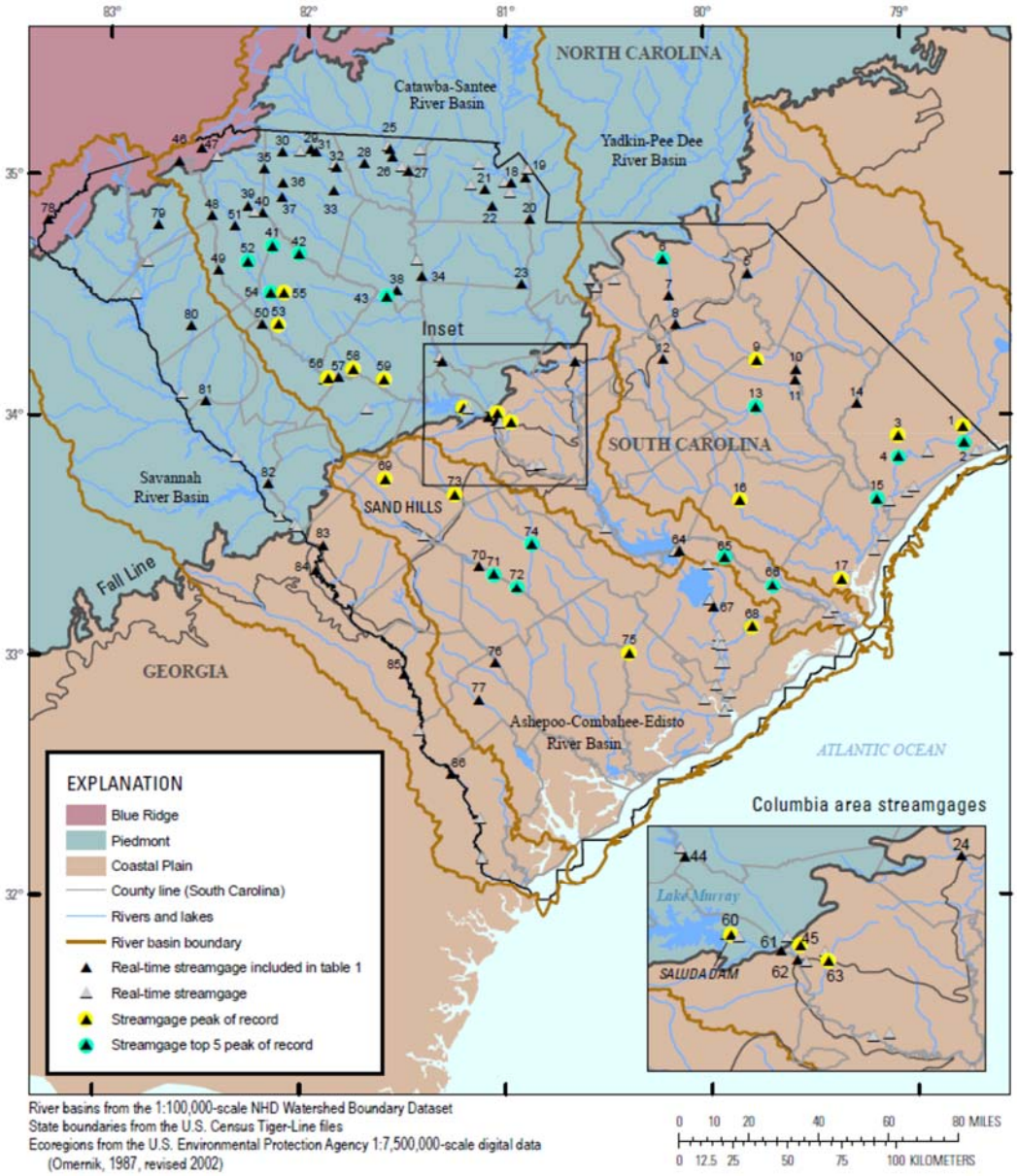


Figure 9. Locations of USGS real-time streamgages in South Carolina.

3 Broad River Basin and Columbia Canal

3.1 Broad River Watershed, Stages and Discharge

Visited dam failures in the Broad River watershed are shown in Figure 10. This includes the Columbia Canal levee breaches, the Broad river embankment breach into the Marietta quarry with a destroyed Northfolk Southern Railway bridge and the Lake Elizabeth Dam breach along the tributary Crane Creek. The area is characterized by the confluence of the Saluda and Broad Rivers forming the Congaree River, but the three failures discussed in this section involve headwaters in the Broad River watershed only. Low-head dams on the Broad River have regulated low streamflows since the late 1880s and early 1900s, but flood flows are essentially unregulated. The Broad River Basin accounts for approximately two-thirds of the drainage area for the Congaree River at Columbia station downstream of Columbia Canal after the confluence of the Saluda River. The discharge and stage data from the available USGS gauge 25 km upstream of Martin Marietta rock quarry failure is shown in Figure 11 and the corresponding data at a USGS gauge 1 mile (1.6 km) upstream of the Columbia Canal diversion dam and intake is shown in Figure 12.

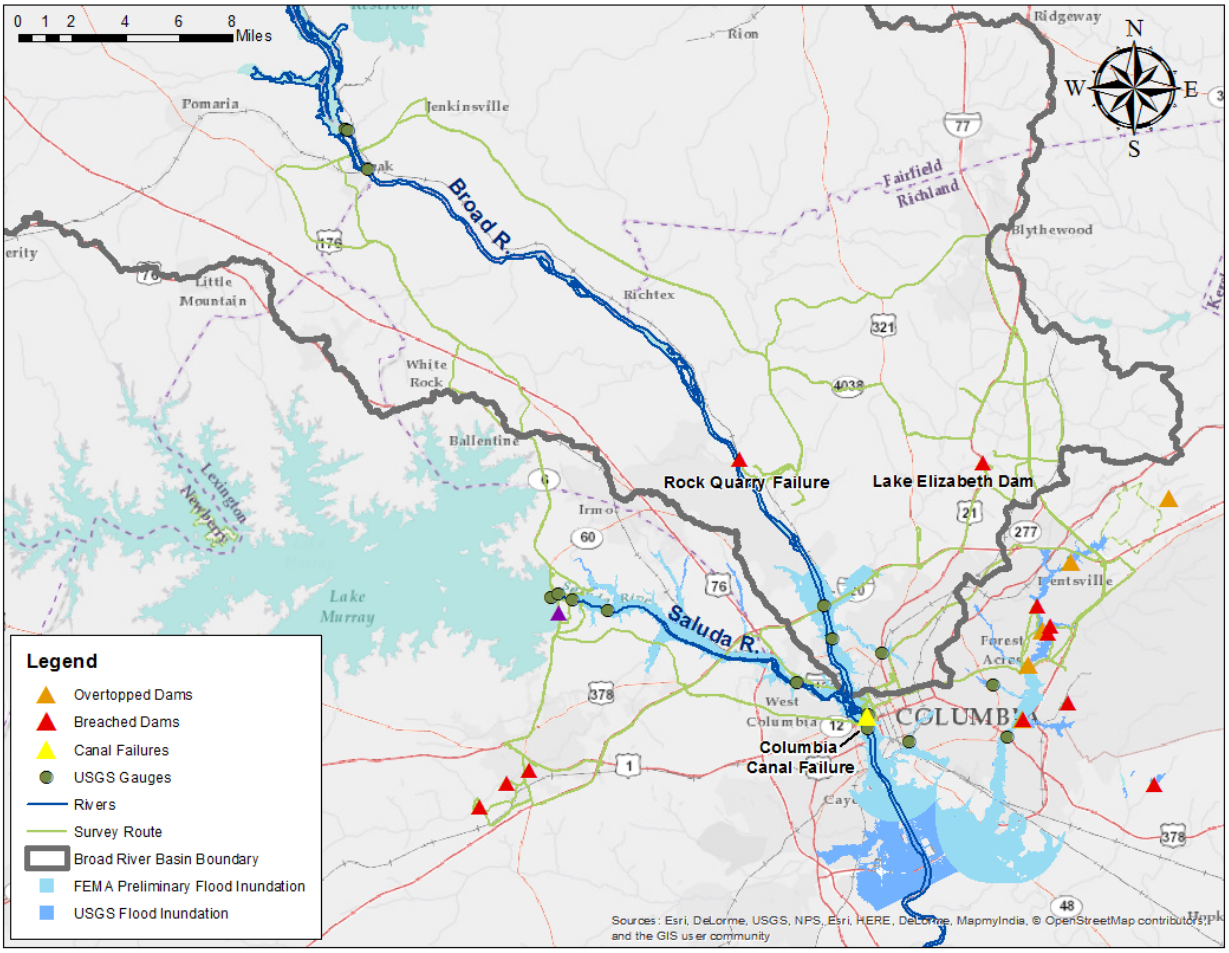
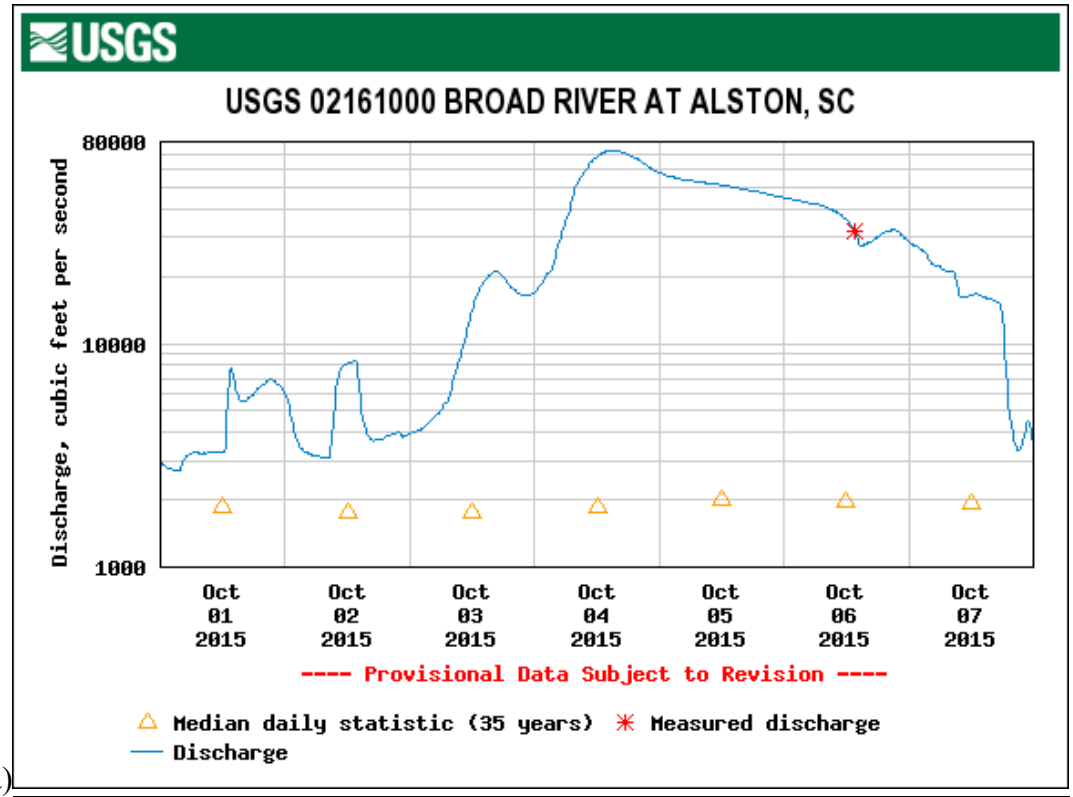
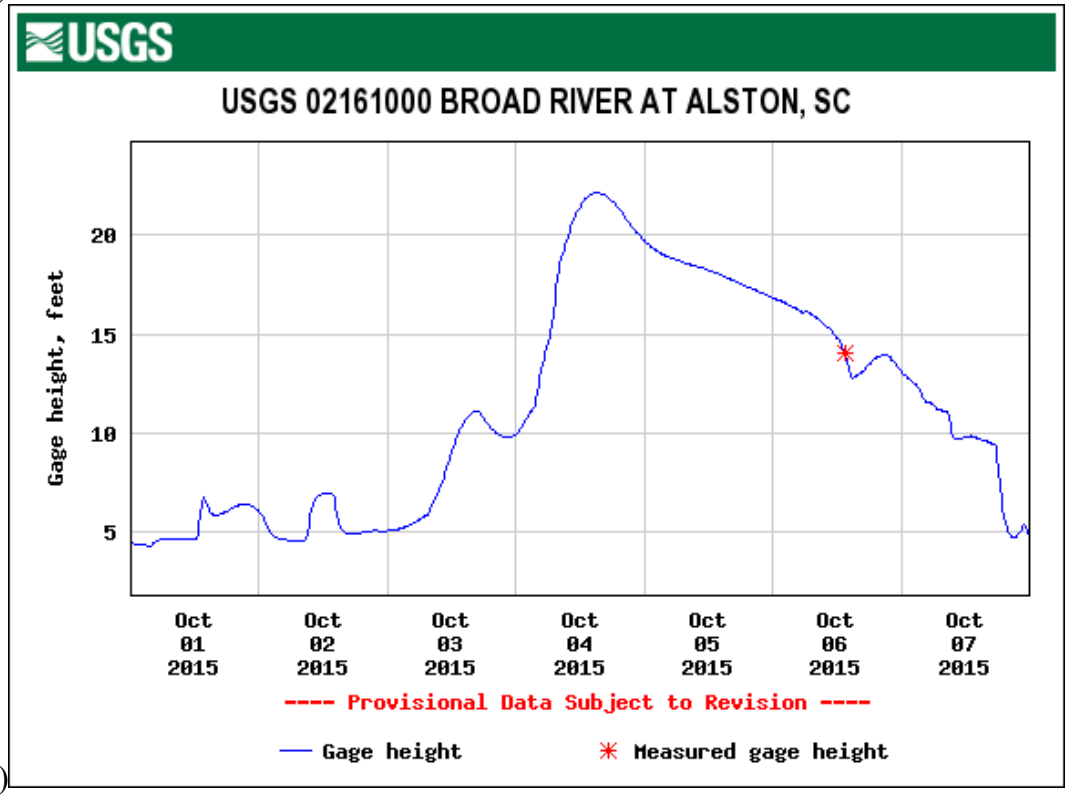


Figure 10. Broad River watershed boundary and visited dam failures with labels include: Columbia Canal levee, Martin Marietta North Columbia granite quarry, and Lake Elizabeth in Richland County. The greater Columbia metropolitan area with an overlaid GPS track indicating the distressed and breached dams covered during the GEER field survey from October 11 to 14, 2015.

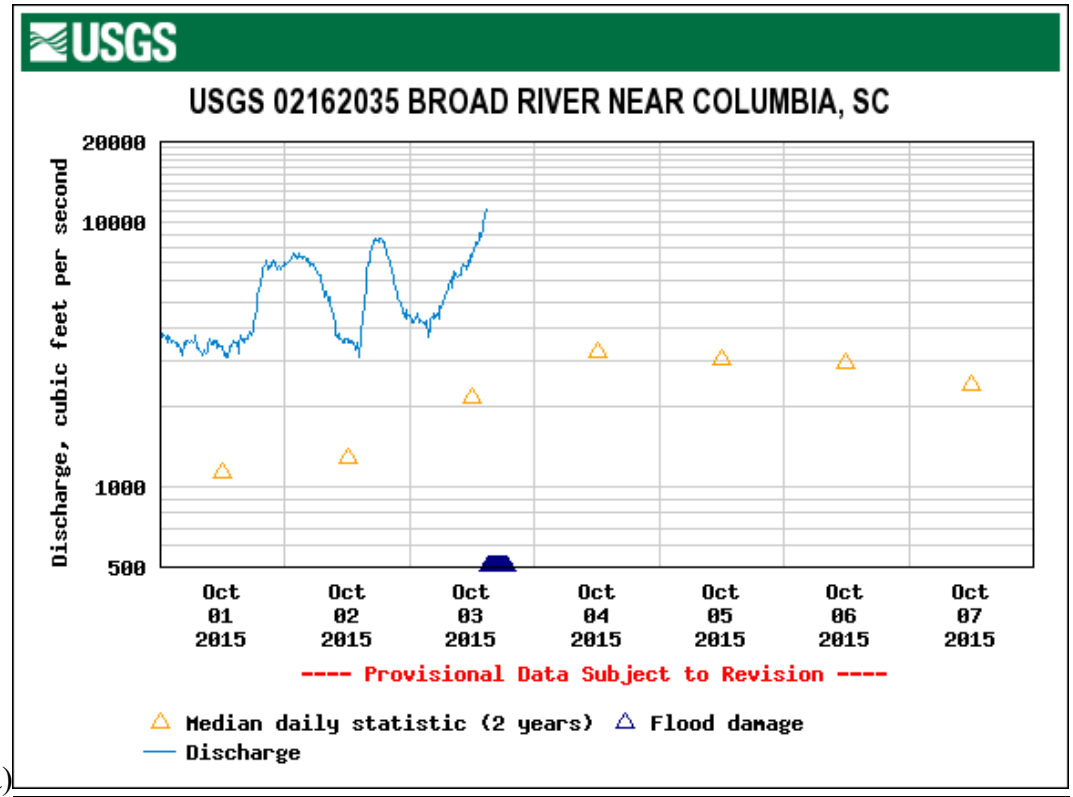


(a)

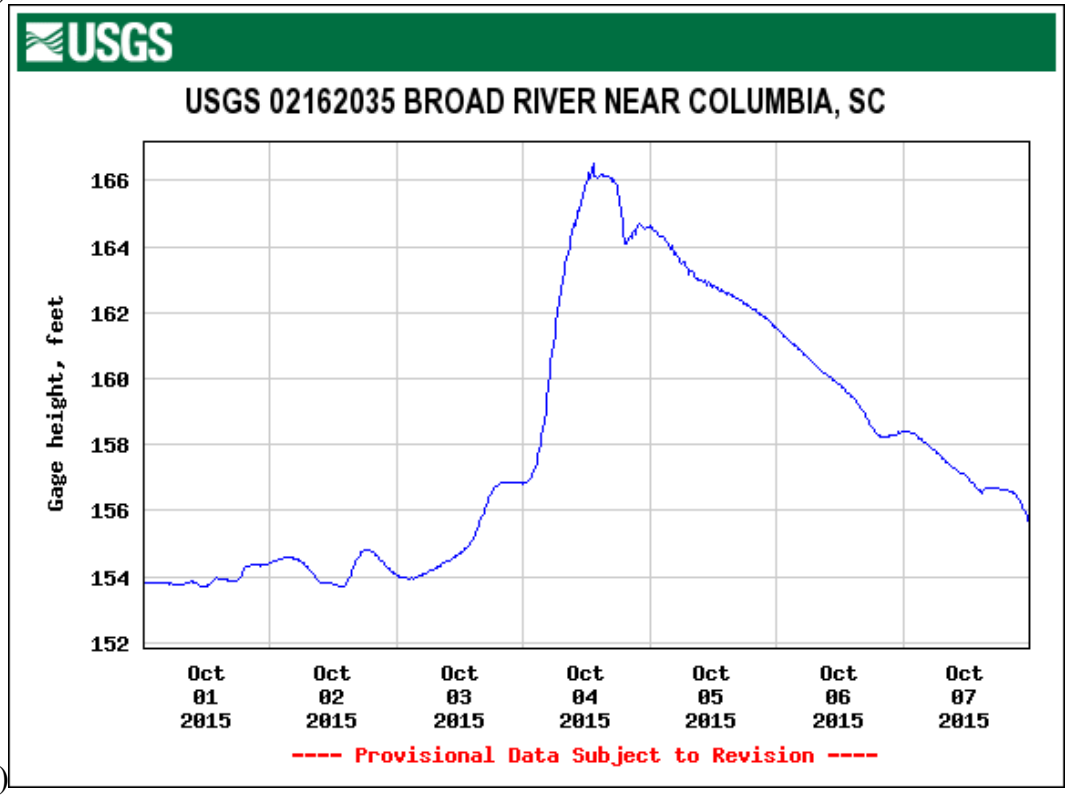


(b)

Figure 11. Broad River USGS gauge 02161000 near the towns of Peak and Alston, SC, which is located some 25 km upstream of the Martin Marietta rock quarry and 35 km upstream of the Columbia Canal diversion dam and intake: (a) discharge with peak of 73,200 cfs at 1500 EST on October 4, 2015; (b) stage with peak of 22.16 ft corresponding to 234.07 ft above NGVD29 at 1500 EST on October 4, 2015 (http://waterdata.usgs.gov/nwis).



(a)



(b)

Figure 12. Broad River USGS gauge 02162035 at I-20 bridge located 1 mile (1.6 km) upstream of the Columbia Canal diversion dam and intake: (a) discharge data failed; (b) stage peaks of 166.50 ft (165.50 ft NAVD88) at 1315 EST, 165.04 ft (164.04 ft NAVD88) at 1830 EST on October 4, 2015 and 164.31 ft (163.31 ft NAVD88) at 0200 EST (Columbia Canal Levee breach) on October 5, 2015 (http://waterdata.usgs.gov/nwis).

The Broad River USGS gauge 02161000 near the towns of Peak and Alston, SC is located some 25 km upstream of the Martin Marietta rock quarry and 35 km upstream of the Columbia Canal diversion dam. This gauge records the full event however it remains unclear whether the discharge has been calibrated for these elevated flood stages. The gauge at Alston records a peak discharge of 73,200 cfs and a coinciding peak stage of 22.16 ft corresponding to 234.07 ft above NGVD29 at 1500 EST on October 4, 2015. The Broad River remains unregulated between the Alston gauge and the Columbia Canal diversion dam and intake, while there are several smaller tributary creeks on this 35 km river segment. The Broad River USGS gauge 02162035 at the I-20 Bridge is located 1 mile (1.6 km) upstream of the Columbia Canal diversion dam and intake. Unfortunately there are no discharge data available after October 3, 2015. The stage has a flat hydrograph apex spanning several hours with peaks of 166.50 ft (165.50 ft NAVD88) at 1315 EST and 165.04 ft (164.04 ft NAVD88) at 1830 EST on October 4, 2015. At the time of the Columbia Canal levee breach at 0200 EST (0300 EDT) on October 5, 2015 the stage had already dropped some 2 feet to 164.31 ft (163.31 ft NAVD88) (Columbia Canal Levee breach) on October 5, 2015. The Broad River USGS gauge 02162103 is located below the Columbia Canal diversion dam, but unfortunately no stage and discharge data are available for 2015.

3.2 Columbia Canal Overview

The Columbia Canal extends 5.6 km (3.5 miles) along the east bank of the Broad and Congaree Rivers shown in Figure 13. The confluence of the Broad and Saluda Rivers forms the Congaree River at Columbia, SC. The Columbia Canal was designed to enable the navigation of the Broad and Congaree Rivers at their confluence in Columbia. The canal was completed in 1824 and enlarged in 1891. The redesigned Columbia Canal was about 46 m wide and 3 m deep. The canal includes a diversion dam, an intake gate, a spillway, and a powerhouse. The Columbia Canal Hydroelectric Plant completed in 1896 was designed to supplement electricity produced by Columbia Mills. It is owned by the City of Columbia and Lockhart Power operates the powerhouse under contract. Water enters the canal through the intake, flows down the canal, is normally released through the powerhouse at the downstream end of the canal, and flows into the Congaree River. The powerhouse contains seven turbine/generator units with a total generation capacity of 10.6 MW. If the powerhouse is not generating or otherwise unable to release water, then the spillway is used for canal outflow. The Columbia Canal is inspected six times a year with results reported to the Federal Energy Regulatory Commission (FERC). The last inspection was less than two months before the flooding on Aug. 14, 2015. FERC classified the Columbia canal as a significant dam given its importance for the water supply of the city of Columbia, while the downstream flood hazard remains limited as any breaches or overflow would spill right back into the Broad and Congaree Rivers.

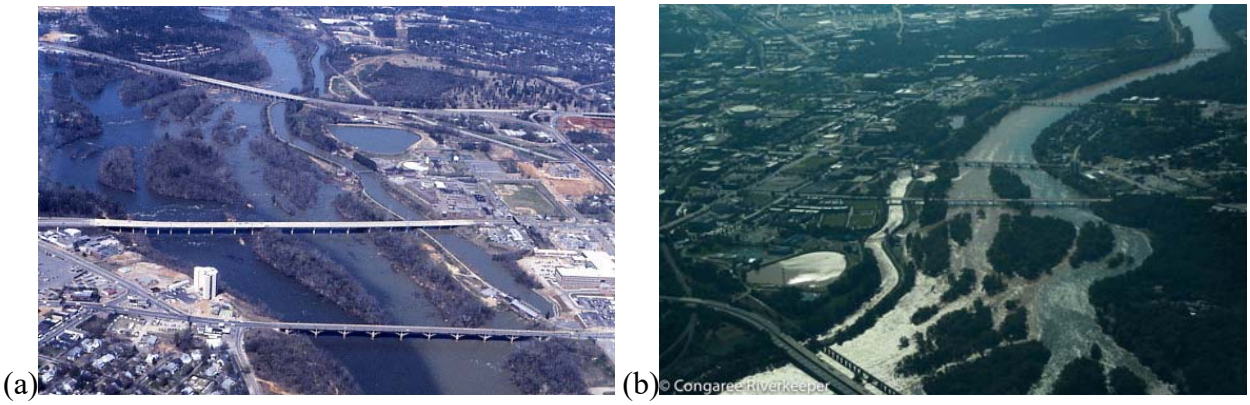


Figure 13. Aerial views of the Columbia Canal along the east bank of the Broad and Congaree Rivers. The confluence of the Broad and Saluda Rivers forms the Congaree River at Columbia, SC (N 33.99841°, W 81.05502°). Note the brown sediment laden water of the Broad River and the dark water of the Saluda River downstream of Lake Murray and the Saluda dam: (a) undated photo from South Carolina Department of Archives and History (SCDAH, www.nationialregister.sc.gov); (b) October 6, 2015 post canal breach photo from Congaree Riverkeeper (www.congareeriverkeeper.org via their Twitter and FB).

3.3 Columbia Canal intake through "inoperable" control gates

The diversion dam along the Broad River forms the Columbia reservoir at the entrance into the Columbia Canal shown in Figure 14. The intake into the Columbia Canal includes inflow control structures in the form of 12 sluice gates and a presently unused navigation lock.

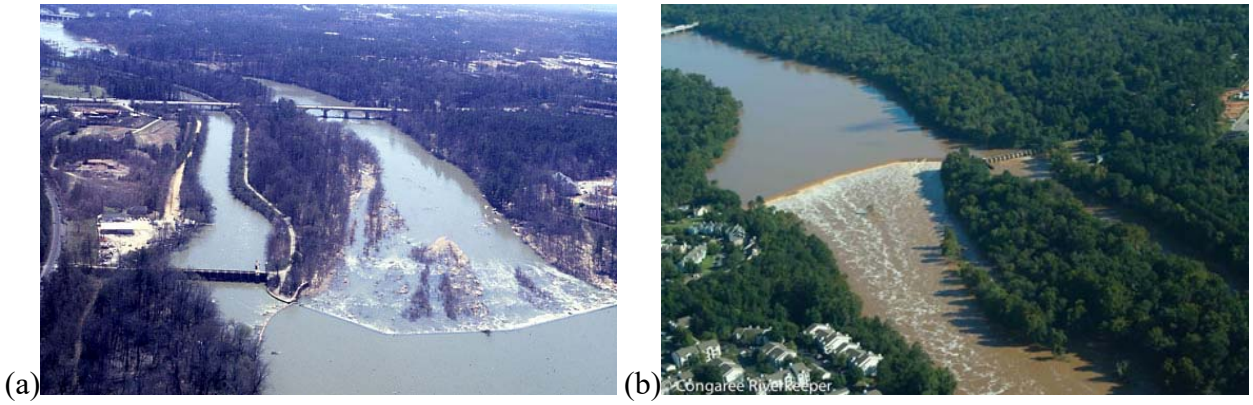


Figure 14. Aerial views of the diversion dam and guard lock regulating the inflow into the Columbia Canal along the east bank of the Broad River some 5 km upstream of downtown Columbia, SC: (a) undated photo from South Carolina Department of Archives and History (SCDAH, www.nationialregister.sc.gov), (b) October 6, 2015 photo from Congaree Riverkeeper (www.congareeriverkeeper.org, N 34.03334°, W 81.06860°).

The headworks structure with the unused navigation lock and the 12 sluice gates in quiet times is shown in Figure 15a. The lifting mechanism with two large gears per gate to rise and lower the sluice gates vertically appear old but seemingly operable (Figure 15b). The 12 intake sluice gates were unable to completely shut off the inflow into the canal as designed for canal maintenance and emergency situations. This structure is owned by the City of Columbia and under operation permit from the Federal Energy Resources Commission (FERC). There is no evidence of Broad River water overtopping the intake structure or the berm that connects eastward to the railroad grade. The bulk of the floodwater in the canal originated from the inflow through incompletely sealed

intake gates. The snippets from the media footage of October 13, 2015 show the inflow through the 12 sluice gates exposed by the lower water level inside the Columbia Canal after the downstream breach (Figure 15c). The media footage also features the attempts to reduce the inflow into the canal by placing thousands of sand bags in front (upstream) of the sluice gates (Figure 15d). Lateral surface runoff over the canal length of 5 km may have further contributed to the inflow.

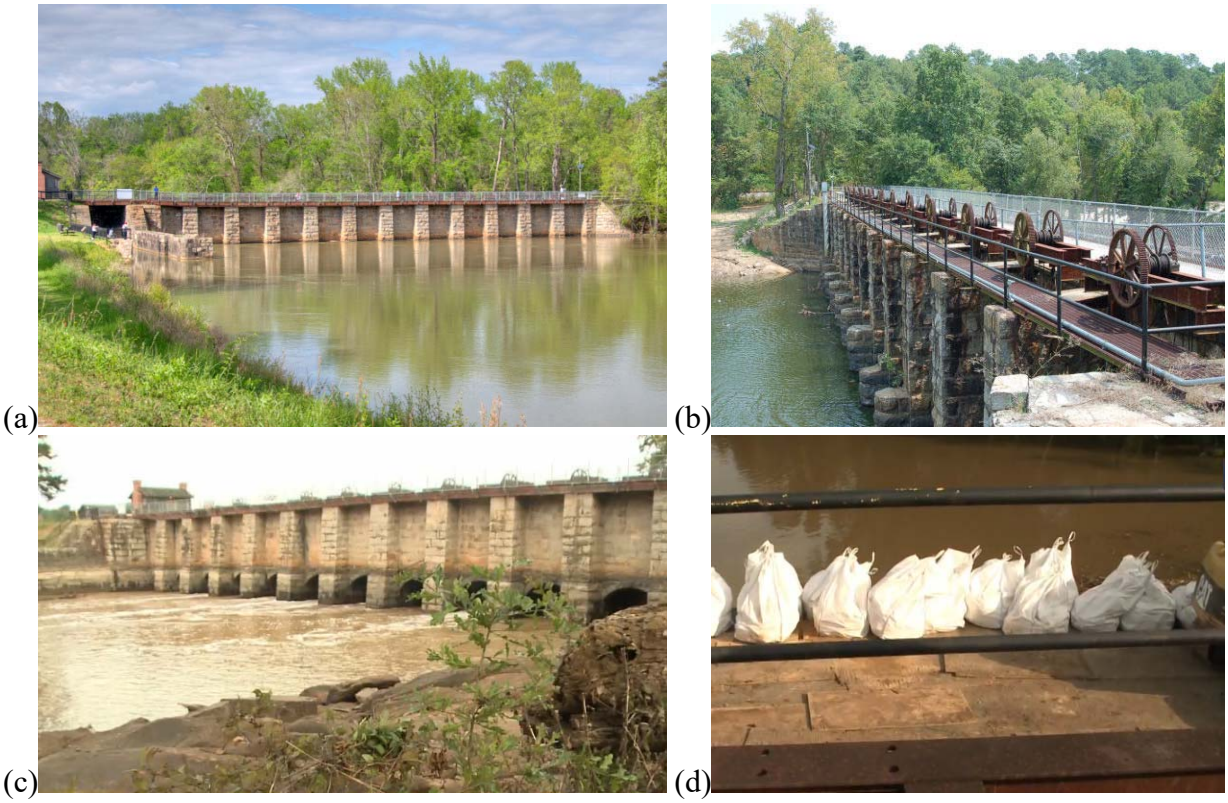


Figure 15. Columbia Canal intake structure: (a) downstream side of the unused navigation lock and the 12 sluice gates for inflow control in Feb. 2011 (www.vickiwilsonphotos.wordpress.com), (b) upstream side of the head-structure with the lifting mechanisms for the 12 sluice gates (www.scgreatoutdoors.com), (c) downstream side on October 13, 2015 with the visible inflow into the Columbia Canal with (d) numerous sand bags emplaced on the upstream side of the sluice gates in an attempt to reduce the inflow (snippets from http://on.wltx.com/1Lt0Eii, N 34.03334°, W 81.06860°).

3.4 Columbia Canal side-weir spillway

The Columbia Canal spillway in the form of a lateral side-weir is located some 250 m upstream of the Jefferson Davis McMahan Bridge, which takes South Carolina Highway 12 (SC 12) or Jarvis Klapman Boulevard across the Congaree River at the confluence of the Broad and Saluda Rivers shown in Figure 16. The Columbia Canal breach is located some 250 m downstream of the Jefferson Davis McMahan Bridge (SC 12) and an equal distance upstream of the Gervais Street Bridge.

Figure 16. Aerial view of the Congaree River formed by the confluence of the Saluda River (blue water in foreground) and Broad River (sediment laden brown water) with the Columbia Canal in the background. In the center of the image is the Gervais Street Bridge with the power house and the breach upstream along the canal dike (N 33.99796°, W 81.05018°). The Jefferson Davis McMahan Bridge (SC 12) is located 0.5 km upstream of the Gervais Street Bridge and the side weir spillway another 250 m upstream of SC 12. October 6, 2015 photo from Congaree Riverkeeper (www.congareeriverkeeper.org via their Twitter and FB).

The spillway is built into the Columbia Canal dike in the form of a side-weir discharging excess water back into the Broad River. The spillway consists of 2 radial (Tainter) gates, which allow regulation of the water level maintained in the canal. The emergency spillway itself consists of 14 weir segments with the original ability to insert stoplogs into vertical slots along the pillars to adjust the crest height above the baseline weir crest. The stoplogs raise the normal crest height up to a height of about 75% of the vertical adjustment slots along the pillars as shown in pre-flood archive photos (Figure 17). Normal spillage level apparently is preferred to be far above the base of the total design opening corresponding to the base of the pillars. The vertical grooves in the pillars are there to allow such adjustments.

Stoplogs are a hydraulic engineering control element widely used in floodgates to adjust the water level or flow rate in a river, canal, or reservoir. Stoplogs are typically long rectangular timber beams or boards that are placed on top of each other and dropped into premade slots inside a weir, gate, or channel. Other materials, including steel and composites, can be used as stoplogs as well. Stoplogs are designed to cut off or stop flow through a conduit. Stoplogs are modular in nature, giving the operator of a gated structure the ability to control the water level in a channel by adding or removing individual stoplogs. Each gate makes use of multiple logs. Each log is lowered horizontally into a space or bay between two grooved piers. The 14 bays in which stoplogs can be

placed in the spillway of the Columbia Canal allow to better control the flow rate through the structure. Stoplogs are typically used in structures where the removal, installation, and replacement of the logs is expected infrequently. Once extreme flows of water are passing through a stoplog gate, it can be difficult to remove or place individual logs. Hydraulic weirs with stoplogs go back to ancient times and have been widely used for centuries in Europe.

The Sunday October 4, 2015 video footage recorded during the flood prior to the nighttime breach shows the water spilling through the 2 sluice gates and the 14 bays of the side weir shown in Figure 18 (snippets from www.thestate.com/news/article37721334.html). The video footage also shows the downstream of the side weir highlighting a free overflow characterized by the nappe flow. The water level in the Broad River downstream of the spillway reaches flood stages but remains well below the base of the weir crest. The upstream water level in the Columbia Canal reaches the underside of the beams of the pedestrian bridge providing access to the Riverfront Park. Water continues to flow strongly under the bridge and towards the spillway.

(a)

(b)

(c)

Figure 17. Side-weir spillway from Columbia Canal to Broad River consisting of 2 regulated radial gates and 14 weir segments with stoplogs (N 34.00199°, W 81.05372°): (a) Columbia Canal spillway to Broad River before flooding event (www.discoversouthcarolina.com), (b,c) downstream of side weir with stoplogs installed in vertical adjustment slots along pillars raising crest height [(b) www.fineartamerica.com/featured/columbia-canal-rob-sellers.html, (c) www.sciway.net/sc-photos/albums/midlands-sc/columbia-canal-spillway.jpg].

(a)

(b)

(c)

Figure 18. Spillway and Columbia Canal prior to breach on Sunday October 4, 2015: (a) View of spillway from canal to Broad River. Note stoplogs remained installed and raise weir crest height up to a height of about 75% of the vertical adjustment slots along the pillars; (b) downstream view of the side weir overflow into Broad River. Note the river stage is well below the base of the weir crest and free overflow occurs. The water level in the canal may have been lowered by removing stoplogs; (c) upstream view of the canal with water level raised to the beams of the pedestrian bridge, which provides access to the Riverfront Park 100 m upstream of the spillway. All snippets from www.thestate.com/news/article37721334.html (N 34.00199°, W 81.05372°).

The head gates did not completely limit inflow into the Columbia Canal. The powerhouse was flooded, due to raising tailwater in the Congaree River, and was knocked offline and ceased releasing water. The water level in the canal continued to rise, and the spillway radial gates were opened, but the emergency spillway stoplogs remained installed blocking the 14 bays to about 75% of the height of the adjustable grooves. The Columbia Canal water level kept rising and eventually overtopped the earthen dike about 0.5 km downstream of the designated side weir spillway. The dike breached at about 3 a.m. on Monday October 5, 2015 based on media reports (www.charlotteobserver.com/news/local/article37956342.html). The downstream dike breach dramatically lowered the water level in the Columbia Canal revealing the side weir crest with installed stoplogs on Monday morning October 5, 2015 (Figure 19a). It appears that the stoplogs were permanently installed either as molded concrete or cement covered. During our visit the stoplogs were removed in the 12 central side weir openings, while the lateral two side weirs are permanently cemented and the lateral radial gates were fully open on October 11, 2015 (Figure 19b,c,d). The reduced water levels after the flood both in the approach to the side-weir of the Columbia Canal and downstream of the spillway are shown in Figure 19.

Figure 19. Spillway and Columbia Canal after the breach: (a) View of the spillway from the canal to the Broad River the Monday morning after the breach at 11:02 am on October 5, 2015. Note the still installed stoplogs raising the weir crest height up to 75% of the vertical adjustment slot height along the pillars visible since the water level dropped due to the downstream breach. (b,c,d) Spillway with stop logs removed in the 12 central side weir openings, while the lateral two side weirs are permanently cemented and the lateral sluice gates are fully open on October 11, 2015. (e) Downstream of the spillway with reduced Broad River water level on October 13, 2015. (f) Pedestrian bridge and canal upstream with significantly lowered canal water level on October 11, 2015 (N 34.00199°, W 81.05372°).

3.5 Columbia Canal breach at 3 am on Monday October 5, 2015

The initial Columbia Canal dike breach of 3 am on Monday October 5, 2015 occurred at the location of a rock wall some 20 m upstream of the Lockhart Power Substation #559 and 80 m upstream of the power house shown in Figure 20. At the crest level the breach extends 26 m upstream from the rock wall, while at the waterline only 12 m with the water surface 9 m below the dam crest as shown in Figure 21. The rock wall on the downstream end of the breach is directly upstream of a buried historic pipe and intake structure with a lifting mechanism for a sluice gate attached to a concrete block on the levee crest shown in Figure 22. The rock wall remained intact from the canal side of the levee profile, but failed from the road way on the levee crest towards downstream exposing the support structure of the historic pipe buried below the levee crest road. The length of the breach along the road on the dam crest expands to 40 m on the river side of the levee (Figure 23). The buried rock walls and pipe were part of the historic hydroelectric station that used to power the Columbia textile mill. As illustrated in the interpretive sketch shown in Figure 24, at the breach location the levee was constructed on top of older fill and/or floodplain sediments that thicken towards the Canal and were abutted against a buried stonemasonry wall. Extensive slumping along the Canal side of the right levee bank (facing downstream in flow direction) occurred after the initial breach due to rapid lowering of the Canal water level. The wrackline in the vegetation growing along the road embankment on the levee crest indicates that the Canal water level rose to within 0.3 m of the levee's crest, but did not overtop directly upstream of the breach. However there was slight overtopping with over wash on the order of 0.1 m on above the levee crest downstream of the breach between the buildings of the Lockhart Power Substation #559 and the power house (Figure 25). The peak discharge in the Broad River 1 mile upstream of the Columbia Canal intake or 4 miles upstream of the initial breach was reached more than 8 hours prior to the levee breach. The peak stage at the breach locations may have been reached approximately 6 hours prior to the breach. The cause of the initial breach was likely due to piping of levee soils along the soil-wall contact exacerbated by overtopping at the breach location. The groves between wall stones and the planar soil-to-stone contact provided the most likely paths for the piping that led to the initial breach at 3 am on Monday October 5, 2015.

(a)

(b)

Figure 20. Initial Columbia Canal Levee Breach (N 33.99796°, W 81.05018°): (a) Aerial view of the Columbia Canal in the foreground with the Congaree River formed by the confluence of Broad River (sediment laden brown water) and Saluda River (blue water in foreground) on October 6, 2015. Note there is only the initial levee breach as cofferdam construction begins downstream of SC-12 Bridge, which will lead to the later horseshoe breach; (b) detail of the 26 m long dike breach some 20 m upstream of the Lockhart Power Substation #559 at 8am on October 5, 2015 (photos from Congaree Riverkeeper: www.congareeriverkeeper.org).

(a)

(b)

Figure 21. Columbia Canal dike breach of 3 am on Monday October 5, 2015 some 20 m upstream of the Lockhart Power Substation #559 and 80 m upstream of the power house: (a) Panoramic southwest-ward view of the levee breach with both upstream and downstream drawdown slumps on the Canal side; (b) detail of the dike breach at the downstream rock wall with a breach length of 26 m at the crest and 12 m at waterline with the water surface 9 m below the dam crest (photos: October 12, 2015; N 33.99796°, W 81.05018°).

(a)

(b)

Figure 22. Columbia Canal dike breach of October 5, 2015 some 20 m upstream of the Lockhart Power Substation #559: (a) Upstream view with the rock wall on the downstream end of the breach. Note the orifice shaped feature marking a buried pipe of a historic intake with a sluice gate lifting mechanism attached to the concrete block at the levee crest. (b) Support structure of the historic pipe buried below the road (photos: October 13, 2015; N 33.99796°, W 81.05018°).

Figure 23. Columbia Canal dike breach of October 5, 2015 some 20 m upstream of the SCE&B Substation #559: Upstream view with the rock wall on the downstream end of the breach (to the right in photo). Note the orifice shaped feature in the rock to brick wall transition marking a buried pipe of a historic intake with a sluice gate lifting mechanism attached to the concrete block at the levee crest (photo March 4, 2016 from Congaree Riverkeeper: www.congareeriverkeeper.org via their Twitter and FB).

(a) 

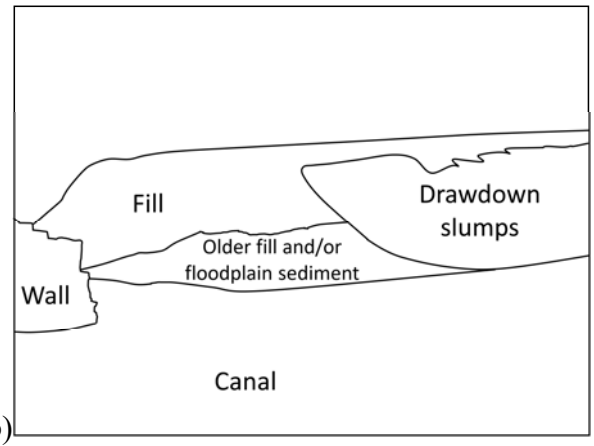
(b) 

Figure 24. Columbia Canal dike breach of 3 am on Monday October 5, 2015: (a) Westward view of the breach and upstream levee on October 14, 2015; (b) interpretive sketch of the geotechnical levee composition (N 33.99796°, W 81.05018°).

Figure 25. Overtopping of Columbia Canal dike: (a,b,c) Over wash erosion between the buildings of Lockhart Power Substation #559 upstream of the power house, but downstream of the breach (photos: October 13, 2015; N 33.99751°, W 81.04965°); (d) erosion on the downstream side of the levee from over wash funneled between the buildings upstream of the power house (photo: October 11, 2015; N 33.99716°, W 81.04932°).

3.6 Horseshoe formation in levee upstream of breach while building the Canal cofferdam

An 80 m long horseshoe-shaped feature formed in the Columbia Canal levee some 90 m upstream of the initial breach shown in Figure 26. Two damaged power poles can be seen in the center of the second breach. A third power pole, at the upstream edge of the breach later fell due to continued erosion of the levee fill (Figure 27). The cofferdam construction initially proceeded only from the landward left Canal bank towards the levee. The cofferdam penetrating from the landward side during construction led to a constriction of the Canal thereby convectively accelerating the still rushing Canal discharge, which carved out the horseshoe from the opposing levee. Apparently the canal intake gates could not completely limit inflow. The levee was completely cut through at this location, but the decreasing discharge and the dropping of sand bags from helicopters and rock-fill from trucks off the SC-12 Bridge stabilized the levee enough to prevent Canal water from flowing through the horseshoe breach back into the Broad River (Figure 28). Finally, after a weeklong engineering and construction struggle the rock-fill cofferdam was completed upstream.

Figure 26. Second horseshoe breach fully formed in the Columbia Canal levee during the one-sided attempt to construct the cofferdam from the landward side by October 8, 2015 (photo from Congaree Riverkeeper: www.congareeriverkeeper.org via their Twitter and FB (N 34.00012°, W 81.05154°).

(a)

(b)

Figure 27. Second horseshoe breach formed in the Columbia Canal levee during construction of the cofferdam: (a) On October 12 during cofferdam construction; (b) with cofferdam installed upstream on October 13, 2015 (N 33.99915°, W 81.05112°).

(a)

(b)

Figure 28. Columbia Canal cofferdam: (a) construction of the cofferdam upstream of the horseshoe breach by dumping rock-fill from the SC-12 Bridge on October 11, 2015; (b) cofferdam installed on October 13, 2015 (N 34.00012°, W 81.05154°).

3.7 Broad River levee breach near Martin Marietta Rock Quarry

The eastern or left (in flow direction) Broad River embankment breached some 8.5 km upstream of the I-20 Broad River Bridge corresponding to 10 km upstream of the intake to the Columbia Canal (Figure 10). The Norfolk Southern Railroad trestle and the Martin Marietta Rock Quarry (North Columbia Quarry) are shown in before and after aerial photographs in Figure 29.

(a)

(b)

Figure 29. Aerial views of the Norfolk Southern Railroad trestle and the Martin Marietta Rock Quarry (North Columbia Quarry) the east bank of the Broad River 10 km upstream of the Columbia Canal: (a) undated archive photo; (b,c) flooded quarry with 200 m breach in left Broad River embankment and collapsed railroad bridge in October 6, 2015 photo from Congaree Riverkeeper (www.congareeriverkeeper.org via Twitter/FB; N 34.11447°, W 81.11935°).

The levee breach and the damaged Norfolk Southern Railroad trestle near the Martin Marietta rock quarry are shown in Figure 30. The construction crews on the newly build gravel dike are working on setting up pump stations to pump the flood water out of the engulfed quarry. The dike also serves the initial stages of trestle repair. Landward of the newly built dike, a near vertical wall of exposed levee and overbank sediments can be seen. This wall of exposed natural sediments was created by flood waters from the Broad River flowing down a pre-existing drainage into the rock quarry. A sample of levee materials collected near where the persons are standing in the foreground of Figure 30 consists of dark yellowish brown sand with silt.

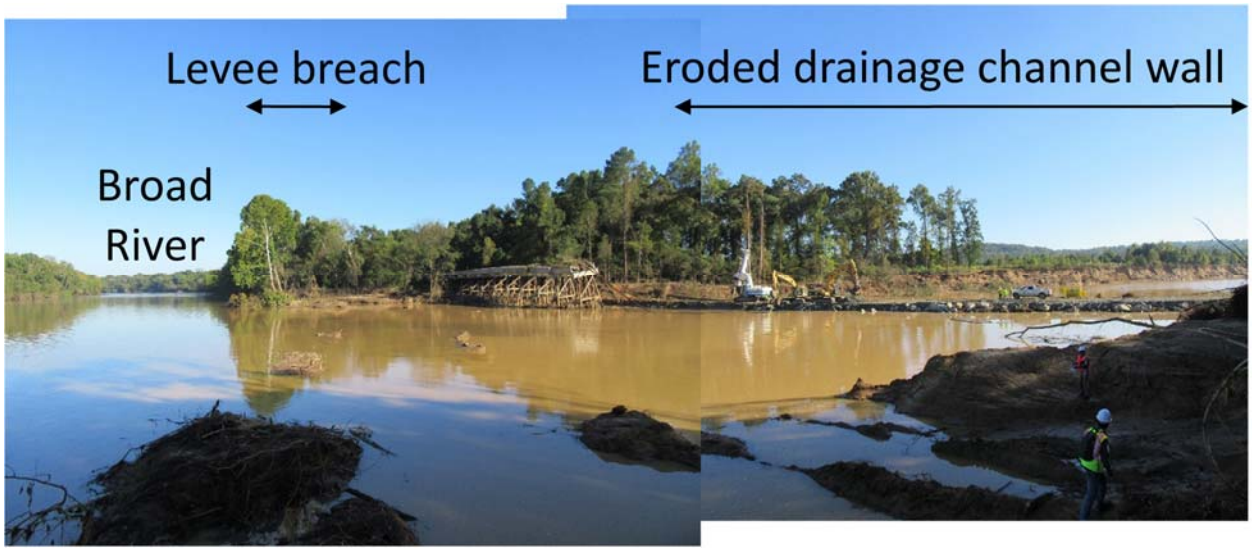


Figure 30. Upstream view of the 200 m long levee breach on the Broad River and damaged Norfolk Southern Railroad trestle on October 14, 2015. Note the newly built gravel dike with construction equipment working on setting up pump stations to pump the flood water out of the engulfed quarry along with the initial stage of trestle repair (N 34.11447°, W 81.11935°).

High water marks were observed in the form of wrack lines and rafted debris at the base of tree stems on the downstream end of the breach as shown in Figure 31. The high water marks indicate the river discharge reached the crest height. Analysis of pre- and post-flooding satellite imagery highlights the 300 m long railroad bridge at the location of the breach. Both upstream and downstream of the breach the railroad runs on the levee. Hence overtopping river discharge breached a 200 m long levee segment, destroyed two thirds of the railroad bridge and flooded the North Columbia Quarry shown in Figure 32. The amount of water in the quarry is estimated to be 3.5 billion gallons (corresponding to 13 million m^3). It will take a few months of pumping to remove the flood water from the quarry.

Figure 31. Embankment at downstream end of levee breach along the Broad River with high water marks at the base of tree trunks and wracklines, which indicate the river discharge reached the crest height and breached the lower levee section due to overtopping (photos: October 14, 2015; N 34.11380°, W 81.11971°).

The 1997 USGS 7.5-minute topographic map of the area is shown in Figure 33 and provides additional insight into the levee breach. The levee was about 30-m-wide in the breached area, which is much narrower than at other locations along the Broad River. Thus, it is likely that the levee in the area of the breach was man-made to prevent flood waters from entering the drainage leading to the quarry.

(a)

(b)

Figure 32. Levee breach on Broad River: (a) Destruction of two thirds of a 300 m long bridge of a Norfolk Southern Railroad trestle; (b) north end of flooded quarry (photos: October 14, 2015; N 34.11447°, W 81.11935°).

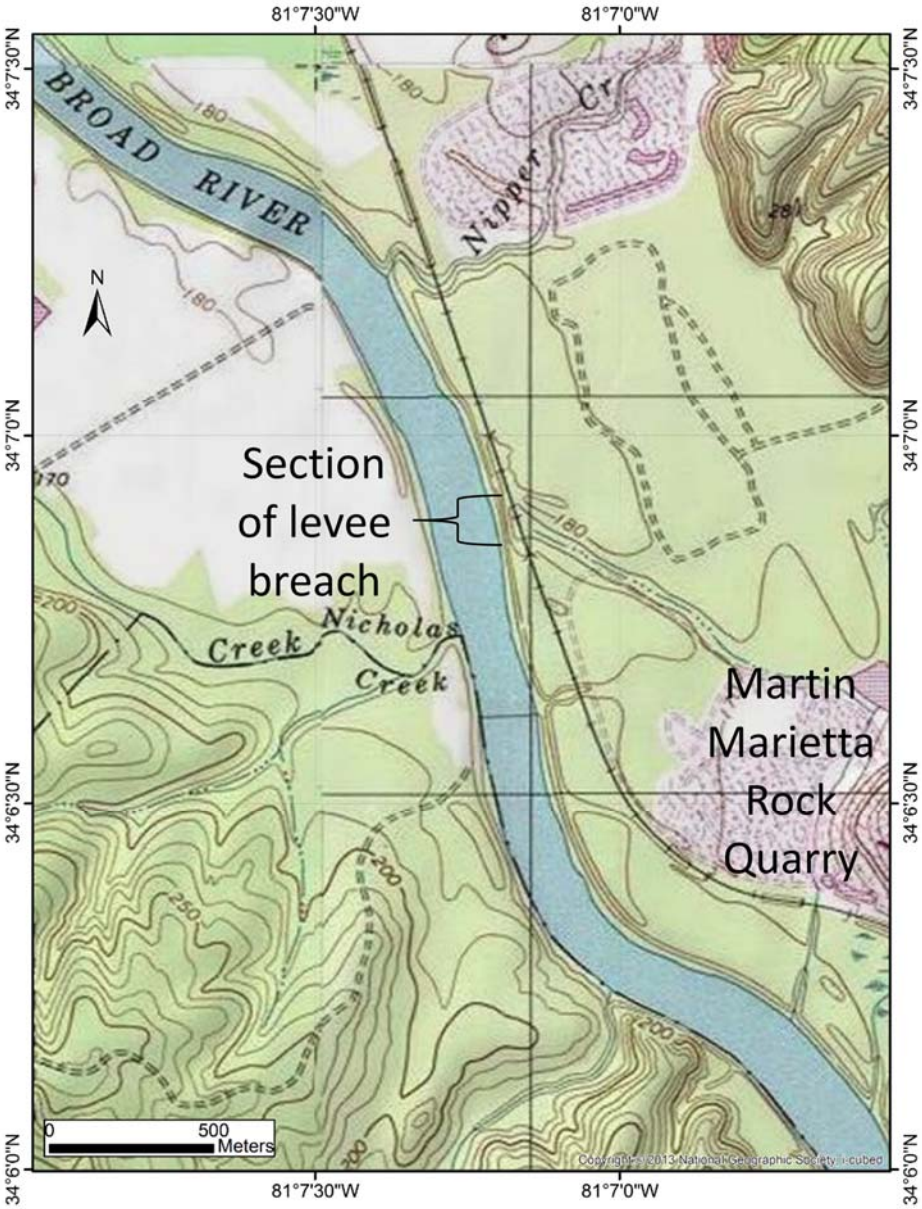


Figure 33. 1997 USGS 7.5-minute topographic map showing locations of the breached levee and the Martin Marietta rock quarry.

3.8 Lake Elizabeth Dam and Crane Creek

Lake Elizabeth Dam impounds Crane Creek with an earthen embankment with U.S. Route 21 (US-21) running along the crest of the dam shown in Figure 34. Crane Creek flows into the Broad River some 700 m south of the I-20 Bridge over the Broad River and some 900 m north of the Columbia Canal diversion dam and canal intake. Lake Elizabeth Dam is located 11 km NE of the tributary inflow into the Broad River. The Crane Creek Watershed includes 67 square miles (174 square km) in the northern part of Richland County. The Crane Creek watershed is directly adjacent northwest of the Gills Creek Watershed. The Upper Crane Creek watershed impounded by Lake Elizabeth Dam includes 22 square miles (58 square km) or about a third of the Crane Creek watershed. Lake Elizabeth Dam (D-0024) is classified by S.C.-DHEC into category C1, which means that failure may cause loss of life or serious damage to infrastructure. The earthen embankment dam breached just to the north of the 30 m long US-21 bridge over Crane Creek shown in Figure 34. The breach is 10 m long on upstream side but widens to 25 m on the downstream of US-21 shown in Figure 35. Two vehicles (Mercury Mariner and Mercury Grand Marquis) were washed off the road (US-21) on the dam crest and were stranded downstream. The normal water level in Lake Elizabeth is controlled by a 20 m long sharp crested weir shown in Figure 36. A spillway through a small orifice (order 1 sq ft opening) with a lift gate allows to lower the lake water surface below the weir crest height. However the spillway was overwhelmed resulting in overtopping of the dam and US route 21 as highlighted by the wrack stuck in guard rails and fences shown in Figure 36.

(a)

(b)

Figure 34. Lake Elizabeth Dam breach : (a) US Route 21 bridge over Crane Creek with dam breach directly adjacent to the north; (b) two cars washed off the road and stranded downstream (photos: October 11, 2015; N 34.11253°, W 80.98766°).

(a)

(b)

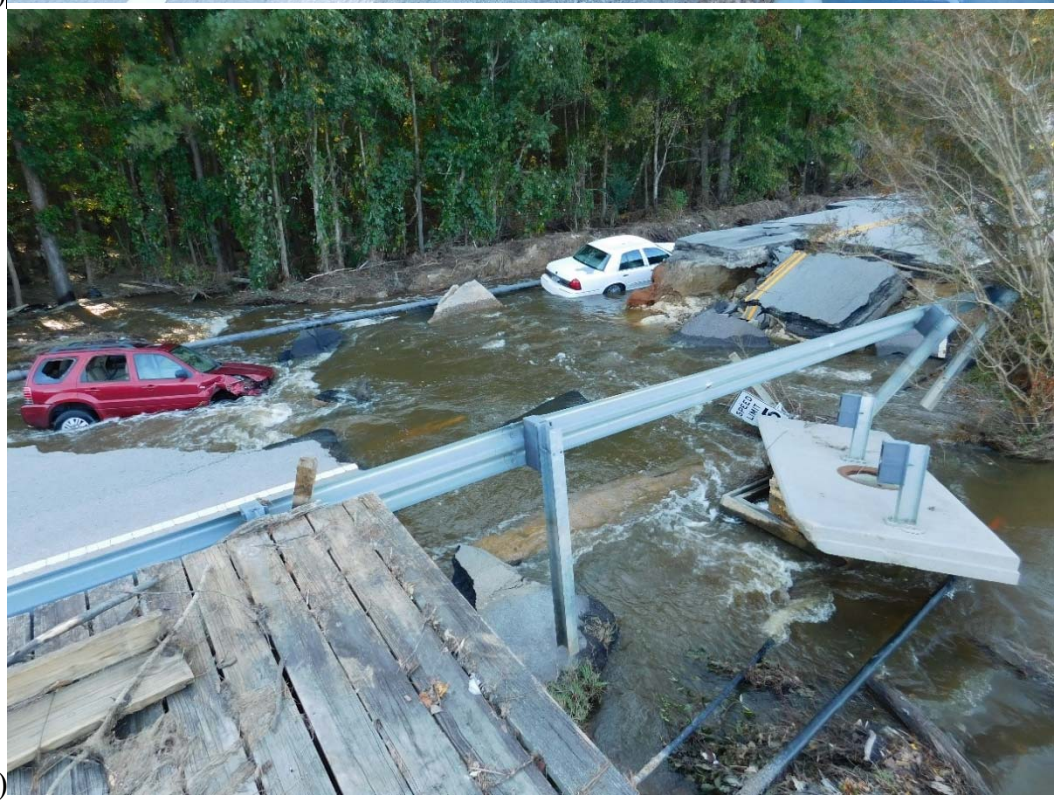


Figure 35. Lake Elizabeth Dam breach: (a) US Route 21 and dam breach; (b) two cars (Mercury Mariner and Mercury Grand Marquis) washed off the road and stranded downstream (photos: October 11, 2015; N 34.11253°, W 80.98766°).

(a)  (b) 

Figure 36. Lake Elizabeth Dam spillway: (a) wrack from overtopping stuck in fence and guard rails of US Route 21 and sharp crested weir with lift gate; (b) US Route 21 Bridge over Crane Creek and sharp crested weir (photos: October 11, 2015; N 34.11224°, W 80.98746°).

4 Saluda River Basin

4.1 Saluda River Watershed, Stages and Discharge

The field sites visited in the Saluda River watershed in Lexington County (SC) are shown in Figure 37. This includes Lake Murray, the Saluda Dam and the Saluda Dam spillway as well as the flooded areas along the Saluda River downstream of the spillway. The cascading dam breach failures visited along the tributary Twelve-Mile Creek include: Barr Lake Dam, Gibsons Pond Dam and Old Mill Pond Dam. The three dam failures discussed in this section involve only headwaters in Twelve-Mile Creek sub-watershed flowing into the Saluda River upstream of the confluence with the Broad River. The Saluda Dam successfully regulates streamflow in the Saluda River downstream of Lake Murray since 1930. The Saluda River Basin accounts for approximately one-third of the drainage area for the Congaree River at Columbia station downstream of Columbia Canal after the confluence with the Broad River.

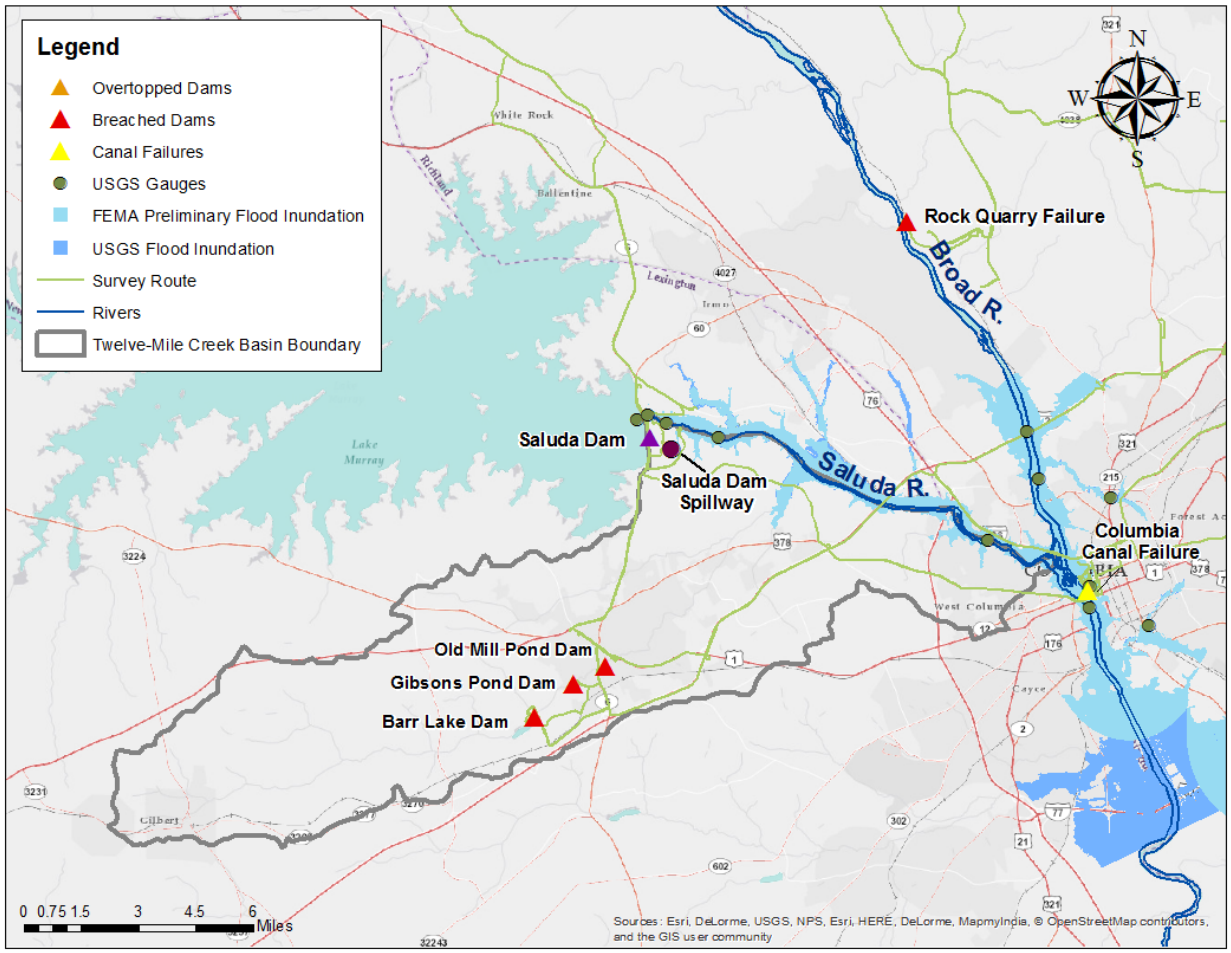


Figure 37. Saluda River watershed boundary with the visited Saluda Dam and Saluda Dam Spillway as well as the visited dam failures along the Twelve-Mile Creek include: Barr Lake Dam, Gibsons Pond Dam, and Old Mill Pond Dam in Lexington County. The west side of the Columbia metropolitan area indicates an overlaid GPS track with distressed and breached dams covered during the GEER field survey from October 11 to 14, 2015.

The Lake Murray USGS gauge 02168500 records the reservoir water surface at the Saluda Dam as shown in Figure 39. The reservoir water surface level peaked at 359.65 ft (359.01 ft NGVD29) at 0000 EST on October 7, 2015. Hence the reservoir water level peaked more than two days after all the unregulated rivers in the vicinity such as the Broad River for example. This demonstrates the potential effectiveness of dams as flood protection structures as they store flood water in the reservoir and release it with a temporal lag. During the entire flood sequence the inflow into Lake Murray exceeded the outflow in the tailrace. The reservoir level is normally kept at 358.50 ft (357.86 ft NGVD29). The highest reservoir level ever reached was in 1936 with 361.60 ft (360.94 ft NGVD29). The operator SCE&G owns the lake front property only up to the reservoir level of 360 ft (359.36 ft NGVD29) and beyond would result in flooding of private lake front property. However dam safety comes first and the spillway gates were rightfully activated. The spillway gates were previously activated during extreme flood events in 1936, 1965 and 1969. The spillways released 53,000 cfs, while the inflow into Lake Murray was 124,000 cfs. This stands in stark contrast to a mean discharge of less than 3,000 cfs based on 27 years of record. Hence the reservoir served flood mitigation by storing some flood water and reducing the peak discharge. All the downstream USGS gauges dropped out during the peak discharge period from October 3-6, 2015, which includes: the Lake Murray tailrace USGS gauge 02168501 (Figure 38a and Figure 39b), Saluda River USGS gauge 02168504 some 700 m downstream of the Saluda Dam (Figure 38b and Figure 40), and Saluda River USGS gauge 02169000 located 12.5 km downstream of the Saluda Dam and 2.5 km upstream of the confluence with the Broad River (Figure 41).

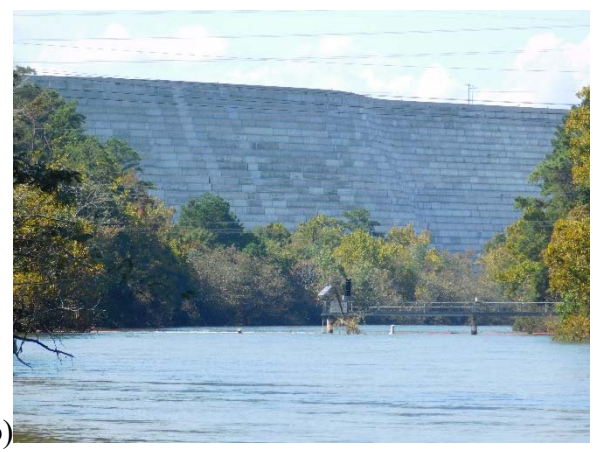
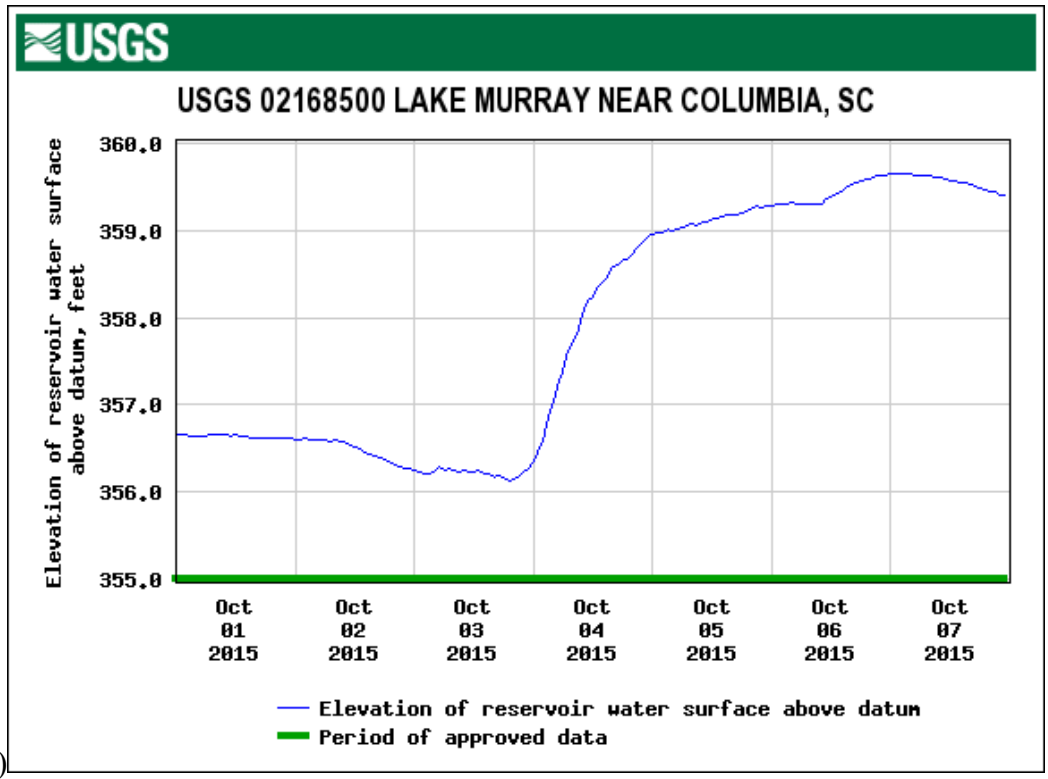
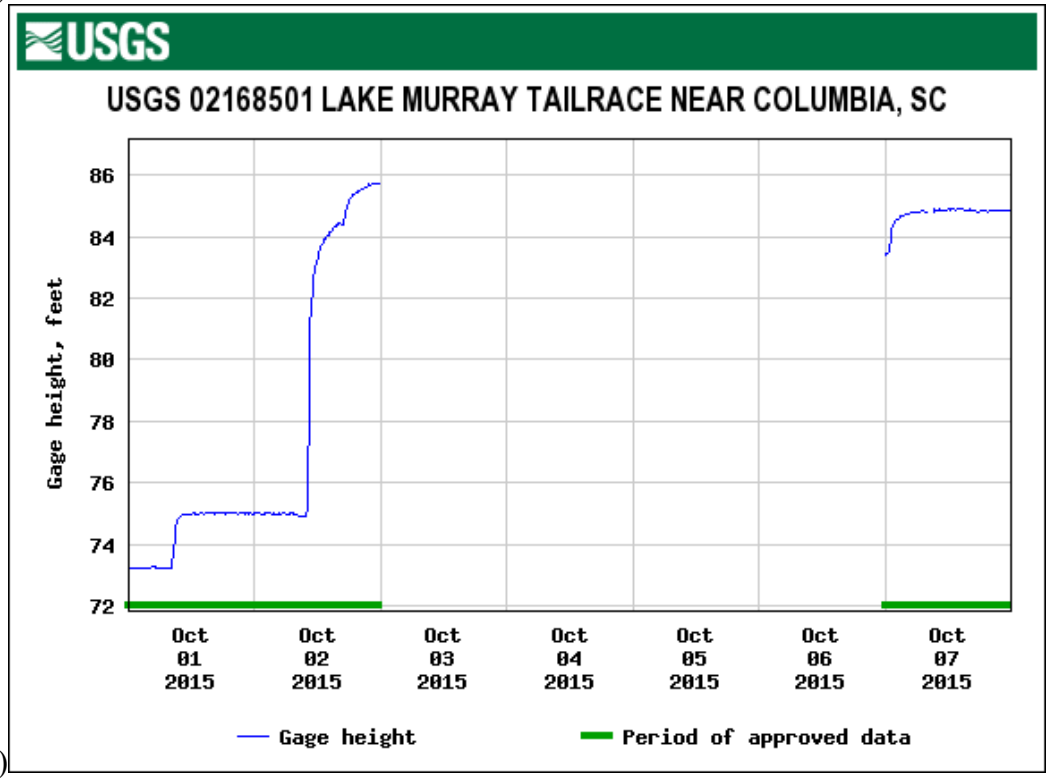
(a)  (b) 

Figure 38. Saluda dam with RCC back-up dam built in 2005 for seismic remediation: (a) powerhouse with tailrace outflow and location of USGS gauge 02168501 (N 34.05390°, W 81.21652°); (b) Saluda River USGS gauge 02168504 some 700 m downstream of the Saluda Dam (N 34.05088°, W 81.20959°). The rafted debris entangled on the support structure marks the engulfing flooding and explains the drop out of the gauges (photos: October 12, 2015).

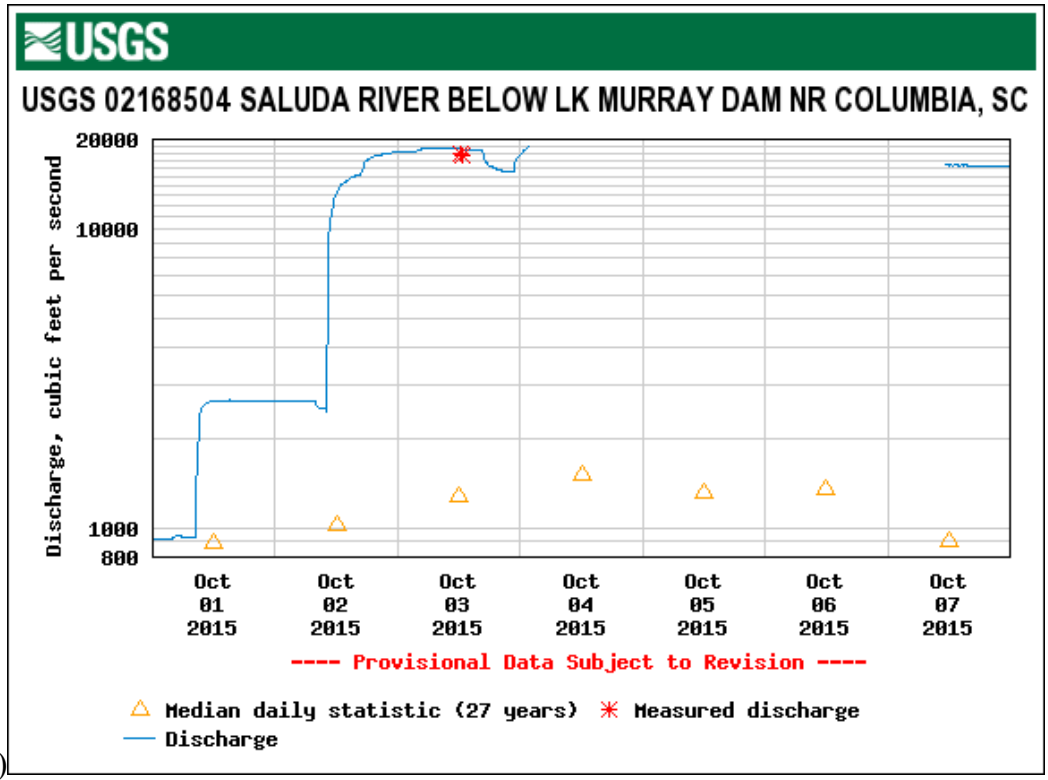


(a)

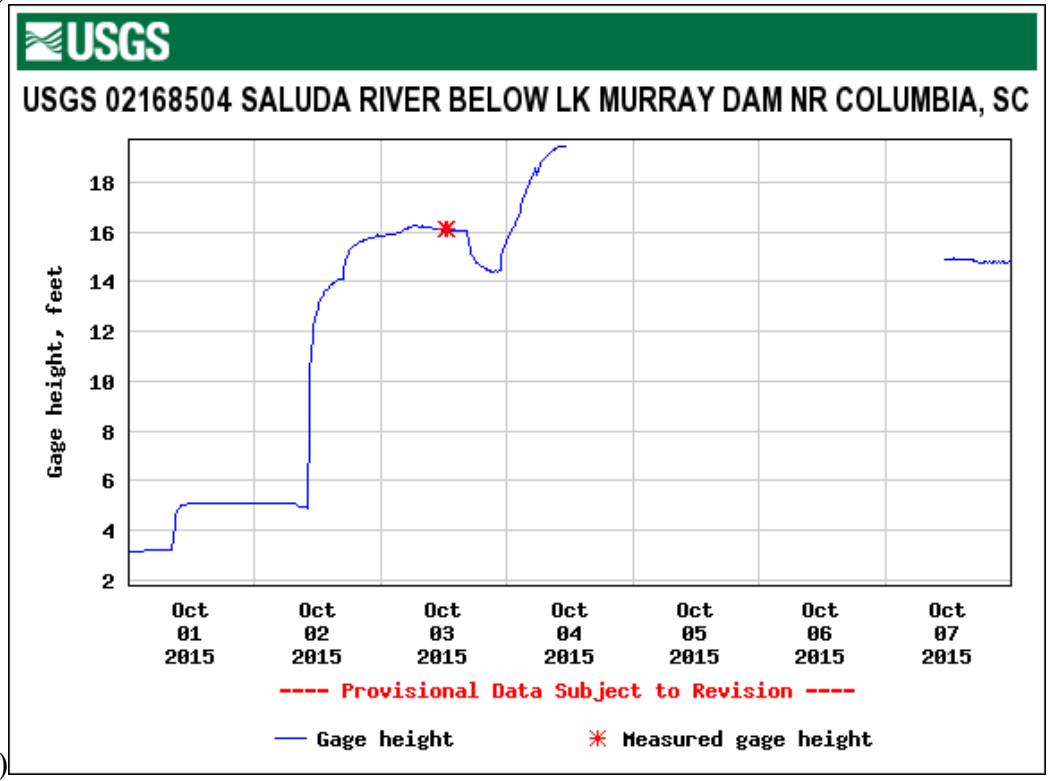


(b)

Figure 39. (a) Lake Murray USGS gauge 02168500 recording of the reservoir water surface at the Saluda Dam. The reservoir water surface level peaked at 359.65 ft (359.01 ft NGVD29) at 0000 EST on October 7, 2015. (b) Lake Murray tailrace USGS gauge 02168501 provides no data for the period October 3-6, 2015; note gauge datum 99.1 ft above NGVD29 (waterdata.usgs.gov/nwis).

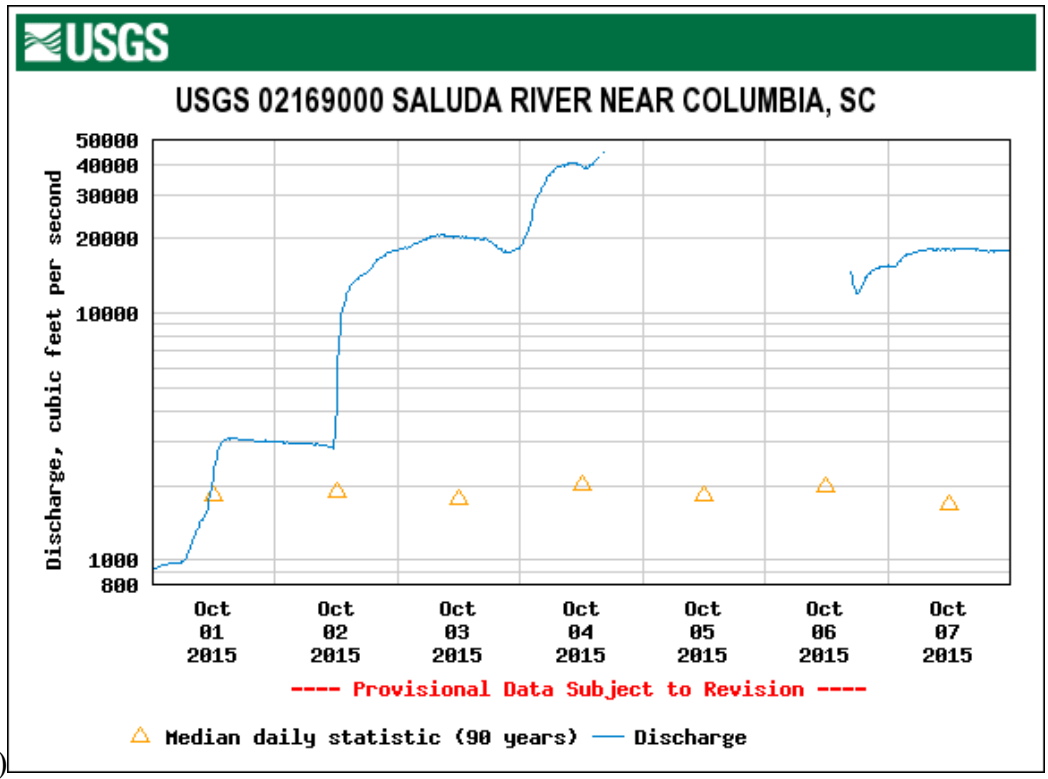


(a)

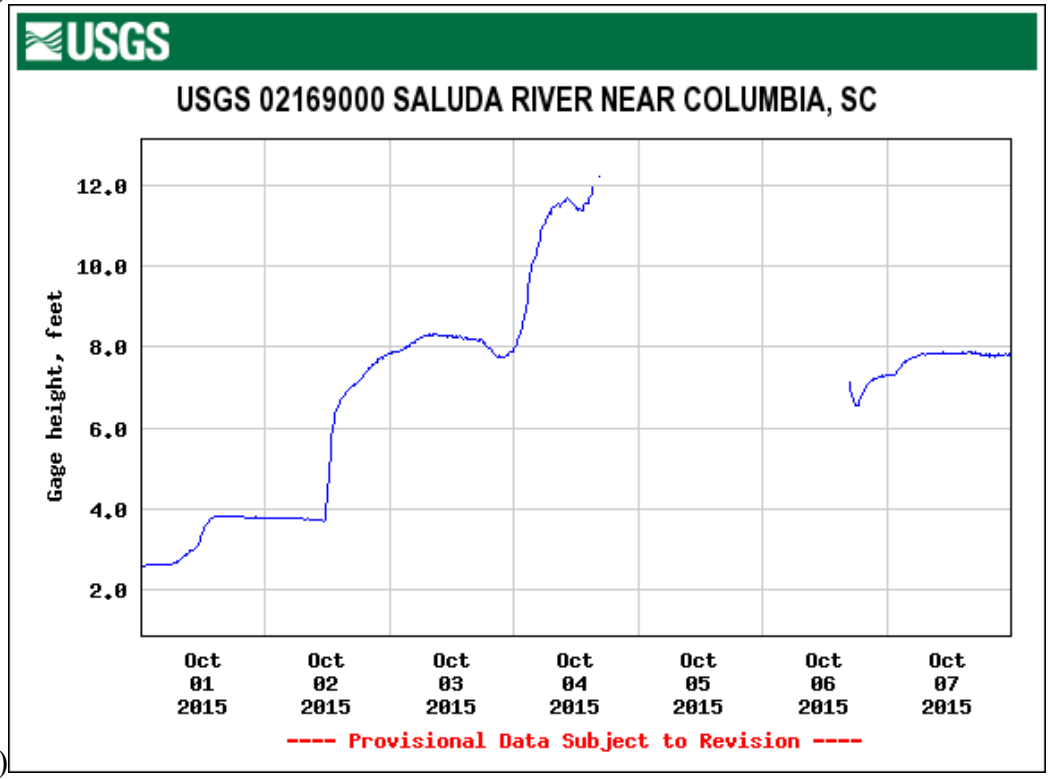


(b)

Figure 40. Saluda River USGS gauge 02168504 less than 1 km downstream of the Saluda Dam provides no data from midday October 4 to midday October 7, 2015: (a) discharge; (b) stage with gauge datum 170 ft above NGVD29 (waterdata.usgs.gov/nwis).



(a)



(b)

Figure 41. Saluda River USGS gauge 02169000 located 12.5 km downstream of the Saluda Dam and 2.5 km upstream of the confluence with the Broad River provides no data from afternoon October 4 to afternoon October 7, 2015: (a) discharge; (b) stage with gauge datum 149.46 ft above NGVD29 (waterdata.usgs.gov/nwis).

4.2 Saluda Dam and Spillway

The Saluda Hydroelectric Project (FERC Project No. 516) is located on the Saluda River in Richland, Lexington, Saluda, and Newberry Counties of South Carolina, near the town of Irmo, approximately 10 miles west of the city of Columbia. The 2,420 square mile watershed area, drained by the Saluda River and its tributaries above Saluda Dam, provides water for Lake Murray and the Saluda Hydroelectric Plant. The Saluda Dam (officially the Dreher Shoals Dam, commonly referred to as the Lake Murray Dam) is an earthen embankment dam on the Saluda River shown in Figure 42. Construction on the dam began in 1927 and was completed in 1930. The purpose of the dam is flood control, hydroelectricity, recreation and water supply. At the time of its completion, the Saluda Dam was the world's largest earthen dam, creating the world's largest man-made lake, Lake Murray. The original Saluda Dam is a 7,800 ft (2,400 m) long, 213 ft (65 m) high earthen-embankment dam. In 2005, construction on a 213 ft (65 m) tall roller-compacted concrete (RCC) dam was completed at the toe of the original dam in order to mitigate an earthquake-caused dam failure. Rock-fill embankment sections also exist on the south and north ends of the backup dam, making a total length of 5,700 ft (1,700 m). South Carolina Highway 6 crosses over the dam and is used as a fast connection between the towns of Lexington, SC and Irmo, SC. The hydroelectricity power station consists of five vertical Francis turbines with an installed capacity of 207 MW. The power station receives water by means of five 223 ft (68 m) high intake towers through penstocks. Water released from the power station moves down a 150 ft (46 m) long tailrace tunnel before being discharged back in the Saluda River. The dam contains a 2,900 ft (880 m) long emergency spillway controlled by a weir with six steel Tainter gates shown in Figure 43. On October 4, 2015 the spillways released a maximum of 54,000 cfs through 4 opened gates (1 large gate and 2 small gates fully open, 1 small gate 2/3 open), while the inflow into Lake Murray peaked at 124,000 cfs. Hence the reservoir served flood mitigation by storing some flood water and reducing the peak discharge. The 1.9 km long spillway channel was excavated in bedrock, and reconnects with the Saluda River approximately 1.2 km downstream of the powerhouse shown in Figure 44. The ski-jump after the 40 m long concrete behind the gates entrains air into the supercritical flow as it transitions onto the bedrock section of the spillway. The bedrock roughness remnant from the excavation essentially serves as baffle blocks to dissipate energy. A 100 m long scour hole formed in the spillway at the end of the bedrock section 200 m upstream of the confluence with the Saluda River. A 60 m long cobble and boulder berm piled up in the spillway 100 m upstream of the confluence with the Saluda River. The spillway gates are operated when the reservoir level reaches or is predicted to exceed elevation 358.5 ft to pass flood inflows. At a flood elevation of 368.5 ft the spillway capacity is approximately 154,000 cfs. Under Probable Maximum Flood (PMF) conditions, the spillway is rated to pass 197,000 cfs with the reservoir at elevation 374.4. Thus, the rated capacity of the spillway exceeds the maximum flow observed during the October 2015 event by a factor of approximately 3.6.

(a)

(b)

Figure 42. Aerial views of the Saluda Dam with Lake Murray on the Saluda River 10 km upstream of Columbia: (a) Earthen Saluda Dam from 1930 with 2005 roller compacted concrete (RCC) backup dam at the toe for seismic remediation; (b) emergency spillway located 150 m south of the Saluda Dam with partially opened Tainter gates on October 6, 2015 (photos: Congaree Riverkeeper, www.congareeriverkeeper.org via Twitter/FB; N 34.04035°, W 81.21579°).

(a)

(b)

Figure 43. Drone aerial views of the activated emergency spillway located 150 m south of the Saluda Dam at Lake Murray: (a) Spillway with South Carolina Highway 6 on top of the earthen Saluda Dam from 1930 with 2005 roller compacted concrete (RCC) backup dam at the toe for seismic remediation; (b) spillway with 3 of the 6 Tainter gates open on October 5, 2015 (drone photos: Ebben M. Aley via NWS; N 34.04035°, W 81.21579°).

Figure 44. Emergency spillway aftermath: (a) Control weir with 6 Tainter gates located 150 m south of the Saluda Dam at Lake Murray; (b) ski-jump transition from the 40 m long concrete apron downstream of the gates to the bedrock; (c) 1.9 km long spillway section excavated into bedrock; (d) 100 m long scour hole 200 m upstream of confluence with Saluda River; (e) cobble and boulders forming a 60 m long berm at the confluence with the Saluda River; (f) fish and rafted debris 5 m up in a tree above the cobble berm along the spillway (photos: October 12, 2015). Locations (a,b,c): N 34.04035°, W 81.21579° and (d,e,f): N 34.04832°, W 81.20556°.

5 Twelve-Mile Creek, Lexington, SC

5.1 Twelve-Mile Creek Watershed, Stages and Discharge

The field sites visited in the Twelve-Mile Creek watershed in Lexington County (SC) are shown in Figure 45. The cascading dam breach failures visited along the tributary Twelve-Mile Creek include: Barr Lake Dam, Gibsons Pond Dam and Old Mill Pond Dam. The three dam failures discussed in this section involve only headwaters in Twelve-Mile Creek sub-watershed flowing into the Saluda River 6 km downstream of the Saluda Dam and 10 km upstream of the confluence with the Broad River. The Twelve-Mile Creek Watershed includes 60 square miles (156 square km) in Lexington County. The Twelve-Mile Creek watershed is south of Lake Murray. Unfortunately, there are no streamflow gauges along Twelve-Mile Creek.

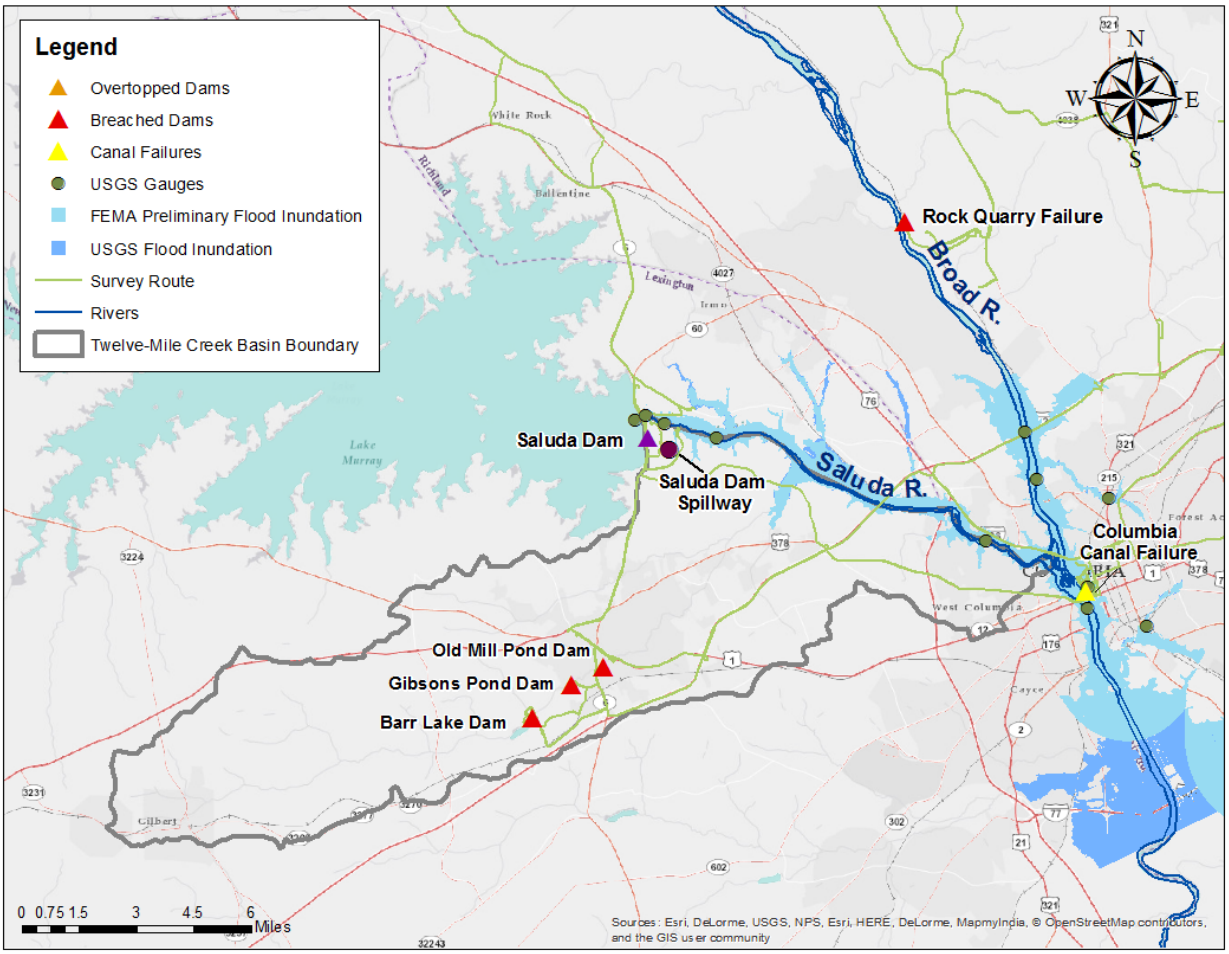


Figure 45. Twelve-Mile Creek watershed boundary with the visited dam failures along the Twelve-Mile Creek: Barr Lake Dam, Gibsons Pond Dam, and Old Mill Pond Dam in Lexington County, SC. The west side of the Columbia metropolitan area indicates an overlaid GPS track with distressed and breached dams covered during the GEER field survey from October 11 to 14, 2015.

5.2 Barr Lake Dam on Twelve-Mile Creek

Barr Lake Dam impounds upper Twelve-Mile Creek with an earthen embankment 2 miles (3.2 km) southwest of Lexington, SC. The Barr Lake Dam is the most upstream along Twelve-Mile Creek. Barr Lake reservoir has a surface area of 100 acres (0.4 square km). The area around Barr Lake is presently transforming with the construction of a 450-house residential development by the Barr Lake Development. Barr Lake Dam is 625 ft (190.5 m) long and 14 ft (4.3 m) high. Barr Lake Dam (D-1717) is classified by S.C.-DHEC into category C2, which means that failure will not likely cause loss of life but may damage infrastructure. The earthen embankment dam breached just 40 m to the west of the left gated concrete Twelve-Mile Creek outflow and 100 m to the west of the right gated concrete outlet shown in Figure 46. The 20 m long breach at a transition from a dam section with a vertical concrete I-wall to a pure earthen dam is shown in Figure 47 with the upstream left wingwall and the downstream left footing remaining. The lake level rose to the crest height overwhelming the emergency spillway and overtopping at the lowest section caused the failure. The breaching was facilitated by channeling along the interface between the concrete wall and the earthen dam. Scouring around the end of the concrete I-wall similar to abutment scour facilitated the erosion and breaching once dam overtopping occurred. Piping may also have played a role in the breaching process. However, the extremely low rise of Barr Lake Dam limits hydraulic pressures available for piping. The massive dam break outflow ultimately draining the reservoir flooded a forest downstream and overflowed the Wildlife Road some 150 m downstream shown in Figure 48.

(a)

(b)

Figure 46. Barr Lake Dam breach with empty reservoir: (a) Drone view towards the dam on the northeast side of the lake on October 6, 2015 (https://www.facebook.com/LexingtonPD/videos); (b) location of the dam breach is the western (left) most opening with the normal outflow 40 m to the east (right) and the spillway 100 m to the east (photo: October 12, 2015; N 33.95876°, W 81.26025°).

(a)

(b)

Figure 47. Barr Lake Dam breach: (a) massive outflow through the breach without evidence of overtopping on October 4, 2015 (https://www.facebook.com/LexingtonPD/videos); (b) 20 m long dam breach at the interface between two dam profiles with and without a vertical concrete I-wall in the earthen dam (photo: October 13, 2015; N 33.95876°, W 81.26025°).

(a)

(b)

Figure 48. Barr Lake Dam breach downstream flooding: (a) massive outflow through the breach into the forest on October 4, 2015 (N 33.95876°, W 81.26025°); (b) flooding of Wildlife road some 150 m downstream of the dam breach on October 4, 2015 (https://www.facebook.com/LexingtonPD/videos; N 33.95954°, W 81.25879°).

5.3 Gibsons Pond Dam on Twelve-Mile Creek

Gibsons Pond Dam impounds upper Twelve-Mile Creek with a concrete structure 1.2 miles (1.9 km) downstream of Barr Lake Dam and 0.8 miles (1.3 km) southwest of Lexington, SC. The Gibsons Pond is the smallest reservoir along Twelve-Mile Creek. The upper Twelve-Mile Creek watershed upstream of Gibsons Pond Dam includes 31 square miles (81 square km) in Lexington County. Some 85% of the watershed draining through Gibsons Pond originates from the watershed flowing through the upstream Barr Lake. The inflow into Gibsons Pond is only 1 km downstream of Barr Lake Dam and highly correlated with the outflow from the upstream Barr Lake dam. Gibsons Pond Dam is 190 ft (57.9 m) long and 15 ft (4.6 m) high. Gibsons Pond Dam (D-0959) is classified by S.C.-DHEC into category C2, which means that failure will not likely cause loss of life but may damage infrastructure. The concrete dam breached directly to the north (left in flow direction) of the weir and spillway shown in Figure 49. The 10 m long breach is shown in Figure 50. Debris damming on the pedestrian steel bridge clogged the overflow area between the weir crest and the bridge reducing the spillway capacity (Figure 50). Ultimately the dam was overtopped as evidenced by the wrack deposited on the lateral tree stems at elevations above the dam crest (Figure 50b). Hence debris damming of the spillway leading to overtopping are the cause of the dam breach at Gibsons Pond. The timing sequence and the exact timing of the dam failures at Barr Lake, Gibsons Pond and Old Mill Pond remain to be determined.

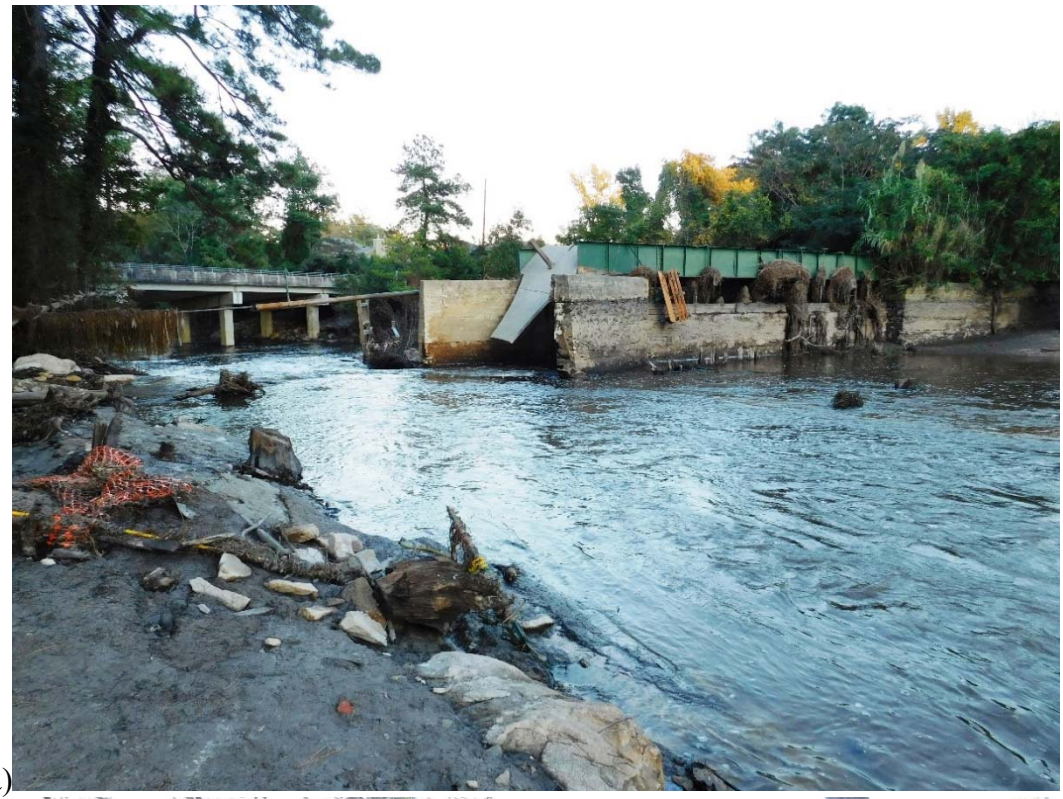
(a)

(b)

(c)

Figure 49. Gibsons Pond Dam: (a) Drone view of concrete dam with weir flow and pedestrian bridge on December 3, 2013 (snippet from video by Robbie Robinson https://www.youtube.com/watch?v=_LpUje-EoPw); (b) massive weir discharge but no debris damming under the bridge on Saturday October 3, 2015 (snippet from video by Firefighter Chris Jackson https://www.youtube.com/watch?v=bHeI8doV1E8); (c) dam breach on northern (left in flow direction, right in photo) abutment and partial debris damming at weir crest under steel bridge on October 4, 2015 (https://www.facebook.com/LexingtonPD/videos; N 33.96949°, W 81.24360°).

(a)



(b)

Figure 50. Gibsons Pond Dam breach on the northern (left in flow direction) abutment: (a) partial debris damming weir opening under the steel bridge; (b) tree stem with wrack from overtopping (photos: October 12, 2015; N 33.96949°, W 81.24360°).

5.4 Old Mill Pond Dam on Twelve-Mile Creek

Since 1891 Old Mill Pond Dam (Lexington Mill Pond Dam) impounds upper Twelve-Mile Creek with an earthen fill structure 0.9 miles (1.5 km) downstream of Gibsons Pond Dam near the intersection of Highway 1 (U.S. Route 1 or East Main Street) and Taylor Drive. Highway 1 crosses over Twelvemile Creek 140 m downstream of the Old Mill Pond dam shown in Figure 51. The dam includes a controlled spillway adjacent to the southern (right) abutment (facing downstream), and an inlet leading to a penstock adjacent to the northern (left) abutment.

(b)

(b)

Figure 51. Old Mill Pond Dam breach in aerial drone views on Sunday October 4, 2015: (a) Old textile mill turned shopping center to the north (left) of breach and US-1 downstream; (b) downstream view from the pond towards the breach flanked by the Old Mill building to the north (left) and remaining earth fill dam to the south (video snippets from: https://www.facebook.com/LexingtonPD/videos; N 33.97683°, W 81.22961°).

The Old Mill Pond is the third reservoir on Twelve-Mile Creek. Some 95% of the watershed draining through Old Mill Pond originates from the watershed flowing through the upstream Gibsons Pond and Barr Lake. The inflow into Old Mill Pond is only 700 m downstream of Gibsons

Pond Dam. Old Mill Pond reservoir has a surface area of 30 acres (0.12 square km). The Old Mill Pond Dam is 475 ft (144.8 m) long and 20 ft (6.1 m) high. Old Mill Pond Dam is classified by S.C.-DHEC into category C1, which means that failure may cause loss of life or serious damage to infrastructure. Old Mill Pond Dam (D-0958) underwent routine inspection on April 4, 2014 by the South Carolina Department of Health and Environmental Control (S.C.-DHEC). It was concluded that the dam is in fair condition. Some of the recommendations in the 2014 inspection report include: Evaluation of flow outside discharge pipe near the building (possible channeling around pipe), evaluation of tree removal, upstream slope rip-rap for wave protection and grass cover on crest should be established, main spillway gate should be checked for functionality. The situation of the conditions at the dam rapidly deteriorated in 2015. An S.C.-DHEC inspection on June 9-10, 2015 concluded that the dam is in unsatisfactory condition. The main additional concern was the sinkhole forming near the gate to the penstock requiring lowering the reservoir level below the intake. This triggered the hiring of Schnabel Engineering and the application for repair work. A follow-up S.C.-DHEC site visit on September 23, 2015 (one week before the beginning of the October rainfall event) verified that the water is not impounding (empty reservoir) and construction started. The sinkhole area next to the building was removed exposing the outlet pipe, which was corroded and penetrated by the earth mover during excavation as shown in Figure 52. The reservoir water level was requested to be lowered by 5 m for the repair work and was empty at the time of last S.C.-DHEC inspection.

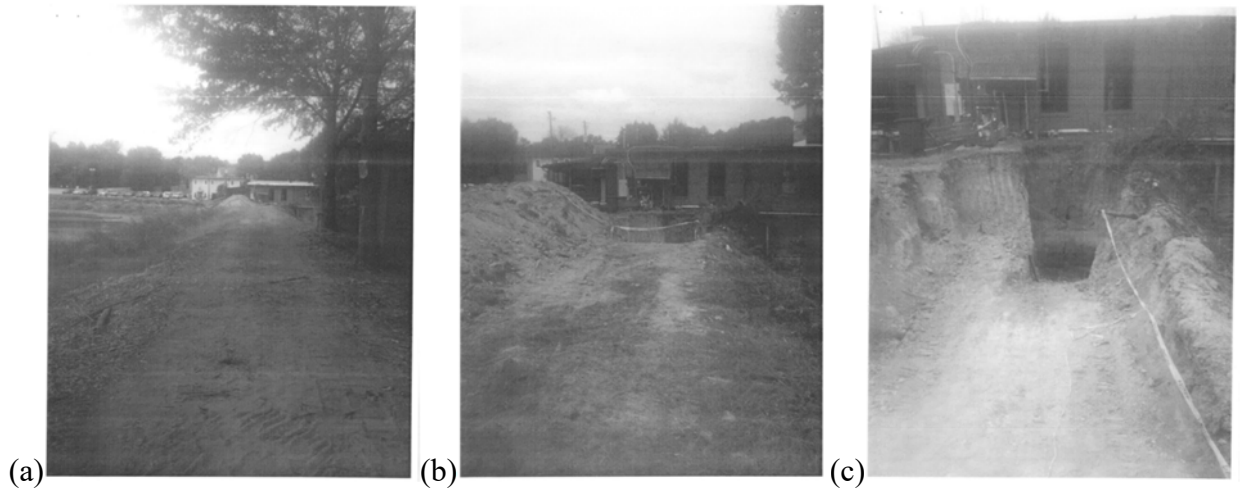


Figure 52. Old Mill Pond Dam S.C.-DHEC inspection photos from September 23, 2015: (a) empty pond reservoir; (b,c) excavation in the sinkhole area on the downstream slope abutment exposing the penstock next to the Old Mill textile mill building turned shopping mall (N 33.97683°, W 81.22961°).

The dam breached at the location of the northern abutment of the earthen fill towards the Old Mill building with the intake and the penstock undergoing repair work. The first mobile photo uploaded at 6:44am (dawn at 6:55am) on October 4, 2015 by the Lexington Police Department shows a fully developed breach with an outflow water level at half the dam crest elevation shown in Figure 53(a). The water level continued to drop in the following hours: Flood discharge through the breach at 9:39am (Figure 53b) and significantly lowered water level in the pond at 12:47pm (Figure 54a). The discharge overwhelms the two box culverts under Highway 1 (US-1) and flooding overtops the highway bridge shutting down Lexington's Main Street shown in Figure 54(b).

(a)

(b)

Figure 53. Old Mill Pond Dam breach on Sunday October 4, 2015: (a) Breach already fully formed at 06:44am adjacent to Old Mill building at penstock location (N 33.97683°, W 81.22961°); (b) breach widened and reservoir water level significantly lowered in upstream view from US-1 towards downstream slope of earthen fill dam at 09:39am (N 33.97730°, W 81.22813°; photos: https://www.facebook.com/LexingtonPD/photos).

(a)

(b)

Figure 54. Old Mill Pond Dam breach on Sunday October 4, 2015: (a) Significantly lowered water level in the pond and reduced outflow at 12:47pm (photo upload: https://www.facebook.com/LexingtonPD/photos; N 33.97683°, W 81.22961°); (b) discharge overwhelms the two box culverts under US-1 and floods the highway at 9:37am (video upload: https://www.facebook.com/LexingtonPD/videos; N 33.97730°, W 81.22813°).

The southern (right) dam abutment is formed by an outcrop of hard rock shown in Figure 55. The spillway consists of one large sluice gate, which was only lifted by 0.3 m or slightly opened at the time of the site visit, and two smaller openings which serve as emergency overflows into the

spillway with a fixed weir crest. The gated spillway has an approach channel excavated into the bedrock, which results in an about 2-meter lower weir crest compared to the fixed weir crest emergency spillways. Some debris was further damming the outflow into the spillway. The northern (left) abutment is formed by the old Lexington Mill structure founded on an extremely weathered rock, called saprolite shown in Figure 56. The mill's penstock remained in its position. The penstock had been partially excavated in September 2015 for repair work on the downstream side of the dam prior to the flooding event in October 2015. The intake to the penstock with the protecting trash rack and controlling vertical sluice gate is shown in Figure 57(a). The left stonemasonry wall directing flow to the intake is intact, while the right stonemasonry wall directing flow to the intake has been carried away by flood waters.

The dam failure exposed trapezoidal embankment profile of the earth fill dam on the southern (right) side of the breach shown in Figure 57(b). The dam consists of fairly homogeneous reddish sandy fill that most likely came from an area of the pond just upstream of the right abutment. Twelve-Mile Creek has eroded some of the upstream section of the dam and carved into the more resistant, tan saprolite foundation material shown in Figure 58(a). At the time of survey, the breach had a length of more than 31 m along the crest. Dam overtopping evidence was found in the form of wrack and rafted debris wrapped around trees on the dam crest shown in Figure 58(b). All along the downstream slope of the Old Mill Pond Dam, at the time of our reconnaissance visit, the vegetation was lying flat. The overtopping induced shooting discharge on the downstream slope caused scour holes and erosional features downstream of the brick tower built on the downstream slope shown in Figure 58(c). The wrack wrapped around trees, flat lying vegetation and erosional features on the downstream slope indicate that the dam had been completely overtopped along the entire crest length shown in Figure 59(a,b). The overtopping and discharge through the dam breach overwhelmed the two box culverts under the US-1 highway shown in Figure 59(c).

The time sequence and the exact timing of the dam failures at Barr Lake, Gibsons Pond and Old Mill Pond remain to be determined. Old Mill Pond Dam was undergoing repair work on the sinkhole near the penstock. The drained lake was rapidly overfilled by the flood discharge. The rising water level restarted the progressing piping failure, which was exacerbated by the overtopping. The excavation of the penstock at the downstream slope for the repair work facilitated erosion once overtopping occurred. It is likely that seepage along the interface between the right inlet stonemasonry wall and the embankment soil contributed to the weakening of this location. The overtopping flow accelerated the piping failure.

(a)

(b)

Figure 55. Spillway intake with sluice gate and two emergency overflow weir crests at southern (right) abutment of Old Mill Pond Dam: (a) downstream view of intake channel excavated into bedrock with sluice gate almost closed and some debris damming; (b) upstream view (photos: October 12, 2015; N 33.97640°, W 81.22908°).

(a)

(b)

Figure 56. (a) Upstream view of breach with exposed penstock at Old Mill on right; (b) northern (left) abutment of earth fill dam with intake to penstock at Old Mill, which had been partially excavated on downstream side for repair work before flooding event (photos: October 12, 2015; N 33.97683°, W 81.22961°).

(a)

(b)

Figure 57. (a) Downstream view of northern (left) abutment at Old Mill with intake to penstock protected with a trash rack and controlled by a vertical sluice gate; (b) southern side of breach in trapezoidal embankment shaped earth fill dam (photos: October 12, 2015; N 33.97683°, W 81.22961°).

(a)

(b)

(c)

Figure 58. (a) Erosion of upstream slope on Old Mill Pond Dam; (b) wrack wrapped around tree stem at dam crest due to overtopping; (c) scour at the building and erosional features on the downstream slope due to overtopping (photos: October 12, 2015; N 33.97653°, W 81.22921°).

(a)

(b)

(c)

Figure 59. Overtopping evidence downstream: (a) Upstream view of Old Mill Dam overtopped along the entire crest length given erosional features on remnant dam from left to right abutment; (b) downstream view of Twelve-Mile Creek towards US-1; (c) two box culverts under US-1 overwhelmed by flood waters given wrack on road signage due to overtopping (photos: October 12, 2015; N 33.97730°, W 81.22813°).

Once overtopping occurred the Old Mill Pond Dam essentially became an embankment shaped weir. Low-crested dams are widely used standard engineering structures along rivers and waterways. There exist literally innumerable such hydraulic structures all over the world, with the type of construction ranging from primitive boulder and tree-trunk embankments, to sophisticated reinforced concrete and steel units. In all cases, however, a properly functioning overflow structure produces a change from subcritical to supercritical flow, and the kinetic energy of the resulting high-velocity stream must then be dissipated, usually by a hydraulic jump. Much research has been done on the process of energy dissipation, and ways and means to enhance it. Similarly, a great deal of information is available on the potential for scouring and air entrainment of plunging water flows. For free dam overflow, the coefficient of discharge determines the overflow capacity. Spillways with sloping aprons are much less prone to discharge reduction due to submergence than a sharp-crested weir, and free flow equations apply up to about 80% of submergence. For studies relating to discharge characteristics reference is made to standard works, such as those of Horton (1907), Kikkawa et al. (1961), Kindsvater (1964), Hulshing (1968) Lakshmana Rao (1975), Bos (1976), or Miller (1994) among others. Submerged dams as found in floodplains may perform under various regimes, including the plunging jet with a surface roller, and the surface wave and the surface jet, both with a bottom recirculation (Hager, 1992). An early classification of various types of flows is due to Escande (1939). His classification refers to the cylindrical-crested weir, but it applies equally to all other overflow structures. Depending on the tailwater depth, four flow types may occur, in the order of raising tailwater level (first two types shown in Figure 60):

1. Type A-hydraulic jump, with the toe located at or downstream of the dam structure.
2. Type B-plunging flow, with the main flow along the tailwater weir body, and a surface roller.
3. Type C-surface wave flow, with the main flow along the free surface, and a bottom recirculation zone.
4. Type D-surface jet flow, analogous to the surface wave flow, but with a nearly horizontal surface (Rajaratnam and Muralidhar, 1969).

In the case of the Old Mill Pond Dam overtopping produced a supercritical high velocity flow down the downstream slope of the dam as shown in Figure 60(a). Dam erosion caused the breach before a rising tailwater could have reduced the flow velocities in the plunging jet (Figure 60b). The dam was significantly weakened by the excavation of the penstock for maintenance work on the downstream slope essentially removing any overtopping and overflow erosion protection. The coincidence of the maintenance work with a record flood event was unfortunate and unpredictable.

Additionally, soil samples were collected at Old Mill Pond Dam with hand augers from crest to toe shown in Figure 61 and from erosional features shown in Figure 62. An octo-copter drone survey of the Old Mill Dam breach was conducted (Figure 63). The video imagery from the octo-copter drone survey was processed with the drone mapping software Pix4D based on Structure-from-Motion (SfM). A 3-dimensional image of the reconstructed Old Mill Pond Dam breach is shown in Figure 64.

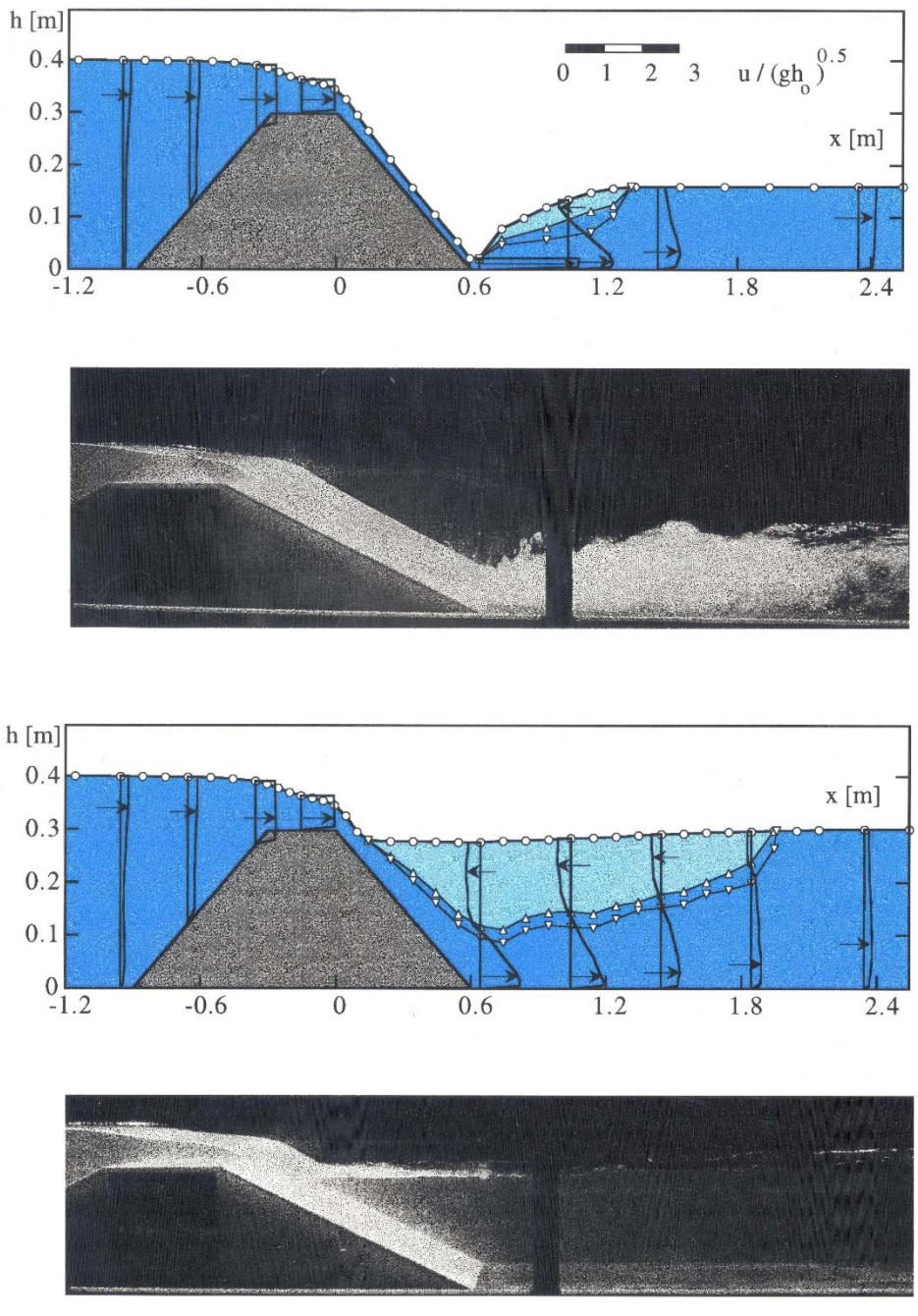


Figure 60. Main overflow patterns for: (a) A-Jump; (b) Plunging Jet. Free surface profiles, mixing layers and measured velocity distributions (upper panels); flow pattern photographs (lower panels) from Fritz and Hager, 1998.

(a)

(b)

Figure 61. Soil samples being collected with hand augers from the crest to the toe of the Old Mill Pond Dam: (a) N 33.97676°, W 81.22950°; (b) N 33.97663°, W 81.22911° (photos: October 12, 2015).

(a)

(b)

Figure 62. Soil sampling in an erosional feature neat the toe of the Old Mill Pond Dam (photos: October 12, 2015; N 33.97663°, W 81.22911°).

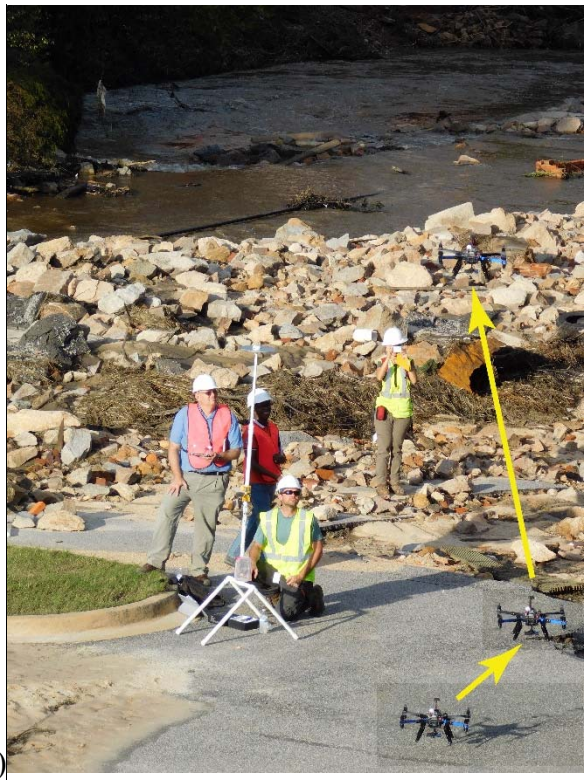
(a)  (b) 

Figure 63. Octo-Copter Drone Survey of the Old Mill Dam breach for SFM-reconstruction: (a) N 33.97663°, W 81.22911°; (b) N 33.97676°, W 81.22950° (photos: October 12, 2015).

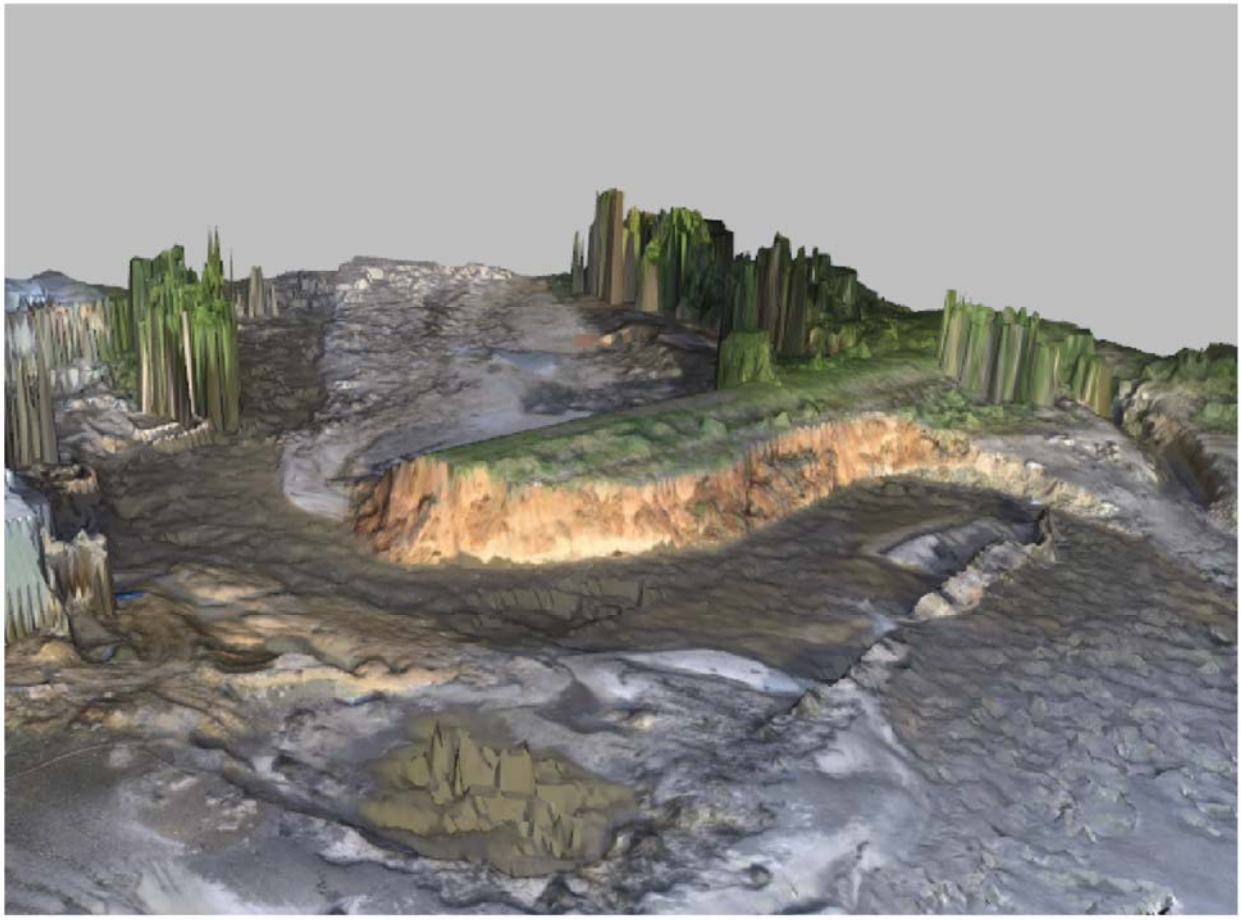


Figure 64. Downstream 3-dimensional view of the Old Mill Pond Dam breach based on SfM-reconstruction from the Octo-Copter Drone Survey (N 33.97683°, W 81.22961°).

6 Congaree River Basin

6.1 Congaree River Watershed, Stages and Discharge

The field sites visited in the Congaree River watershed in Lexington and Richland Counties (SC) are shown in Figure 65. All the sites visited and discussed in this report are along tributaries into the Congaree River. The Saluda Dam successfully regulates streamflow in the Saluda River downstream of Lake Murray since 1930. The Saluda River Basin accounts for approximately one-third of the drainage area for the Congaree River at Columbia station downstream of Columbia Canal after the confluence with the Broad River. Low-head dams on the Broad River have regulated low streamflows since the late 1880s and early 1900s, but flood flows are essentially unregulated. The Broad River Basin accounts for approximately two-thirds of the drainage area for the Congaree River at Columbia station downstream of Columbia Canal after the confluence of the Saluda River. The Congaree River flows south and joins the Wateree River at Lake Marion. From there the Santee River carries the water to the Atlantic Ocean.

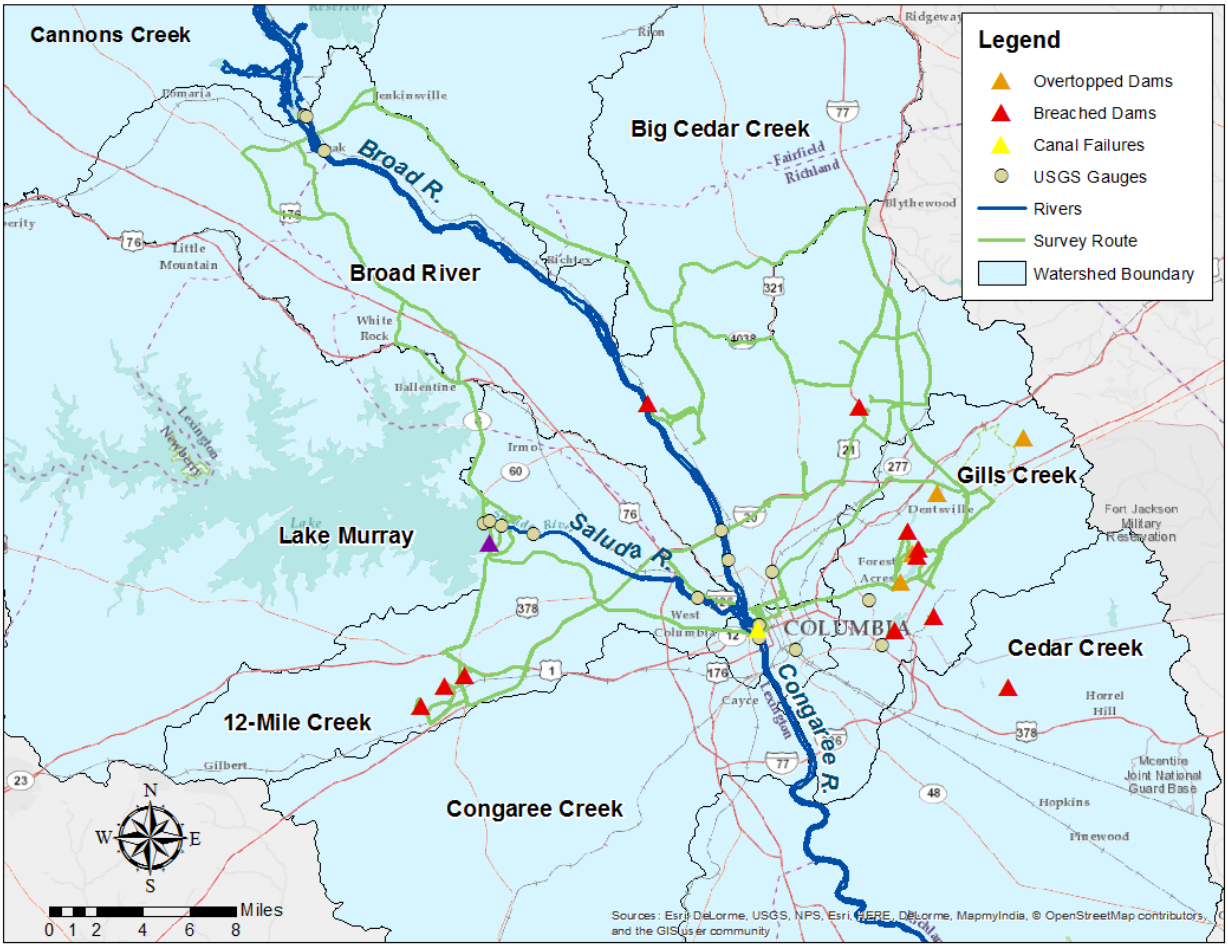
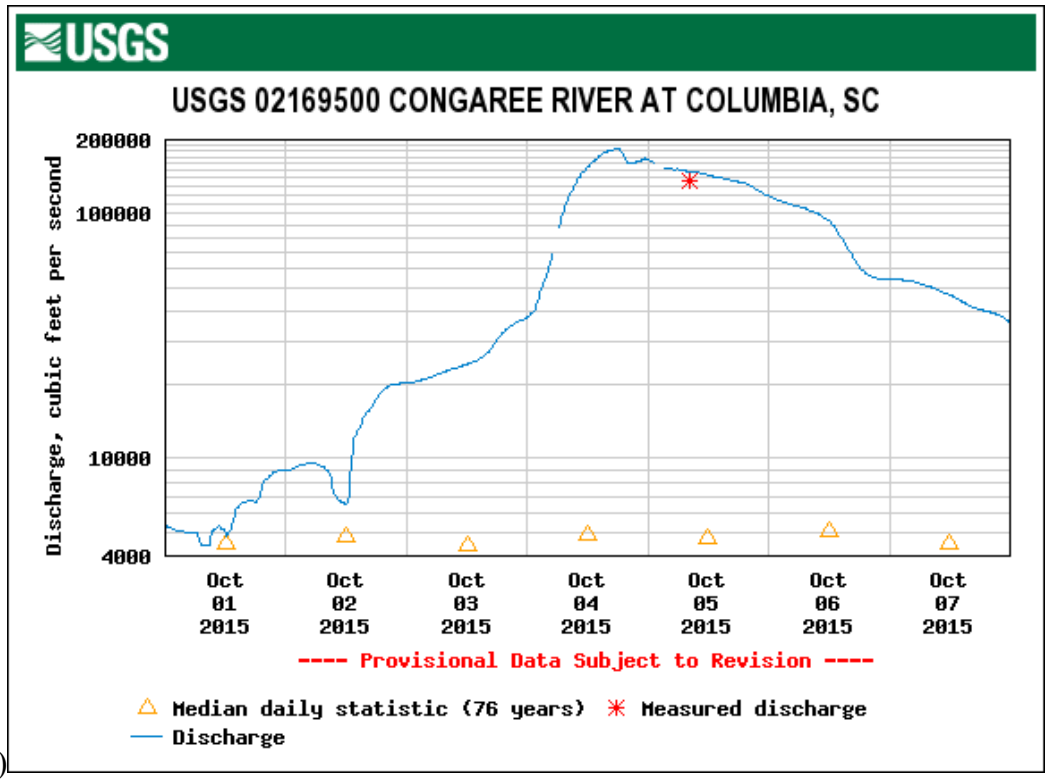


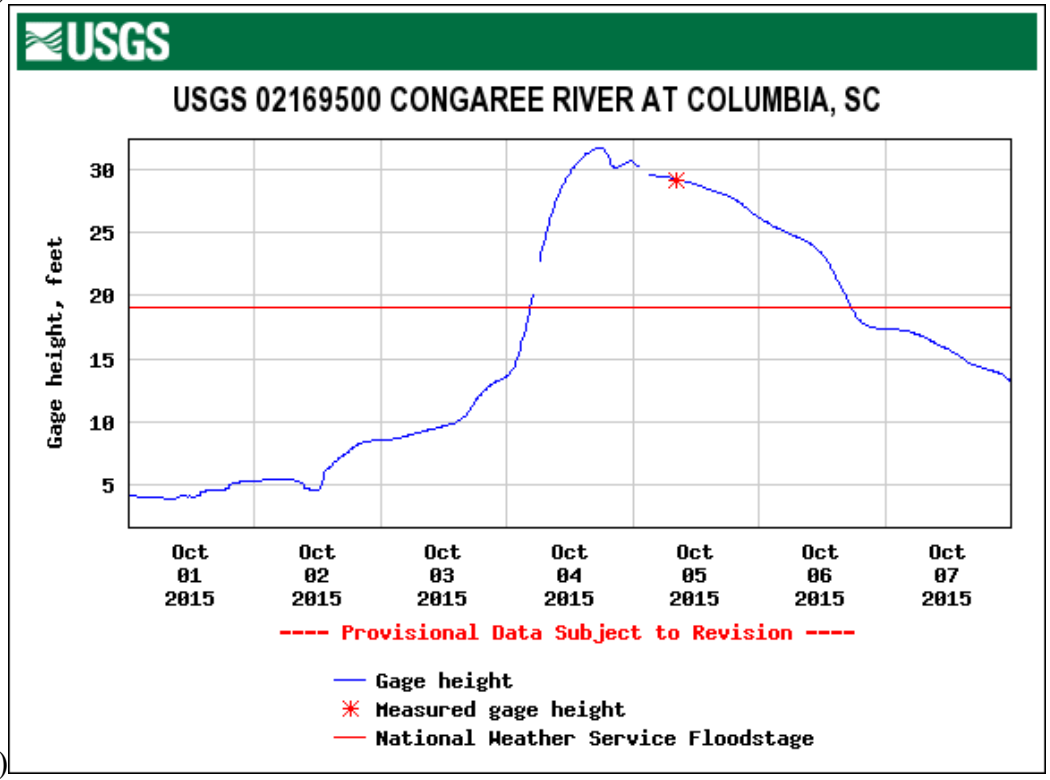
Figure 65. Congaree River watershed is characterized by confluence of the Broad and Saluda Rivers. The Columbia metropolitan area indicates an overlaid GPS track with distressed and breached dams covered during the GEER field survey from October 11 to 14, 2015.

Congaree River USGS gauge 02169500 at Columbia is located 1.9 km downstream of confluence of the Broad and Saluda Rivers and 300 m downstream of the Gervais Street Bridge and the Columbia Canal tailwater. The Congaree River USGS gauge 02169500 recording is shown in Figure 66. The Congaree River gauge at Columbia peaks with a discharge of 184,000 cfs and a corresponding peak stage of 31.71 ft (144.73 ft above NGVD29) at 1745 EST on October 4, 2015. The Congaree River gauge at Columbia has one of the longest records of annual peak flows of the USGS gauges in South Carolina, with systematic records of annual peak streamflow from 1892 to present. Additional information for a flood in 1852 is available; therefore, the gauge locations is of great value in placing the October 2015 flood in context to other historical floods. Conrads et al. (2008) assessed the impact of the Saluda Dam on the flood frequency of flows in the Congaree River. The 1-percent chance flood (also referred to as the 100-year flood) is likely reduced by about 18 percent due to the Saluda River regulation since the construction of the Saluda Dam in 1930. Consequently, comparison of major floods on the Congaree River after construction of the Saluda Dam with those prior to the dam construction provides insight to historical floods. The Congaree River at Columbia peaked at 185,000 ft3/s at a peak stage of 31.8 ft on October 4, 2015. In comparison with the historical flood record, the October 4, 2015 discharge peak of 184,000 cfs at a peak stage of 31.71 ft ranks eighth in a 124 year record. The peak in the historical record occurred on August 27, 1908 with a peak discharge of 364,000 cfs at a peak stage of 39.8 ft. Hence the 1908 flood almost doubled the 2015 flood discharge of the Congaree River at Columbia, SC. The last flood since the construction of the Saluda dam to exceed the October 4, 2015 peak at the Congaree River at Columbia site occurred on April 8, 1936, when the river peaked at 231,000 cfs at a peak stage of 33.3 ft. The more comparable 1936 flood exceeded the 2015 flood discharge in the Congaree River at Columbia by 25%. Hence the October 2015 floods were not unprecedented.

Musser et al. (2016, USGS) present the high-water-mark (HWM) data collected along with the flood peak magnitudes, and flood-inundation products generated by the USGS in support of the Federal Emergency Management Agency (FEMA) response and recovery operations following the October 2015 flood event in South Carolina. The flood-inundation map depicting estimates of the areal extent and depth of flooding along the Saluda, Broad and Congaree Rivers is shown Figure 67.



(a)



(b)

Figure 66. Congaree River USGS gauge 02169500 located 1.9 km downstream of confluence of the Broad and Saluda Rivers and 300 m downstream of the Gervais Street Bridge and the Columbia Canal tailwater: (a) discharge with peak of 184,000 cfs at 1745 EST on October 4, 2015; (b) stage with peak of 31.71 ft corresponding to 144.73 ft above NGVD29 at 1745 EST on October 4, 2015 (waterdata.usgs.gov/nwis).

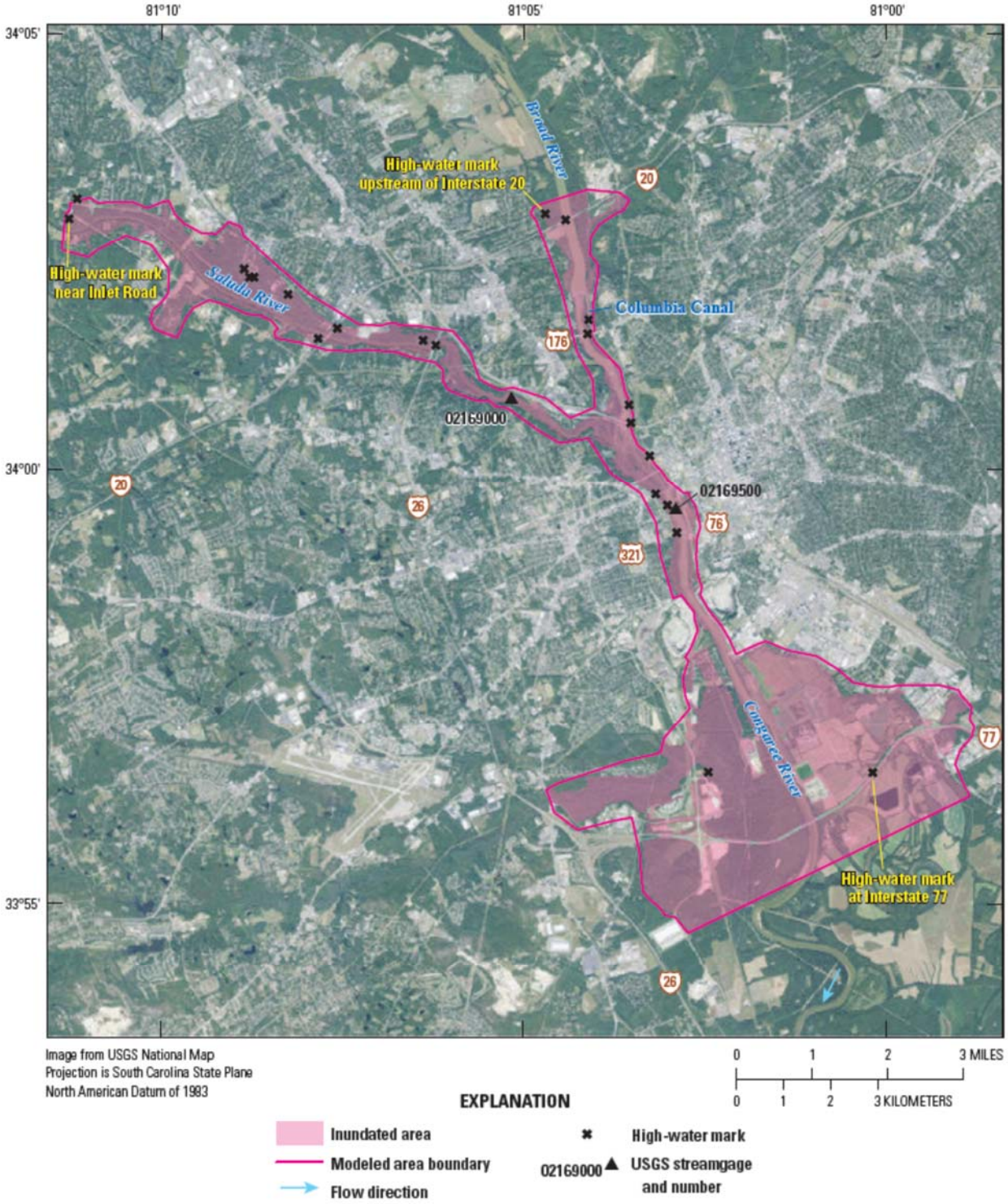


Figure 67. Flood-inundation map of Saluda, Broad, and Congaree Rivers near Columbia, South Carolina, October 1–5, 2015 (Musser et al, 2016, USGS).

(a) 

(b) 

Figure 68. Aerial views of the Congaree River flood plain south of Columbia at the I-77 Bridge: (a) Northward (upriver) view with Columbia in the background; (b) southward (downstream) view with a meandering river in October 6, 2015 photos from Congaree Riverkeeper (www.congareeriverkeeper.org via Twitter and FB; N 33.93222°, W 81.01736°).

7 Gills Creek, Columbia, SC

7.1 Gills Creek Watershed, Stages and Discharge

The field sites visited in the Gills Creek watershed in Richland County (SC) are shown in Figure 69. The sites visited along the Gills Creek include: Cary's Lake Dam, Rockbridge Bridge Failure, Spring Lake Dam, Upper and Lower Rockyford Lake Dams, and Forest Lake Dam. The Gills Creek Watershed is the main watershed flowing through the City of Columbia, and is among the largest urban impaired watersheds in South Carolina with 75 square miles (193 square km) in the central part of Richland County. The watershed reaches from Sesquicentennial State Park to the Congaree River. It is directly southeast of the Crane Creek Watershed with the Lake Elizabeth dam failure discussed earlier in this report. The Gills Creek watershed includes most of Columbia, all of Arcadia Lakes and Forest Acres. The upper reaches of the Gills Creek are split into the Upper Gills Creek and Jackson Creek. The Gills Creek flows through Columbia and enters the Congaree River upstream of the Congaree National Park some 10 km downstream of downtown Columbia.

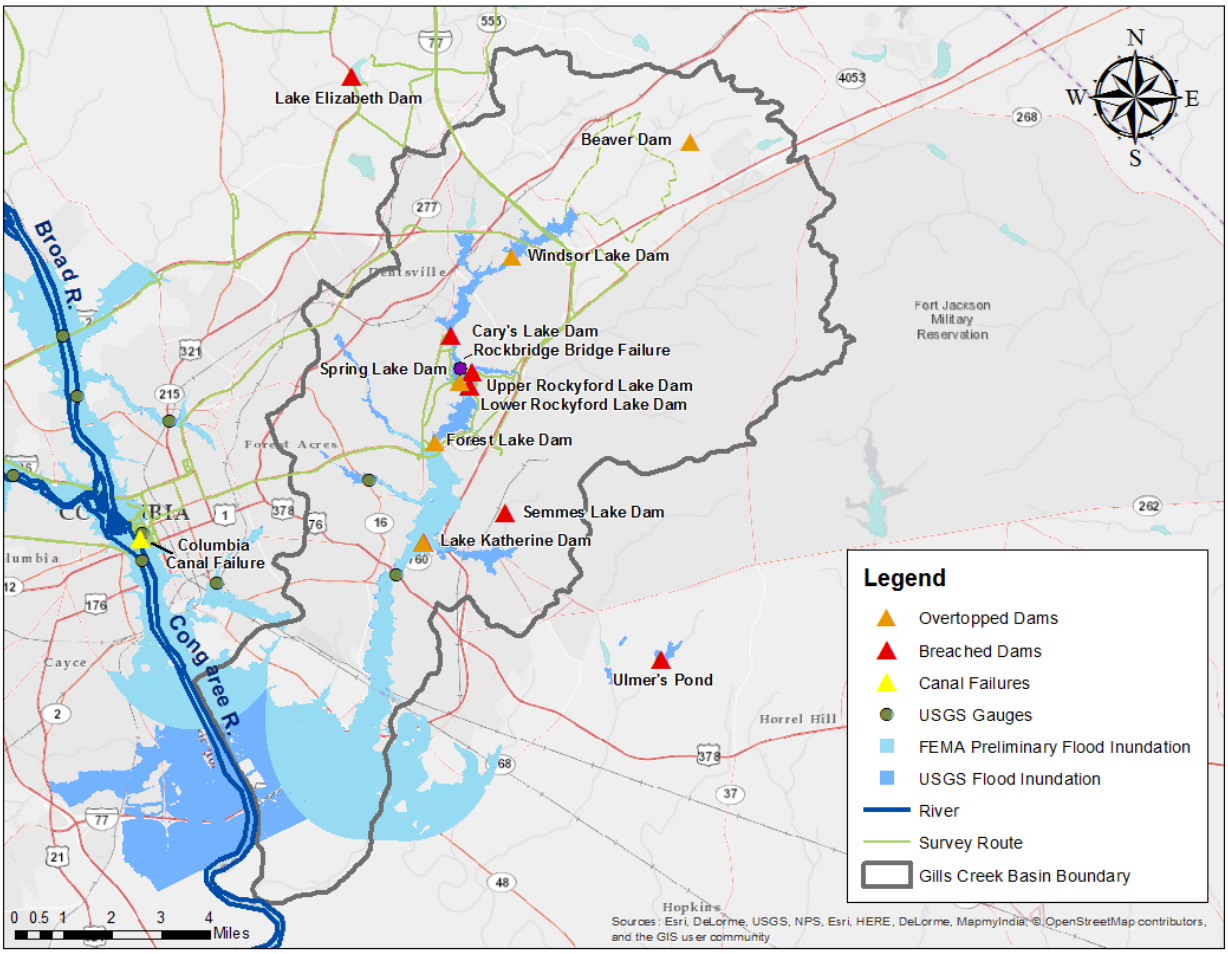
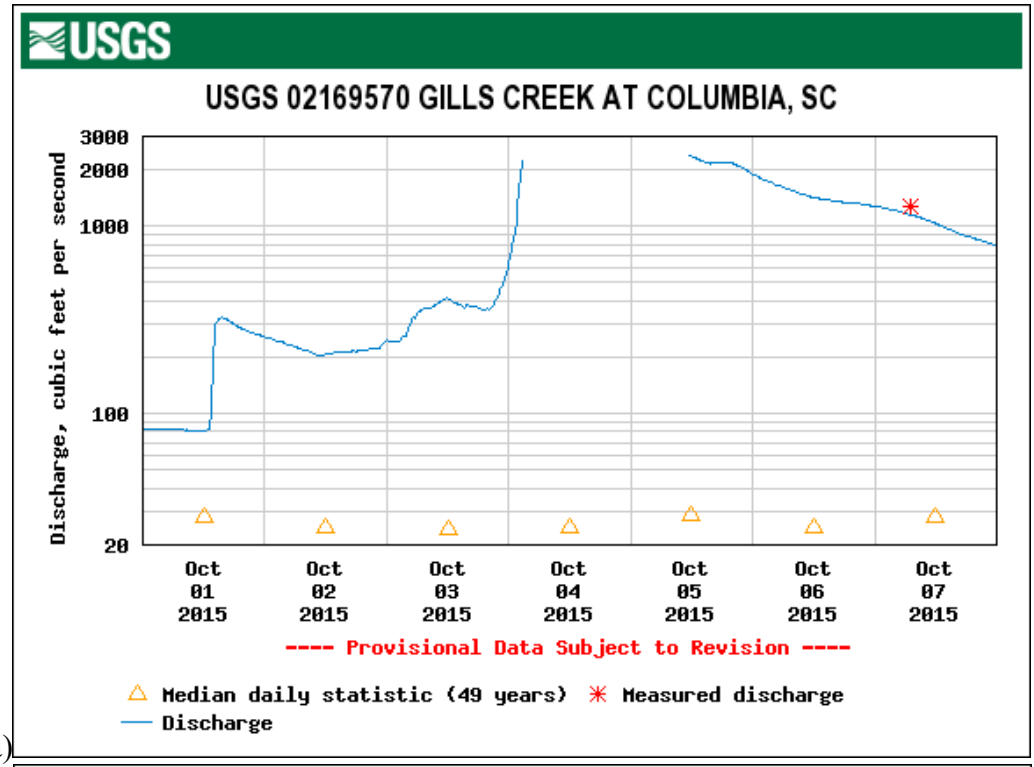


Figure 69. Gills Creek watershed boundary with the visited sites along the Gills Creek: Cary's Lake Dam, Rockbridge Bridge Failure, Spring Lake Dam, Upper and Lower Rockyford Lake Dams, and Forest Lake Dam. The east side of the Columbia metropolitan with an overlaid GPS track with distressed and breached dams covered during the GEER field survey from October 11 to 14, 2015.

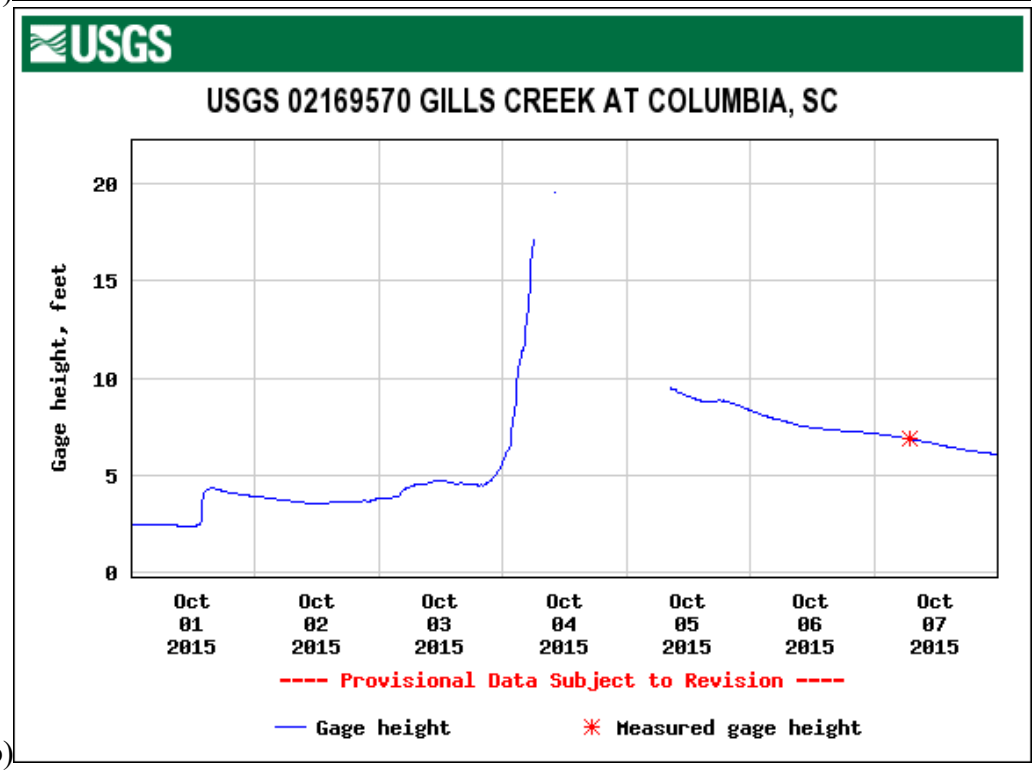
In the Gills Creek watershed 3 dams were breached out of 23 dams regulated by S.C.-DHEC. Cary's Lake Dam, Upper and Lower Rockyford Lake Dams were breached, while many more dams were overtopped. The GEER team visited the 3 breached dams in the Gills Creek watershed, which were all among the 17 dams classified as high hazard C1 by S.C.-DHEC.

The Gills Creek USGS gauge 02169570 is located at the US-378 Bridge crossing Gills Creek 1 km downstream of Lake Katherine. The gauge provides no discharge data for the critical timespan from 2:30 EST October 4 until 11:30 EST October 5, 2015 (Figure 70a). The stage data is also intermittent with a last recorded data point of 17.08 ft (15.46 ft NGVD 29) at 6:00 EST on October 4, 2015, a single recorded data point of 19.57 ft (156.95 ft NGVD 29) at 10:00 EST on October 4, 2015 and no data thereafter until 08:30 EST October 5, 2015 (Figure 70b). Hence the flooding peaked in the morning of October 4, 2015.

Musser et al. (2016, USGS) present the high-water-mark (HWM) data collected along with the flood peak magnitudes, and flood-inundation products generated by the USGS in support of the Federal Emergency Management Agency (FEMA) response and recovery operations following the October 2015 flood event in South Carolina. The flood-inundation map depicting estimates of the areal extent and depth of flooding along the Gills Creek is shown Figure 71.



(a)



(b)

Figure 70. Gills Creek USGS gauge 02169570 located at the US-378 Bridge over Gills Creek 1 km downstream of Lake Katherine: (a) discharge with no data from 2:30 EST October 4 until 11:30 EST October 5, 2015; (b) stage with a last recorded data point of 17.08 ft (15.46 ft NGVD 29) at 6:00 EST on October 4, 2015, a single recorded data point of 19.57 ft (156.95 ft NGVD 29) at 10:00 EST on October 4, 2015 and no data thereafter until 08:30 EST October 5, 2015 (waterdata.usgs.gov/nwis).

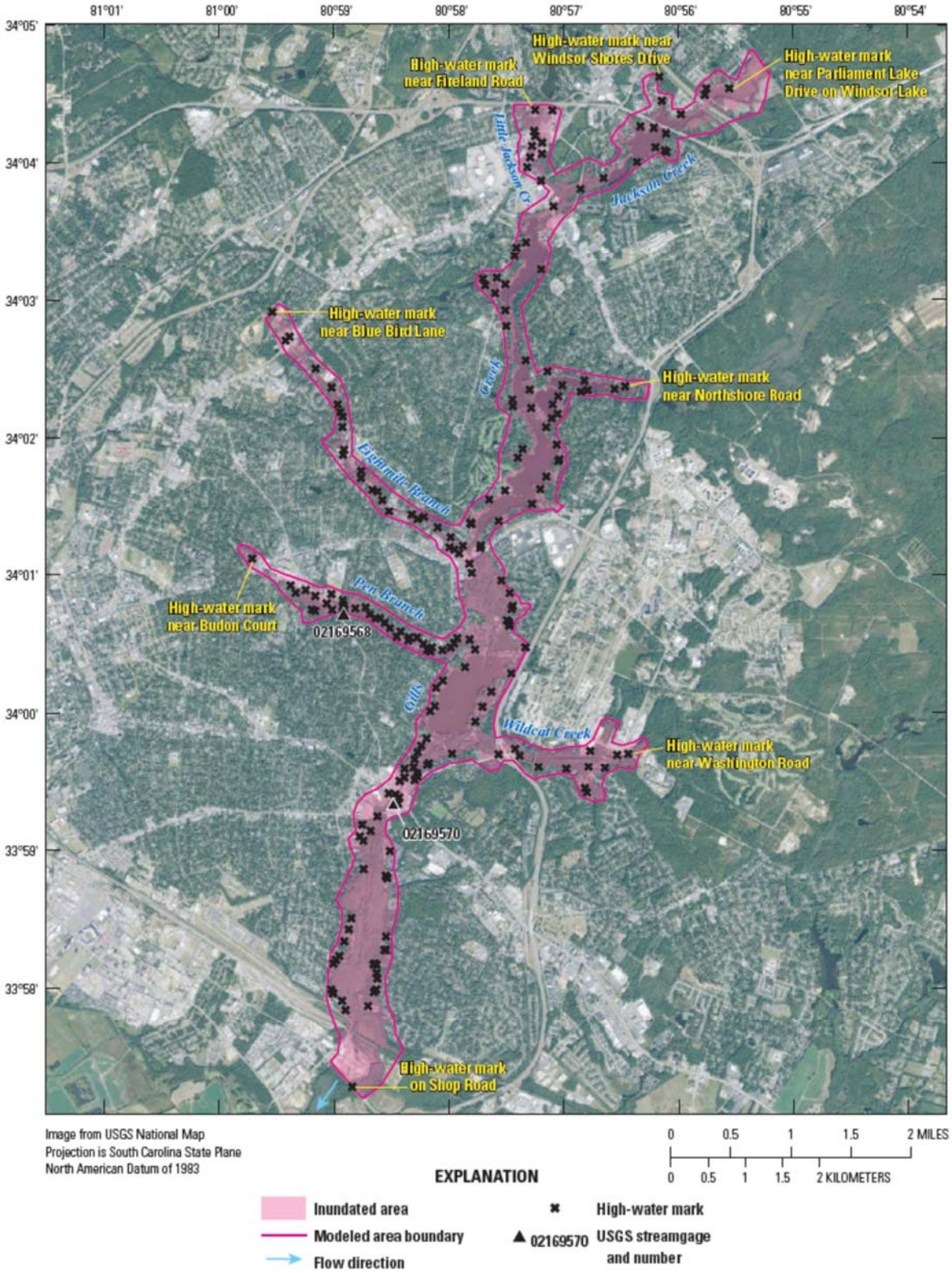


Figure 71. Flood-inundation map of Gills Creek in Columbia, South Carolina, October 1–5, 2015 (Musser et al, 2016, USGS).

7.2 Cary's Lake Dam on Jackson Creek (Gills Creek tributary)

Cary's Lake Dam is an earth fill structure impounding Jackson Creek (a Gills Creek tributary) near the intersection of Arcadia Lake Drive and Roadway S-40-1575 in Columbia's Arcadia Lakes neighborhood in Richland County, SC. Cary's Lake Dam is located less than 3 km downstream of the Windsor Lake Dam and 9 km downstream of the Beaver Dam. Cary's Lake Dam is 0.4 km upstream of the Rockbridge Road Bridge and 1.3 km upstream of the Spring Lake Dam marking the confluence of the Jackson Creek into the Gills Creek at Forest Lake. The Cary Lake is the third main reservoir on Jackson Creek. The Jackson Creek watershed bounded by the confluence with the Gills Creek downstream of Spring Lake Dam includes 19 square miles (50 km^2). The Jackson Creek watershed draining through Cary's Lake Dam includes more than 95% of the total Jackson Creek watershed given the short 1.3 km distance from the Cary's Lake Dam to Spring Lake Dam. Cary Lake is a 56 acre (0.23 km^2) artificial lake with a shallow water depth of up to 13 feet (4 m) shown in Figure 72. There are 48 single family homes on the lake and 4 vacant lots. The lake bed is owned by Cary Lake Homeowner's Association (CLHA). An early dam was located in the same place and was owned by a local family, but the dam failed in 1983 resulting in a muddy plain. In 1987 the not-for-profit homeowner's association (CLHA) was formed and a new, replacement dam built. The dam is 350 ft (106.68 m) long and 19.8 ft (6.04 m) high. Roadway S-40-1575 crosses over the top of the dam, making a 90-degree bend onto the left (eastern) abutment. The dam includes a larger uncontrolled spillway adjacent to the right abutment 2 m below the dam crest, a low-level bottom outlet located left of the dam's center, and a smaller uncontrolled spillway adjacent to the left abutment shown in Figure 73. The water discharges over an unregulated sharp crested box weir intake to the bottom outlet, which maintains the normal lake level. The 12' x 12' drop box is 4 m tall and discharges into a 6.5' x 6.5' box outlet. A sluice gate at the bottom of the box intake allows to lower the lake level by 6 ft during maintenance shown in Figure 74.

Cary's Lake Dam is classified by S.C.-DHEC into category C1, which means that failure may cause loss of life or serious damage to infrastructure. Cary's Lake Dam (D-0026) underwent routine inspection on December 30, 2014 by the South Carolina Department of Health and Environmental Control (S.C.-DHEC). It was concluded that the dam is in satisfactory condition.

The dam breached at the location of the left (eastern) spillway as shown in Figure 75(a) as the breach is forming in a photo without an exact time stamp. Overtopping occurred for a short period of time based on the debris at the tilted road marker sign near the center of the dam. The solid concrete wall with small drainage openings on top of the bridge crossing the right spillway would limit initial overtopping at this location. The later photo uploaded at 12:07pm on October 4, 2015 by the Gills Creek Watershed Association shows a fully developed breach with a significantly lowered outflow water level shown in Figure 75(b). The water level continued to drop in the following hours with flood discharge through the breach and the right (western) spillway at 2:51pm shown in Figure 76. The road way collapsed on a 47 m section or almost half the dam crest length. The washed away section formed a 36 m long open breach, while the remnants of an 11 m long collapsed road way segment remained dislocated.

(a)

(b)

Figure 72. Cary's Lake Dam aerial upstream (northward) views: (a) full lake with flood waters discharging over both spillways on September 10, 2008; (b) lake level lowered by 6 feet for maintenance highlights the reservoir sedimentation in February 2012 (photos: Elliott Powell, Gills Creek Watershed Association www.gillscreekwatershed.org; N 34.04866°, W 80.95764°).

(a)

(b)

Figure 73. Cary's Lake Dam with flood waters discharging over both spillways in aerial views on January 16, 2014. Note design differences between the concrete lined western (right) spillway with a trapezoidal cross-section and the concrete lined slab on the eastern (left) spillway. The regular box weir intake to the bottom outlet is centered between the two spillways. (a) Eastward view; (b) southward view from lake towards downstream (photos: Gills Creek Watershed Association www.gillscreekwatershed.org; N 34.04866°, W 80.95764°).

(a)

(b)

(c)

Figure 74. Cary's Lake Dam: (a) aerial view during maintenance with a lake level lowered by 6 feet highlighting the drop box intake with the bottom outlet and the two spillways in February 2014. Note the concrete armored western (right) spillway with a trapezoidal cross-section and the less armored eastern (left) spillway (photo: Gills Creek Watershed Association www.gillscreekwatershed.org). (b) Unregulated sharp crested box weir intake to maintain normal lake level. (c) Sluice gate on the box intake allows to lower the lake level for maintenance and flushing (photos from Cary Lake HA via: http://slideplayer.com/slide/4326846/; N 34.04866°, W 80.95764°).

(a)

(b)

Figure 75. Cary's Lake Dam breach on Sunday October 4, 2015: (a) Breach forming at location of left (eastern) spillway (exact time of photo remains to be determined as via Pinterest); (b) Fully formed breach at 12:07pm with significantly lowered reservoir level due to the downstream propagating dam break wave (photo: Gills Creek Watershed Association www.gillscreekwatershed.org; N 34.04866°, W 80.95764°).

(a)

(b)

Figure 76. Cary's Lake Dam breach on Sunday October 4, 2015: (a) Westward view of the fully formed breach with the intact right (western) spillway in the background at 2:51pm with a significantly lowered reservoir water level; (b) downstream view with the breach at the failed left (eastern) spillway at 2:51pm; (photos: Gills Creek Watershed Association www.gillscreekwatershed.org; N 34.04866°, W 80.95764°).

The western and larger spillway located on the right abutment and to the right of the breach in flow direction is lined with concrete and 18 m wide at the roadway crossing as shown in Figure 77. The roadway bridge over the right spillway is supported in the middle by three rows of timber columns. Two logs wedged between the columns shown in Figure 77(b), indicating significant flows down the larger spillway without significant debris damming as the overflows remained wide open. The roadway pavement has been pulled apart 10 to 12 cm at the eastern approach to this bridge crossing corresponding to the right end of the bridge (Figure 77b). Erosion caused by overtopping for a short period of time created a gap between the concrete spillway and the earth fill at the eastern approach to the bridge. The remains of the bottom outlet structure are shown in Figure 78(a). The low level box outlet with a 6.5' x 6.5' cross-section was originally about 18 m long. The joint between the last two segments of conduit is offset vertically 30-60 cm, due to settlement cause by scour of supporting fill. The trapezoidal-shaped outlet has not moved from its original position. The overturned 12' x 12' drop box inlet is shown in Figure 78(b). The drop box has been carried 5 m from its original position and flipped upside down before coming to rest left of the conduit. The originally upstream facing sluice gate to open the bottom outlet is facing downstream. The steel sluice gate is closed.

The smaller left spillway was confined laterally by rock walls and lined with unreinforced concrete slabs that rest directly on earth fill and saprolite foundation material shown in Figure 79. The left spillway was about 6 m wide at the roadway crossing, which is supported by short, square concrete columns extending out of the spillway slabs, but not into the foundation soils. The roadway crossing and underlying spillway dropped vertically 0.5 to 1.0 m on an 11 m long segment due to scour and undercutting beneath the spillway. Parts of the spillway right wall has also been carried away by overflow flood discharge. Reddish fill material is exposed upstream of the roadway. Reddish brown to olive brown to whitish gray shale-like saprolite foundation materials is exposed beneath the roadway and the downstream spillway. Two close-up photographs of the exposed saprolite foundation material are shown in Figure 80.

Soil samples were collected with hand augers throughout the failure surface towards the larger spillway on the right abutment (Figure 81). The earth fill making up the dam was zoned as shown in Figure 82. Select locations of soil sampling are shown in Figure 82(b). The upstream zone was formed of medium stiff, light reddish brown clayey sand with angular pieces of white clay (Sample #5) to medium stiff white to pinkish gray silty clay with some sand (Sample #4). The white clay was likely brought to the site from a kaolin mine located about 17 km northeast of the site, just off of Interstate I-20. Flood discharge over this more erosion-resistant clay left it without vegetation and moderately scoured. The center and part of the downstream zones were formed of yellowish red silty sand with some gravel and clumps of white clay (Sample #1). This material appears to be a mixture of local reddish residual soils and imported white kaolin clay. A second downstream zone was formed of light yellowish brown silty gravel with some sand and clay (Sample #2) to soft, light olive brown sandy silt (Sample #3).

An octo-copter drone survey of Cary's Lake Dam breach was conducted (Figure 83). The video imagery from the octo-copter drone survey was processed with the drone mapping software Pix4D based on Structure-from-Motion (SfM). A 3-dimensional image of the reconstructed Cary's Lake Dam breach is shown in Figure 84.

(a)

(b)

Figure 77. Cary's Lake Dam breach: (a) Upstream view of dam breach with remnants of low level box culvert, trapezoidal outlet structure; (b) upstream view of large western spillway (right in flow direction, left in image) with concrete lining and roadway bridge (photos: October 13, 2015; N 34.04866°, W 80.95764°).

(a)

(b)

Figure 78. Cary's Lake Dam breach: (a) Low level bottom 6.5' x 6.5' box outlet with overturned drop box inlet; (b) upstream view of the overturned 12' x 12' drop box inlet with a closed bottom outlet sluice gate facing downstream, which was originally on upstream side (photos: October 13, 2015; N 34.04866°, W 80.95764°).

(a)

(b)

Figure 79. Cary's Lake Dam breach with collapsed road crossing over the damaged and smaller spillway at the eastern or left abutment in the background: (a) downstream and (b) upstream view (photos: October 13, 2015; N 34.04866°, W 80.95764°).

(a)

(b)

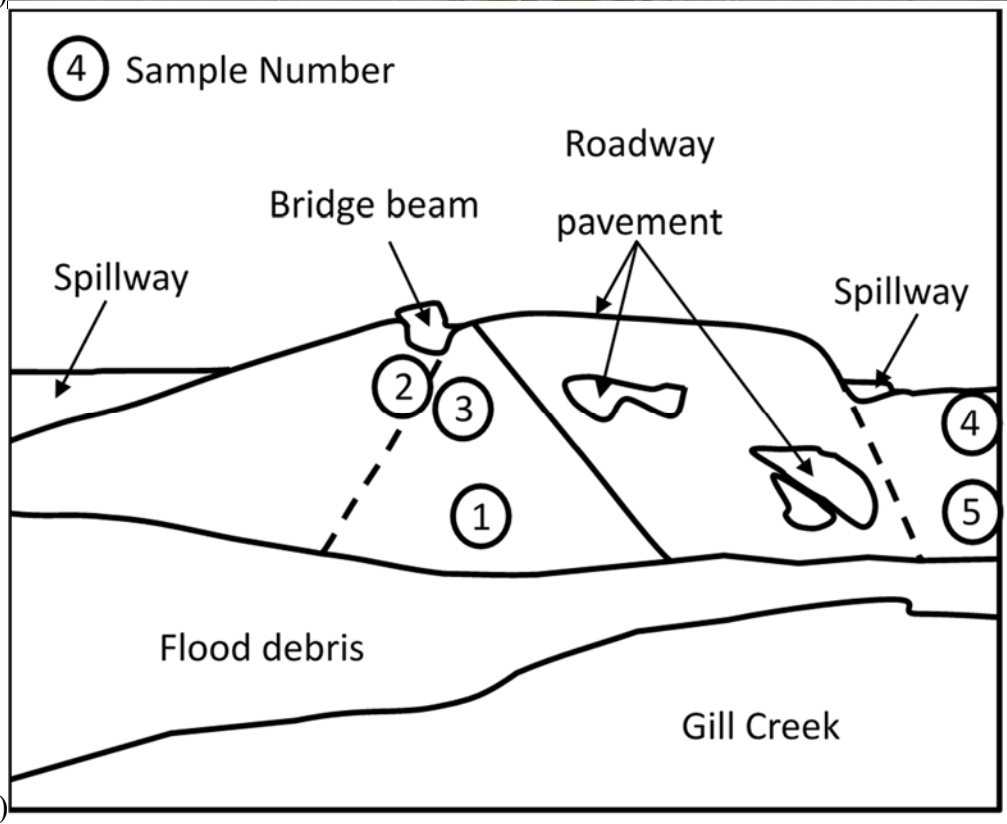
Figure 80. Cary's Lake Dam breach: Saprolite foundation soils exposed at the left abutment below the smaller spillway (photos: October 13, 2015; N 34.04866°, W 80.95764°).

(a)

(b)

Figure 81. Cary's Lake Dam breach: Soil samples collection with hand augers from below the crest to the toe of the right abutment failure surface (photos: October 13, 2015; N 34.04866°, W 80.95764°).

(a)



(b)

Figure 82. Cary's Lake Dam breach: (a) Exposed earth fill making up the dam taken facing the large spillway and right abutment; (b) corresponding interpretive sketch with soil sampling locations (photo: October 13, 2015; N 34.04866°, W 80.95764°).

Figure 83. Octo-copter drone survey of the Cary's Lake Dam breach for SFM-reconstruction (photos: October 13, 2015; N 34.04866°, W 80.95764°).

Figure 84. Downstream 3-dimensional view of the Cary's Lake Dam breach based on SfM-reconstruction from the octo-copter drone survey (N 34.04866°, W 80.95764°).

Cary's Lake Dam failure is located some 2.9 km downstream of Windsor Lake Dam (D-0571), which sustained damage, but did neither breach nor drain Windsor Lake during the flood event. The early reports of a Windsor Lake Dam failure turned out to be false. However, the small and unregulated Pine Tree Lake Dam located 0.5 km downstream of Windsor Lake Dam did breach. Whether the cascading dam break wave from the Pine Tree Lake Dam failure correlates with the breach of Cary's Lake Dam located 2.4 km downstream could not be determined. Overtopping of Cary's Lake Dam occurred based on the debris and tilted sign on top of the road near the center of the dam and the scour on the edge of the larger spillway. The breach likely started with overtopping erosion along the right edge of the smaller spillway to the left of the dam center. The breach forming was accelerated by simultaneous and/or subsequent seepage and erosion of soil supporting the smaller left spillway at the roadway crossing. The piping and erosion led to the collapse of the unreinforced concrete spillway along with the road crossing and to the breakage of the unreinforced concrete spillway protection wall. As flood waters flowed over the collapsed spillway, earth fill was quickly eroded and carried away. The resting position of the overturned inlet gate box and the scour pattern left in the upstream clay fill provide additional support for breaching flows directed towards the smaller spillway. This corresponds with the photo of the

breach forming at the location of the smaller left spillway shown in Figure 75(a). Aerial views of Jackson Creek with the flushed out Cary's Lake upstream and the Rockbridge Road Bridge downstream of Cary's Lake Dam breach are shown in Figure 85.

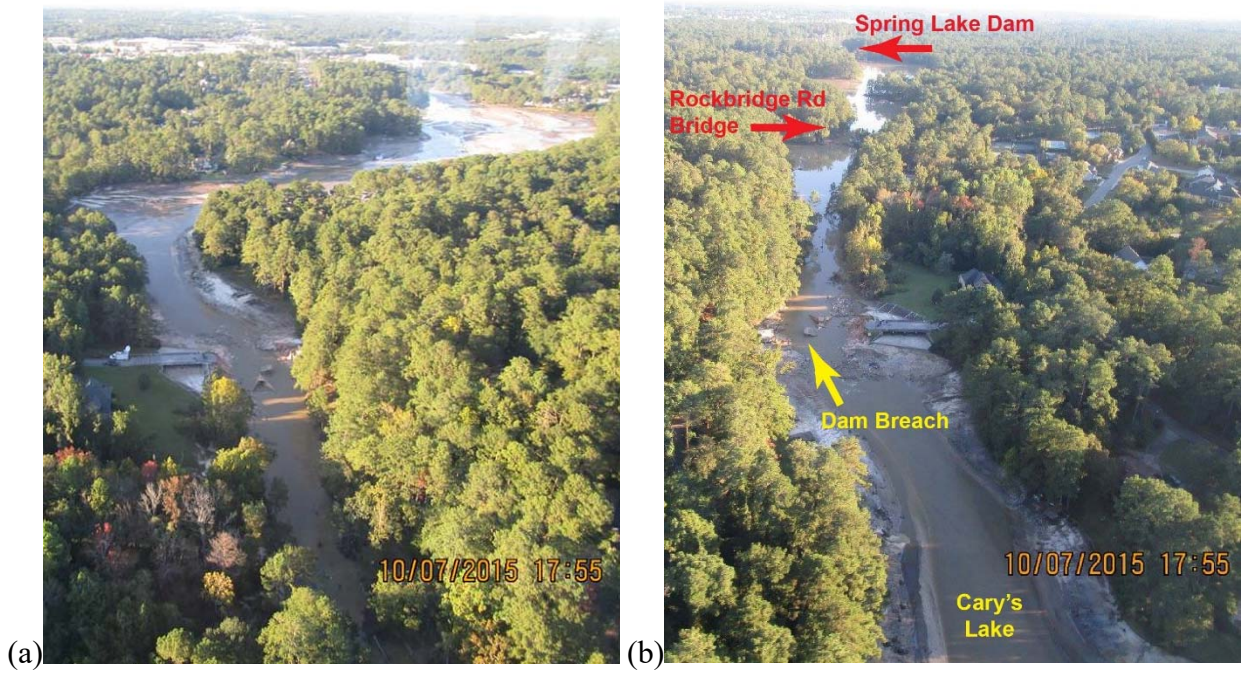


Figure 85. Cary's Lake Dam breach in aerial views on October 7, 2015: (a) upstream (northward) view of the breached dam with intact right (western) spillway and empty Cary Lake bed in the background; (b) downstream (southward) view of the breached dam with intact right (western) spillway and Jackson Creek with the washed away Rockbridge Rd Bridge and Spring Lake in the background (photos from Gills Creek Watershed Association via: www.facebook.com/GillsCreekWatershedAssociation; N 34.04866°, W 80.95764°).

7.3 Rockbridge Road Bridge on Jackson Creek (Gills Creek tributary)

Rockbridge Road Bridge crosses Jackson Creek 400 m downstream of the Cary's Lake Dam breach. Rockbridge Road Bridge was overtopped, washed out and completely destroyed by the flood discharge as shown in Figure 86. The flood discharge overtopped the road way and bridge deck by at least 0.7 m based on high-water marks in trees along the right bridge abutment. The overflow carried the bridge away over the entire Jackson Creek width leaving a 24 m long gap in Rockbridge Road. The bridge was rebuilt and reopened in June 2016.

(a)

(b)

Figure 86. Rockbridge Road Bridge washed away: (a) upstream view from the right (western) abutment; (b) wash out on the right bridge abutment (photos: October 13, 2015; N 34.04516°, W 80.95709°).

7.4 Spring Lake Dam on Jackson Creek (Gills Creek tributary)

Spring Lake Dam is an earth fill structure impounding Jackson Creek (a Gills Creek tributary) in the Forest Acres municipality of the City of Columbia in Richland County, SC. Spring Lake Dam on Jackson Creek is located 1.3 km downstream of the Cary's Lake Dam breach. Spring Lake Dam is directly upstream of the confluence of the Jackson Creek into the Gills Creek at Forest Lake. The Spring Lake is the fourth main reservoir on Jackson Creek. The Jackson Creek watershed bounded by the confluence with the Gills Creek downstream of Spring Lake Dam includes 19 square miles (50 km^2). The dam is about 160 m long and 5 m high. Shorebrook Drive (Roadway S-1725) crosses over the top of the dam. The dam includes a large uncontrolled spillway adjacent to the left abutment, a low-level bottom outlet located right of the dam's center. Spring Lake Dam (D-0025) is classified by S.C.-DHEC into category C1, which means that failure may cause loss of life or serious damage to infrastructure.

The roadway on Spring Lake Dam was overtopped by about 1m based on high watermarks in the vegetation along the lakeside of the dam. The overflow severely damaged the concrete spillway due to scouring at downstream interfaces between the concrete and earth fill shown in Figure 87. The overtopping flood discharge eroded the downstream embankment of the earthen dam up to the roadway shown in Figure 88(a). A Toyota Tacoma pick-up truck attempted to drive through the discharging floodwaters overflowing the roadway and was washed off the road. Fortunately the vehicle was stopped by trees 20 m downstream as shown in Figure 88(b). The driver was stuck in the vehicle for four hours until he could be rescued. This serves as a warning not to drive through rushing flood discharges even when water depths appear small.

(a)

(b)

Figure 87. Spring Lake Dam: (a,b) Damage to concrete spillway and embankment dam (photos: October 13, 2015; N 34.03708°, W 80.95531°).

(a)

(b)

Figure 88. Spring Lake Dam: (a) Massive erosion on the downstream embankment due to overtopping the roadway; (b) pick-up truck (Toyota Tacoma) washed off the road by flood waters, while attempting to drive across the dam, was stopped by trees downstream (photos: October 13, 2015; N 34.03708°, W 80.95531°).

7.5 Forest Lake Dam on Gills Creek

Forest Lake Dam is an earth fill structure impounding Gills Creek in the Forest Acres municipality of the City of Columbia in Richland County, SC. Forest Lake Dam on Gills Creek is located 1.8 km downstream of the breached Rockyford Dam on Gills Creek and 1.9 km downstream of the overtopped Spring Lake Dam on Jackson Creek. Forest Lake Dam is the first dam downstream of the confluence of the Jackson Creek into the Gills Creek at Forest Lake. The total Gills Creek watershed bounded by the Forest Lake Dam includes 43.77 square miles (113.44 km^2). The dam is about 183 m long and 7 m high. The embankment dam includes a gated spillway in the center and an uncontrolled concrete chute spillway on the left abutment. The embankment dam is armored with articulating block mats that increase resistance to overtopping induced erosion. Forest Lake Dam (D-4434) is classified by S.C.-DHEC into category C1, which means that failure may cause loss of life or serious damage to infrastructure.

The Forest Lake Dam was overtopped on October 4, 2015 by the combined flood discharges from Jackson Creek and Gills Creek as shown in Figure 89. The flood discharge in Jackson Creek was amplified by the cascading dam breaks and dam break waves. The dam breaks upstream in Gills Creek occurred later on October 5, 2015. Forest Lake Dam was overtopped by up to 1m based on high watermarks in the railings and fences along the dam crest as shown Figure 90. The overflow also washed a shallow draft pontoon boat over the embankment dam as shown in Figure 91(a). The articulating bag mats served as overtopping protection and prevented erosion on the embankment dam itself. Incipient erosion was apparent at the toe of the embankment dam at the transition from the articulated bag mat armor to downstream soil as shown in Figure 91(b). Essentially Forest Lake Dam serves as an example of how slope armor can prevent or significantly reduce erosion and damage due overtopping of earthen dams.

(a)

(b)

Figure 89. Forest Lake Dam overtopping on October 4, 2015: (a) Flood waters discharging through the uncontrolled concrete chute spillway on the left abutment; (b) overtopping on the articulating block mats armored embankment dam (photos: Associated Press; N 34.02191°, W 80.96162°).

(a)

(b)

Figure 90. Forest Lake Dam overtopping: (a) High water marks in the fence on the dam crest; (b) debris damming of the gated spillway reduced the spillway capacity (photos: October 13, 2015; N 34.02217°, W 80.96281°).

(a)

(b)

Figure 91. Forest Lake Dam overtopping: (a) Pontoon boat washed over the left embankment dam; (b) erosion and incipient scouring at the transition from the articulating bag mats to downstream soil (photos: October 13, 2015; N 34.02217°, W 80.96281°).

7.6 Lower Rockyford Lake Dam on Gills Creek

Lower Rockyford Lake Dam is an earth fill structure impounding Gills Creek in the Forest Acres municipality of the City of Columbia in Richland County, SC. Lower Rockyford Lake Dam on Gills Creek is located 1.8 km upstream of the overtopped Forest Lake Dam on Gills. Forest Lake Dam is the first dam upstream of the confluence of the Jackson Creek into the Gills Creek at Forest Lake. The upper Gills Creek watershed bounded by the Lower Rockyford Lake Dam includes 22.07 square miles (57.16 km^2). The dam is about 79 m long and 6.1 m high. The embankment dam includes a service spillway with drop inlet and low-level outlet pipe at right abutment and an uncontrolled overflow concrete spillway at left abutment. Eastshore Road runs along the dam crest and crosses the overflow spillway with a bridge. Lower Rockyford Lake Dam (D-0028) is classified by S.C.-DHEC into category C1, which means that failure may cause loss of life or serious damage to infrastructure.

The uncontrolled spillway at Lower Rockyford Lake Dam was completely removed on October 5, 2015 by the mostly unregulated flood discharges from upper Gills Creek as shown in Figure 92 and Figure 93. The concrete spillway was completely washed out from under the bridge along with the underlying earth fill and abutment scouring as shown in Figure 94. The remains of the concrete spillway were scattered in the Gills Creek downstream of the bridge as shown in Figure 95. The discharge from Lower Rockyford Lake flows directly into Forest Lake, where it is joined by the waters from the tributary Jackson Creek. However, the dam breaks upstream in the tributary Jackson Creek watershed to the north occurred earlier on October 4, 2015. Hence the upper Gills Creek and Jackson Creek watersheds upstream of Forest Lake can be viewed independently.

Figure 92. Lower Rockyford Lake Dam wash out of the uncontrolled overflow concrete spillway in an aerial view from the Rockyford Lake towards Forest Lake on October 7, 2015 (photos from Gills Creek Watershed Association via: www.facebook.com/GillsCreekWatershedAssociation; N 34.03595°, W 80.95195°).

(a)

(b)

Figure 93. Lower Rockyford Lake Dam: (a) Emptied lake upstream of the dam; (b) wash out of the uncontrolled overflow concrete spillway under the bridge (photos: October 13, 2015; N 34.03609°, W 80.95208°).

(a)

(b)

Figure 94. Lower Rockyford Lake Dam: (a) Wash-out of the entire uncontrolled overflow concrete spillway under the bridge; (b) erosion and scour on the downstream edge of the left abutment (photos: October 13, 2015; N 34.03595°, W 80.95195°).

(a)

(b)

Figure 95. Lower Rockyford Lake Dam: (a) Uncontrolled overflow concrete spillway washed-out under the bridge; (b) remains of concrete spillway scattered downstream in Gills Creek (photos: October 13, 2015; N 34.03595°, W 80.95195°).

7.7 Upper Rockyford Lake Dam on Gills Creek

Upper Rockyford Lake Dam is an earth fill structure impounding Gills Creek in the Forest Acres municipality of the City of Columbia in Richland County, SC. Upper Rockyford Lake Dam on Gills Creek is located directly upstream of Lower Rockyford Lake and 0.4 km upstream of the Lower Rockyford Lake Dam. Upper Rockyford Lake Dam is the first dam on the mainly unregulated upper Gills Creek. The dam is about 213 m long and 3.5 m high. The embankment dam includes a service spillway at the left bridge abutment with a drop box inlet as shown in Figure 96(a), a low-level outlet pipe and an uncontrolled overflow concrete spillway in the center. Overcreek Road runs along the dam crest and crosses the overflow spillway with a bridge. Upper Rockyford Lake Dam (D-0029) is classified by S.C.-DHEC into category C1, which means that failure may cause loss of life or serious damage to infrastructure.

The uncontrolled spillway at Upper Rockyford Lake Dam was completely removed on October 5, 2015 by the mostly unregulated flood discharges from upper Gills Creek as shown in Figure 96(b). The concrete spillway was completely washed out from under the bridge along with the underlying earth fill and downstream abutment scouring as shown in Figure 97. The discharge from Upper Rockyford Lake flows directly into Lower Rockyford Lake. The damage patterns characterized by a complete wash-out of the uncontrolled overflow concrete spillways and downstream abutment scouring were almost identical at Upper and Lower Rockford Lake Dams.

(a)

(b)

Figure 96. Upper Rockyford Lake Dam: (a) Emptied lake upstream of the dam with the drop box inlet; (b) wash out of the uncontrolled overflow concrete spillway under the bridge (photos: October 13, 2015; N 34.03955°, W 80.95151°).

(a)

(b)

Figure 97. Upper Rockyford Lake Dam: (a) wash out of the uncontrolled overflow concrete spillway under the bridge; (b) erosion and scouring on the downstream edge of the left abutment (photos: October 13, 2015; N 34.03955°, W 80.95151°).

8 Conclusions

This report presents the field observations of the GEER team made during the field reconnaissance from October 11 to 14, 2015 in South Carolina's Richland and Lexington Counties encompassing the greater Columbia and Lexington metropolitan area. Hurricane Joaquin was a category 4 hurricane on the Saffir–Simpson hurricane wind scale (SSHWS). Although Hurricane Joaquin ultimately tracked far to the east of the United States, a non-tropical low over the Southeast tapped into the hurricane's moisture, resulting in record-shattering rains and flooding across South Carolina. Several areas of South Carolina saw precipitation accumulations exceeding the threshold for a 1-in-1,000-year event from October 1 to 5. The subsequent floods caused inundations throughout the state with areas around Charleston and Columbia hardest-hit and killed 19 people. The damage in South Carolina alone is estimated at $12 billion. For comparison 1989 Hurricane Hugo made landfall in Charleston County, South Carolina as a category 4 hurricane (SSHWS) causing damage of $10 billion (1989 USD), which would correspond to $19 billion after inflation adjustments.

The study area in the Richland and Lexington Counties of South Carolina essentially covered a rectangle centered on downtown Columbia and spanning 30 km (East-West) and 20 km (North-South). The coverage includes the dam breaks along the Columbia Canal, the heavily devastated neighborhoods along Gills Creek in Columbia and the Twelvemile Creek in Lexington, but also includes observations along the Saluda dam spillway, the Broad river embankment breach into the Marietta quarry with a destroyed Northfolk Southern Railway bridge and the breach along Lake Elizabeth. In total 52 dams are known to have failed in the historic flooding event. The GEER team visited a dozen dams including 9 breached dams and 2 overtopped dams without a breach. The Saluda Dam was the only dam visited by the GEER team, where the reservoir level remained below the dam crest as the lake level was regulated by adjusting the controlled discharge through the spillways. All other dams visited by the GEER team showed signs of water levels reaching and/or exceeding the dam crest resulting in various degrees of overtopping both in terms of overflow depths and duration. The 9 dam breaches visited involved activation of emergency spillways. Incipient erosion on the earthen embankment dams occurred along the activated spillways mainly downstream at the transition from the concrete lining to bedrock or soil. Similar erosion was observed laterally at transitions of the sidewall lining to earthen fills. The Upper and Lower Rockyford Lake Dams had their concrete spillways completely washed out from under the roadway bridges, while overtopping of the roadway remained marginal. Cary's Lake Dam involved spillway and overtopping induced erosion potentially accelerated by piping. The dam breaches at the two 19th century dams occurred along material interfaces at the sharp transition from earthen fill to rock or brick walls involving piping and overtopping erosion. The Columbia Canal levee was overtopped marginally for a short period of time but the breach also involved significant piping and seepage force induced erosion along a rock-masonry wall. In contrast the Old Mill Pond Dam was overtopped over the entire length failing due to erosion of the downstream embankment at the location of a previously formed piping sinkhole and maintenance excavation along the old penstock. The overtopped Spring Lake Dam displayed significant erosion downstream but the dam did not breach. The intact Forest Lake Dam serves as example of an overtopped dam with overflow armor in the form or articulated bags, which prevented significant erosion during sustained overflow conditions.

Several lessons were learned, which may improve reconstruction efforts and future dam operations. The two dam failures along heritage dams highlight the vulnerability of sharp earth fill to rock wall transitions and the need to protect these areas. Coordinated watershed management along with early reservoir level adjustments may provide some extra buffer during anticipated extreme rainfall events and allow to spread out the flood discharge. Ultimately emergency spillway activations are inevitable during extreme flood events. Given the apparent dam overflow situations most spillway capacities were insufficient for this extreme event. Depending on a dam's hazard classification it may be advised to increase spillway capacities and the capabilities to sustain those design discharges over an extended time period from hours to days without significant downstream erosion and/or protect the embankment from overtopping erosion. In some cases, dam overtopping and sustained overflow may become inevitable due to for example an upstream dam breach releasing a dam break wave. The mostly intact Forest Lake Dam despite upstream dam breaks and dam overflow highlights the effectiveness of armor layers at preventing significant erosion resulting in dam breaching.

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Appendix A – Before and After Aerial/Satellite Imagery of Dams[1]

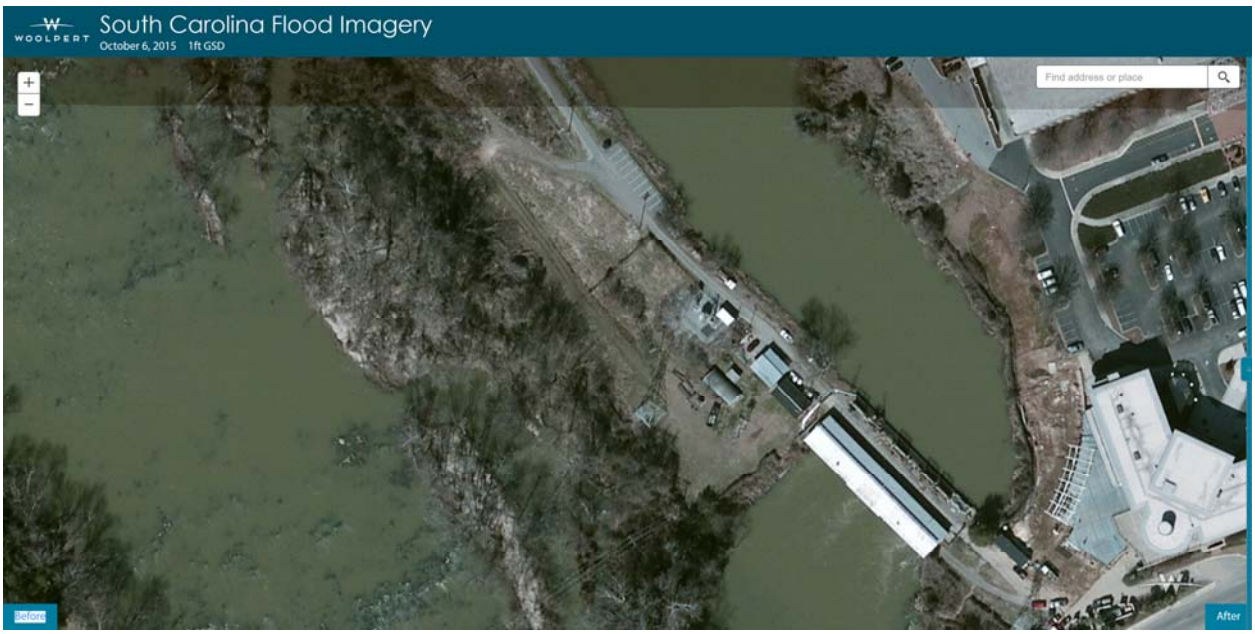
Columbia Canal levee breach (N 33.99796°, W 81.05018°)

Imagery: Before Flood

Imagery: 10/06/2016 aerial orthophoto with 1ft GSD flown by Woolpert

[1] Imagery obtained from: http://maps.woolpert.com/sites/sc-flood/

Columbia Canal levee breach (N 33.99796°, W 81.05018°)

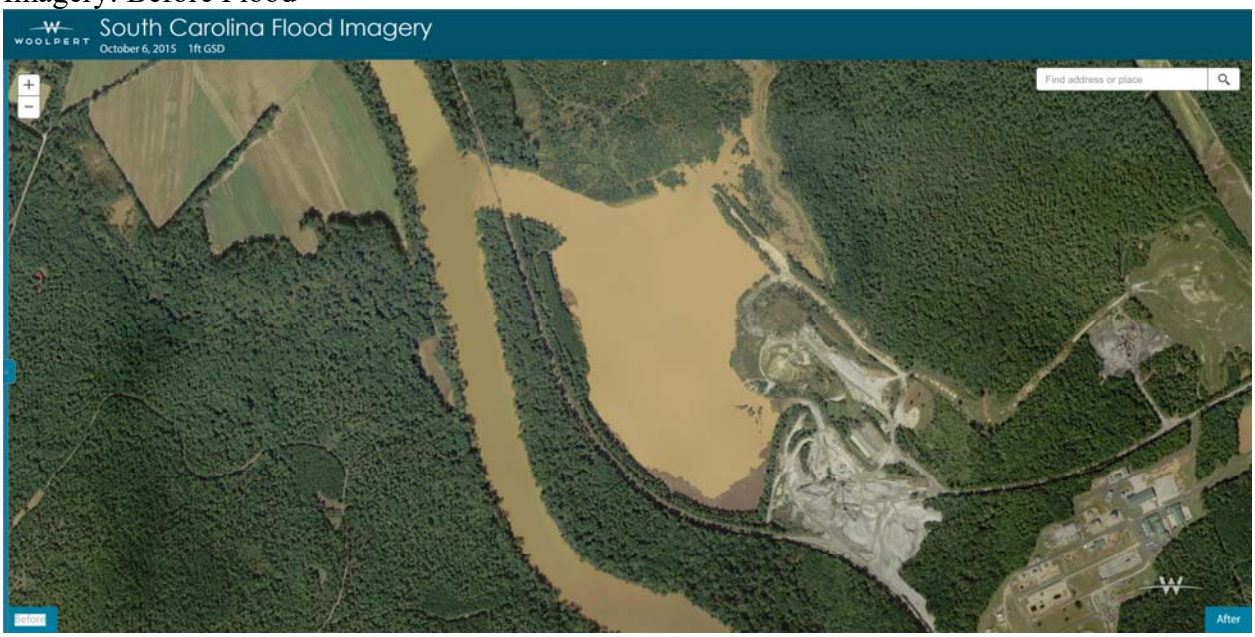


Imagery: Before Flood

Imagery: 10/06/2016 aerial orthophoto with 1ft GSD flown by Woolpert

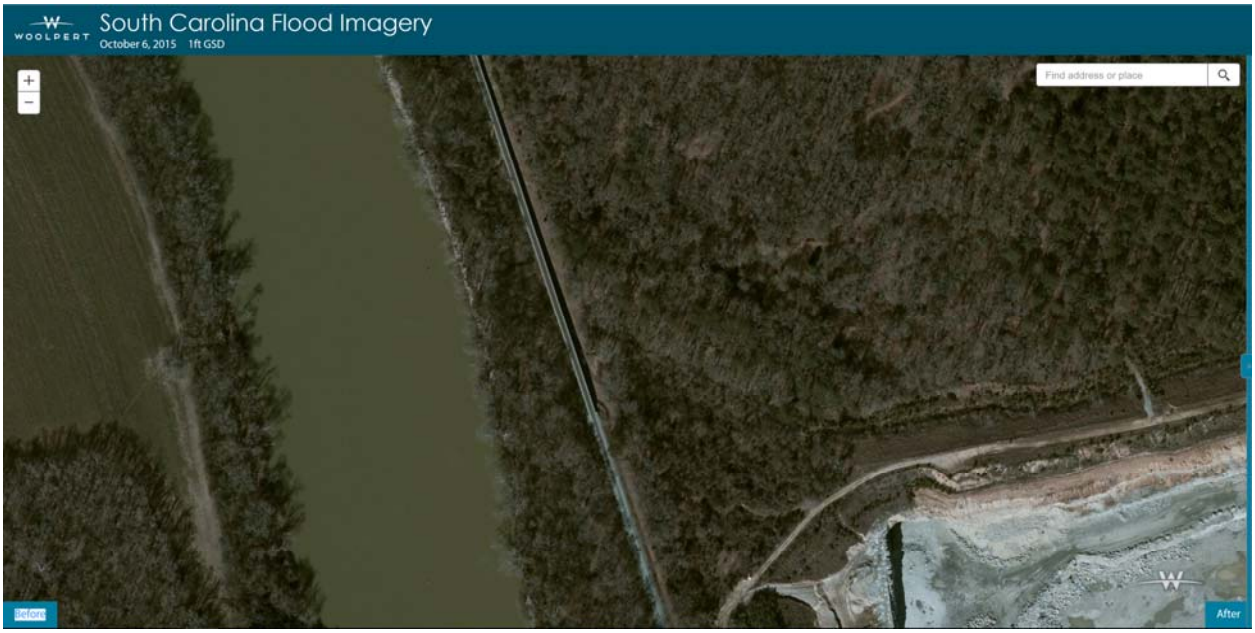
Broad River levee breach (N 34.11447°, W 81.11935°)

Imagery: Before Flood



Imagery: 10/06/2016 aerial orthophoto with 1ft GSD flown by Woolpert

Broad River levee breach (N 34.11447°, W 81.11935°)



Imagery: Before Flood

Imagery: 10/06/2016 aerial orthophoto with 1ft GSD flown by Woolpert

Lake Elizabeth Dam breach (N 34.11253°, W 80.98766°)

Imagery: Before Flood

Imagery: 10/06/2016 aerial orthophoto with 1ft GSD flown by Woolpert

Saluda Dam spillway and Saluda River (N 34.04035°, W 81.21579°)

Imagery: Before Flood

Imagery: 10/06/2016 aerial orthophoto with 1ft GSD flown by Woolpert

Saluda Dam spillway and Saluda River (N 34.04832°, W 81.20556°)

Imagery: Before Flood

Imagery: 10/06/2016 aerial orthophoto with 1ft GSD flown by Woolpert

Barr Lake Dam breach (N 33.95876°, W 81.26025°)

Imagery: 10/04/2014

Imagery: 09/30/2016

Gibsons Pond Dam breach (N 33.96949°, W 81.24360°)

Imagery: 10/04/2014

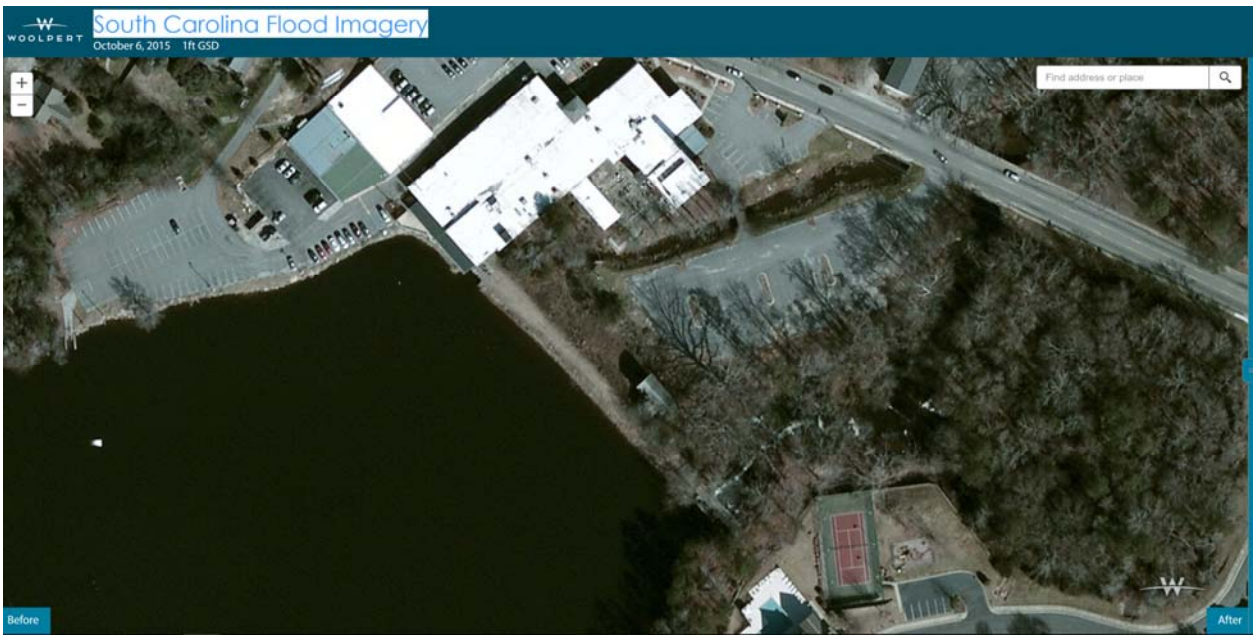
Imagery: 10/18/2015

Old Mill Pond Dam breach (N 33.97683°, W 81.22961°)

Imagery: 10/04/2014

Imagery: 10/18/2015

Old Mill Pond Dam breach (N 33.97683°, W 81.22961°)



Imagery: Before Flood

Imagery: 10/06/2016 aerial orthophoto with 1ft GSD flown by Woolpert

Cary's Lake Dam breach (N 34.04866°, W 80.95764°)

Imagery: Before Flood

Imagery: 10/06/2016 aerial orthophoto with 1ft GSD flown by Woolpert

Rockbridge Road bridge washed away (N 34.04516°, W 80.95709°)

Imagery: Before Flood

Imagery: 10/06/2016 aerial orthophoto with 1ft GSD flown by Woolpert

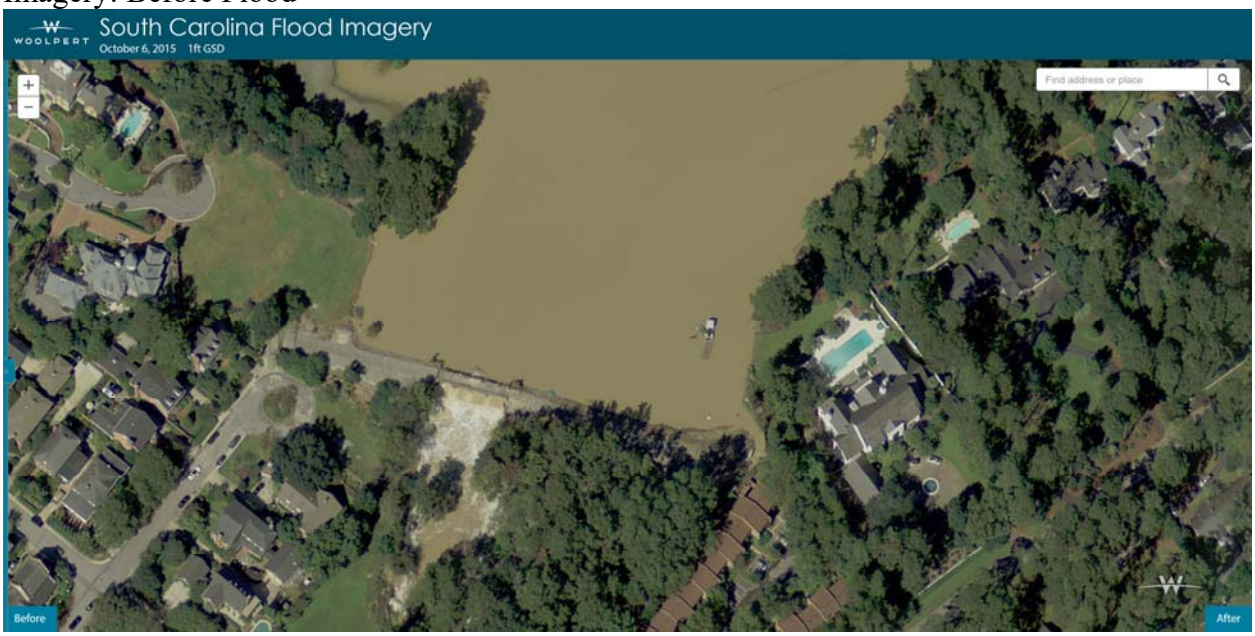
Spring Lake Dam overtopped (N 34.03708°, W 80.95531°)

Imagery: Before Flood

Imagery: 10/06/2016 aerial orthophoto with 1ft GSD flown by Woolpert

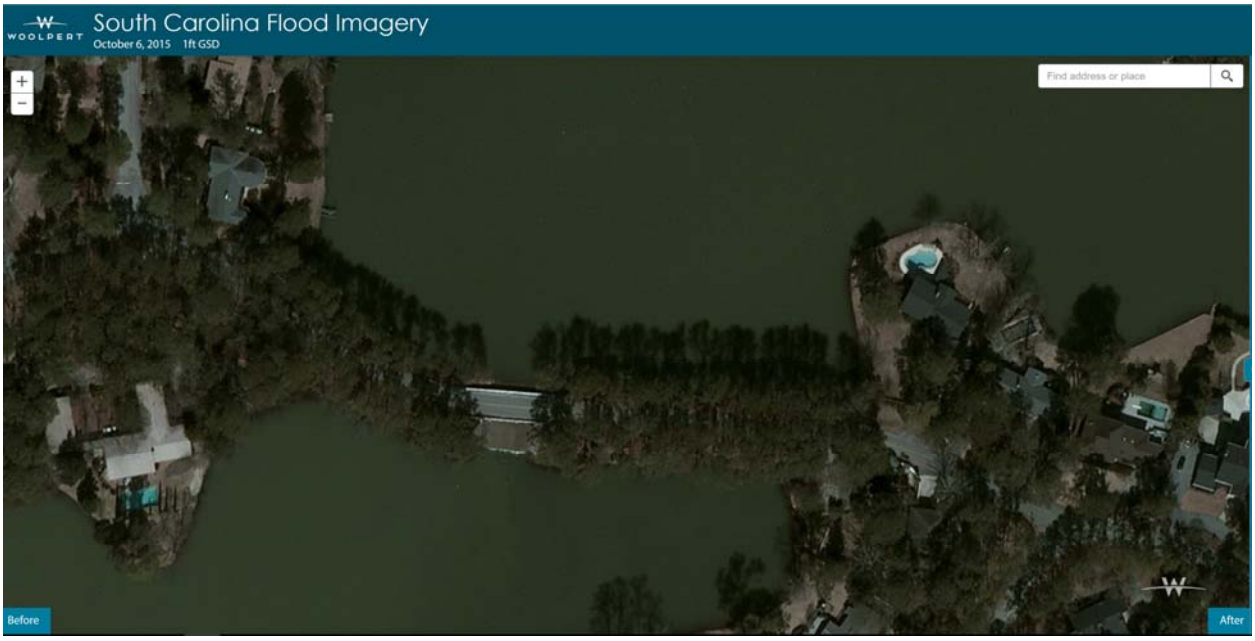
Forest Lake Dam overtopped (N 34.02217°, W 80.96281°)

Imagery: Before Flood



Imagery: 10/06/2016 aerial orthophoto with 1ft GSD flown by Woolpert

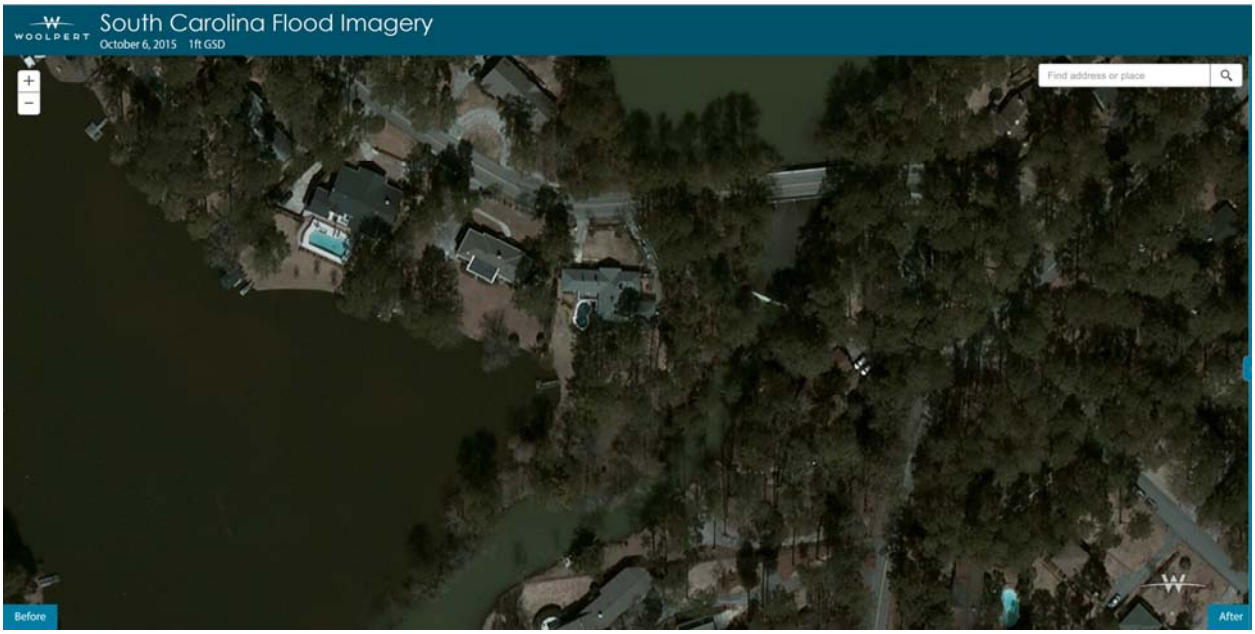
Upper Rockyford Lake Dam spillway washout under bridge (N 34.03955°, W 80.95151°)



Imagery: Before Flood

Imagery: 10/06/2016 aerial orthophoto with 1ft GSD flown by Woolpert

Lower Rockyford Lake Dam spillway washout under bridge (N 34.03595°, W 80.95195°)



Imagery: Before Flood

Imagery: 10/06/2016 aerial orthophoto with 1ft GSD flown by Woolpert