Geotechnical Extreme Event Site Reconnaissance in Puerto Rico After The Passage of Hurricane Maria

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ABSTRACT: *The National Weather Service classified Hurricane Maria as a strong Category 4 Hurricane on the Saffir-Simpson hurricane wind scale at the time of its landfall in Yabucoa, Puerto Rico, U.S.A., on September 20, 2017. The immediate aftermath of Hurricane Maria was a devastated island with at least 64 people killed, severe infrastructure loss, a devastated electric power grid, and numerous geotechnical failures related to the intense rainfall and strong winds associated to this extreme event. This paper will summarize the event timeline and the geotechnical consequences of Maria's path across Puerto Rico. The impacts of Hurricane Maria on infrastructure and geomorphology are documented through the data and observations of the engineers and geologists that comprised the Geotechnical Extreme Events Reconnaissance (GEER) team. The main reconnaissance mission took place between October 25 and November 6, 2017, followed by a second field component involving terrestrial LiDAR surveys and UAV photogrammetry performed January 8 to 11, 2018.*

This paper summarizes observations on geotechnical impacts such as: the Guajataca Dam spillway failure, coastal erosion events (including foundation failures due to coastal erosion in Córcega, Rincón), bridge abutment scour failures, over 2,000 landslides along the PR highway system (e.g., along the PR-10, region of Lares, Barranquitas and Utuado); foundation failures, and other failures related to this destructive hurricane. Rainfall-induced landslides in Puerto Rico have been a serious recurring problem (e.g., Jibson, 1987; Larsen and Simon, 1993; Larsen and Santiago-Roman, 2001; Pando et al., 2005) observed in the different physiographic regions of the island as result of Maria and other hurricanes such as Hortense (1996), Georges (1998), and Debby (1999). The passage of Hurricane Maria triggered thousands of landslides, with the most common type of failure mode consisting of shallow debris flows. However, many deeper-seated failures were also observed, typically at sites with a road fill and blocked drainage. The geotechnical failures presented in this article provide insight to help identify typical modes of failure and to help the engineering community adapt and improve design and construction practices to improve resiliency of our infrastructure and lifelines.

KEYWORDS: Hurricane, landslide, debris flow, rainfall-induced instability, coastal erosion, scour, foundation failure, bridge failure, infrastructure damage, flood damage, storm damage, natural disaster.

SITE LOCATION: Geo-Database

INTRODUCTION

The 2017 Atlantic hurricane season included hurricanes Harvey, Irma, and Maria, which together caused over 3,300 deaths and more than $265 billion (USD) in damages (USNHC, 2018). Hurricane Maria is among the ten most intense Atlantic hurricanes on record, as it caused catastrophic damage and numerous fatalities not only in Puerto Rico but also across other islands in the Caribbean. With winds of up to 269 km/h (167 mph) and a maximum total storm rainfall exceeding 950 mm (38 in), Hurricane Maria devastated Puerto Rico's electric power grid, as well as its water supply systems (Silva-Tulla et al., 2018). Hurricane Maria also caused widespread flooding and destruction of residential dwellings throughout the island, which resulted in major humanitarian and economic crises in Puerto Rico (PR).

As part of this Special Issue on Hurricane Reconnaissance by GEER (Geotechnical Extreme Event Reconnaissance) missions, this paper presents a synthesis of the observations, lessons learned, and conclusions reported in the GEER final report (Silva-

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Tulla et al., 2018). Specifically, we summarize the event timeline and the geotechnical consequences of the passage of Hurricane Maria across PR. The impacts of Hurricane Maria on infrastructure and geomorphology were documented in detail through the data and observations of the engineers and geologists who constituted the GEER team. Table 1 presents the full list of team members and collaborators. The primary reconnaissance mission took place between October 25 and November 6, 2017. A second field visit performed from January 8 to January 11, 2018, involved Light Detection and Ranging (LiDAR) surveys, as well as photogrammetry using an Unmanned Aerial Vehicle (UAV).

On the morning of Wednesday, September 20, 2017, Hurricane Maria made landfall near the southeastern town of Yabucoa, PR as a powerful Category 4 storm. Hurricane Maria moved diagonally across the island with sustained winds of 249 km/h (155 mph)—the worst storm to hit PR in over 80 years. Hurricane Maria arrived only two weeks after Hurricane Irma; this prior hurricane had passed just north of the island, ensuing in heavy rainfall throughout the island and leaving about one million residents without power.

The scale of Hurricane Maria's destruction was even more devastating, causing as much as $95 billion in damages according to an estimate released on September 28, 2018, by Moody's Analytics. Electricity was cut off for 100% of the island, and most residents suffered from limited access to clean water and food. Puerto Rico's power outage was, by far, the most severe in United States history in terms of total customer-hours lost; in March 2018 (six months after the event), many areas of central Puerto Rico were still without power and water. The estimated time since the hurricane landfall for restoring power to 50%, 75%, and 90% of customers in PR was reported as 70, 145, and 190 days respectively (Kwasinski et al., 2019). There were several thousand fatalities attributed to Hurricane Maria, but there are conflicting reports associated to methodology, dramatic population displacement after the hurricane, and issues related to data such as death registration. A study published in *The New England Journal of Medicine* (Kishore et al., 2018) estimated fatalities as high as 4,645 based on a study of excess deaths from September 20 through December 31, 2017. An independent study by the Milken Institute of Public Health at George Washington University reported an estimation of 2,975 lives lost, with a 95% confidence interval between 2,658 and 3,290 from September 2017 to February 2018 (MISPH, 2018). The exact number of fatalities attributed to Hurricane María remains controversial to this day, but almost everyone considers the death toll high.

The impact of Hurricane Maria was evident everywhere the GEER team went. The numerous geotechnical failures observed were not only due to the size and magnitude of Hurricane Maria's strong winds and high precipitation, but also to the intense antecedent rainfall from Hurricane Irma two weeks earlier. Hurricane Maria wind and water related forces wreaked havoc throughout the island. Based on the GEER team's observations, slope instability was the dominant geotechnical failure mechanism during Hurricane Maria in Puerto Rico. The forces from the ferocious winds overwhelmed the foundation's resisting forces for many structures, resulting in numerous bearing capacity failures. The reduced soil strength due to the heavy rainfall, which increased pore pressures and thus decreased the effective stresses in the foundations, contributed to many of these aforementioned failures. The decreased effective stresses also resulted in the thousands of landslides and debris flows reported throughout the island. The erosive power of the storm surge and river floods destroyed or damaged coastal infrastructure (e.g., piers, seawalls, roads, buildings, houses, and utilities) and inland facilities (e.g., bridges, houses, highway embankments, and pipelines).

Several investigators have recognized rainfall-induced landslides as a serious recurring problem in Puerto Rico (Jibson, 1987; Larsen and Simon, 1993; Larsen and Santiago-Roman, 2001; Pando et al., 2005). The passage of Hurricane Maria and other hurricanes, e.g., Hortense (September 10, 1996), Georges (September 21-22, 1998), and Debby (August 22, 2000) have resulted in landslides in the different physiographic regions of the island. Monroe (1979) and, more recently, Lepore et al. (2012) both published maps of landslide susceptibility for PR, which generally agree with the location of landslides after Hurricane Maria. As will be described in further detail later in this paper, Hurricane Maria triggered thousands of landslides, with the most common type of failure mode consisting of shallow debris flows. Many deeper-seated failures were also observed, however, typically at stream or gully crossings with a road fill and blocked culvert drainage.

This paper summarizes observations of geotechnical impacts such as: the Guajataca Dam spillway failure; foundation failures due to coastal erosion in Córcega, Rincón; bridge abutment scour failures; some of the more than 2,000 landslides along the PR highway system (e.g., along the PR-10, region of Lares, Barranquitas, and Utuado); foundation failures; and other failures related to this destructive hurricane. The GEER mission report by Silva-Tulla et al. (2018) describes in greater detail the reconnaissance observations summarized in this article. The summary of geotechnical failures presented in this article provides insight to help identify typical modes of failure and help the engineering community adapt and improve design and construction practices to increase the resiliency of infrastructure and lifelines.

Table 1. Team members of GEER mission to PR after Hurricane Maria.

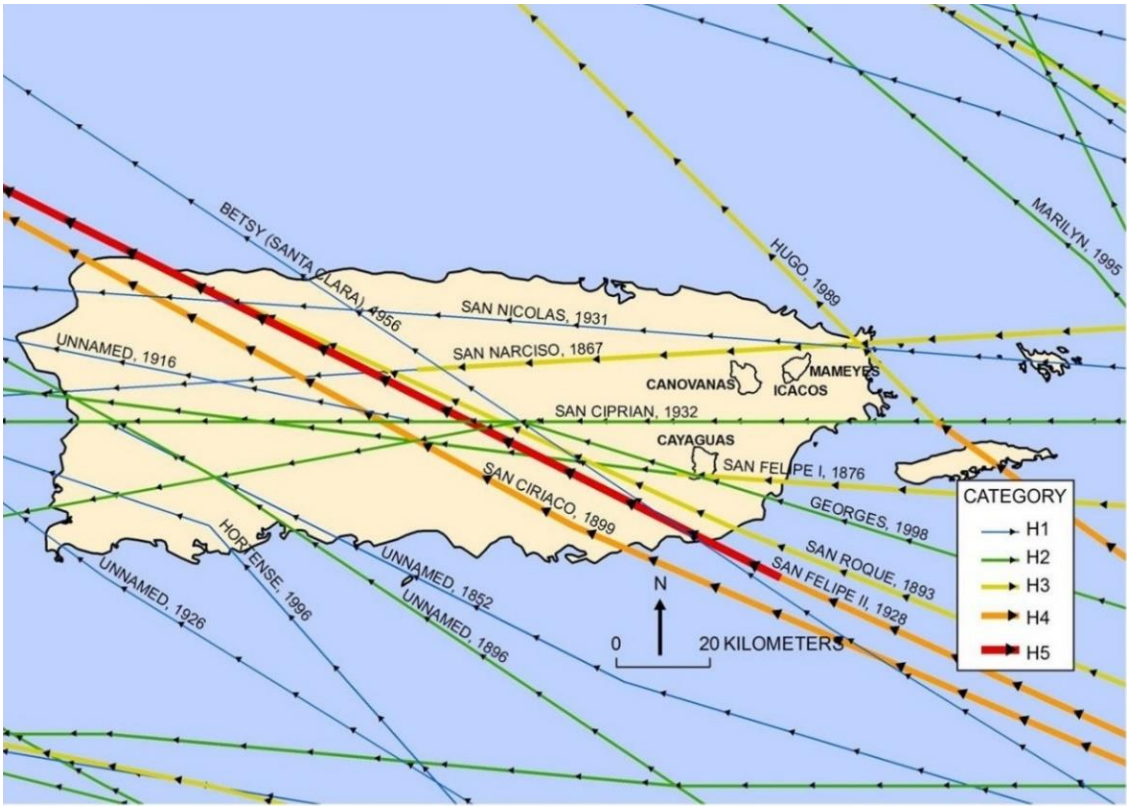
First Name	Last Name	Team Role	Organization	Expertise	Home Base
Francisco	Silva-Tulla	Leader*	Consulting Civil Engineer	Geotechnical Engineering, Earth Structures	MA
Miguel A.	Pando	Co-Leader*	University of NC at Charlotte	Geotechnical Engineering	NC
Tiffany	Adams	Member*	AECOM	Geotechnical Engineering	CO
Juan R.	Bernal Vera		University of PR, Mayagüez		PR
Luis Oscar	García		GeoCim		
Carlos	García Echevarría		GeoCim		
Stephen	Hughes		University of PR, Mayagüez	Geology of PR, UAV	
Gokhan	Inci		FEMA	Civil Engineer, Dam Safety	Washington, DC
Robert	Kayen		USGS	Geometry Determination, UAV, LIDAR	CA
Alesandra C.	Morales Velez		University of PR, Mayagüez		PR
Youngjin	Park		University of NC at Charlotte	Geotechnical Engineering	NC
Daniel	Pradel		The Ohio State University		OH
Inthuorn	Sasanakul		University of SC	Geotechnical Engineering, Erosion and Scour	SC
Alex	Soto		GeoCim	Geology of PR, Landslides	PR
George W.	Annandale	Collaborator	Consultant	Water Resources Engineering, Erosion and Scour	CO
José Miguel	Bermudez		PRASA	PR State Dam Safety Official	PR
Ruben	Estremera		PRASA	Dam Safety	
Jaime	Lopez		PRASA	Dam Safety	
Aurelio	Mercado-Irizarry		University of PR, Mayagüez	Oceanography	

* Co-author of GEER report (Silva-Tulla et al., 2018).

PATHS OF HISTORICAL HURRICANES AND THE 2017 EVENTS

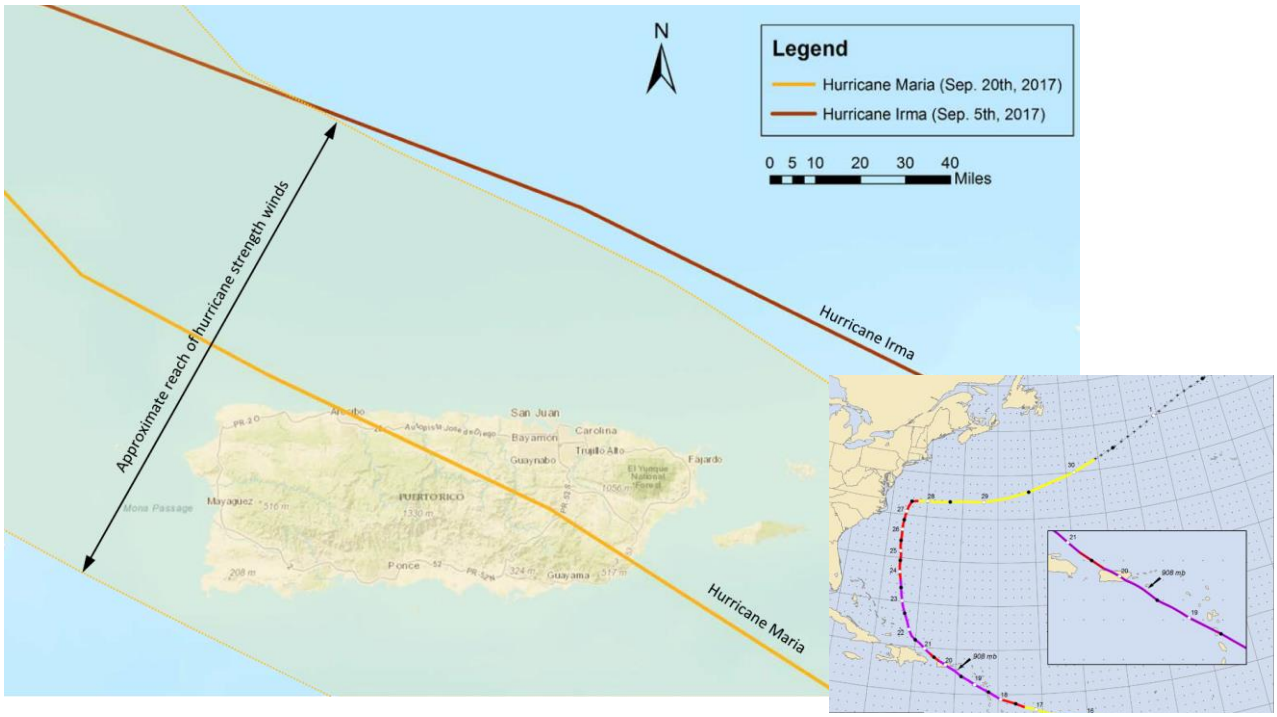
The island of PR, the easternmost and smallest of the Greater Antilles, is a United States territory flanked to the north by the Atlantic Ocean and to the south by the Caribbean Sea. The island measures approximately 160 km (100 mi) from east to west and 55 km (34 mi) from north to south. Centered at latitude 18.2°N and longitude 66.4°W, PR lies in the commonly designated "Caribbean Hurricane Alley", thus making it very vulnerable to hurricane impacts. Hurricane frequency in PR is among the highest in North America (Neumann et al., 1987). Reviewing historical records since the European settlement, Boose et al. (2004) documented 85 hurricanes that affected PR between 1508 and 1997. The hurricane dataset of Boose's study, which considers only hurricanes with sustained wind speeds above 26 m/s, found that the hurricane season for PR runs from June through October,with 84% of the events occurring during the months of August and September. Figure 1 shows historical hurricanes from 1852 to 1998 with paths through or near PR (USGS, 2018). In this figure, the categories of the different hurricanes are denoted with the line type labeled with the category from Category 1 (H1) to Category 5 (H5) on the Saffir-Simpson hurricane wind scale. Recent hurricanes that made landfall in Puerto Rico include: Hugo (Category 3 to 4; September 18, 1989), Hortense (Category 1; September 10, 1996), and Georges (Category 3; September 21-22, 1998).

Two hurricanes impacted PR in September 2017: Irma and Maria. Hurricane Irma was a Category 5 storm when it passed just north of PR on Wednesday, September 6, 2017. The trajectory of the eye of this hurricane is shown in Figure 2. Despite not making landfall in PR, hurricane strength winds extended about 129 km (80 mi) from the hurricane's center, and heavy rainfalls were reported throughout the island. Hurricane Irma left over 1 million people without power (NBC, 2018). Hurricane Maria reached Category 5, the highest category of the Saffir–Simpson scale, just before making landfall in Yabucoa, PR, on September 20, 2017, about two weeks after the passage of Hurricane Irma. At landfall, the wind speed was about 269 km/h (167 mph), corresponding to a strong Category 4 hurricane. The path of the eye of this powerful hurricane took a northwesterly direction, as shown in Figure 2. Hurricane force winds extended from 80 to 97 km (~50 to 60 mi) from its center. The extended path of this hurricane from September 16 to October 3, 2017, is also shown on the inset of Figure 2.



[Source: https://www.usgs.gov/media/images/puerto-rico-hurricanes-map]

Figure 1. Path of historical hurricanes that have impacted Puerto Rico (USGS, 2018).



Inset: Extended path of Hurricane Maria from 9/16 to 10/2/17 (adapted NOAA, 2018)

Figure 2. Path of Hurricanes Irma and Maria with respect to Puerto Rico (adapted from Feng et al., 2018).

THE HURRICANE MARIA GEER MISSION TO PR

On September 27, 2017, seven days after the passage of Hurricane Maria through Puerto Rico, the GEER mission began. Although the intent was to travel to Puerto Rico as soon as possible after the hurricane's departure, travel to the island was delayed until October 25, 2017 due to the difficult living conditions on the island, focus on emergency operations, and the unavailability of return flights and reasonably priced hotel rooms. The team leaders flew to Puerto Rico that day to finalize the advance coordination efforts started by University of PR Mayagüez campus (UPRM) professors and team members Dr. Stephen Hughes and Dr. Alesandra Morales-Velez. By the time the team leaders arrived on the island, four weeks after Hurricane Maria made landfall, conditions in Puerto Rico had improved somewhat but still remained very difficult. Most of the island continued to lack electricity or potable water, traffic in the urban areas without traffic signals moved slowly, and telephone communications proved difficult and unreliable. On October 26 and 27, the team leaders met with different local agencies, including Puerto Rico's Secretary of Transportation and Public Works and his engineering advisors, to go over the main landslide and river scour locations affecting roads and other infrastructure. During that meeting, the team learned that more than 2,000 landslides had been recorded by that time. The team leaders also met with Puerto Rico's Dam Safety Official, José Miguel Bermudez, to arrange for escorted visits to Guajataca Dam, the site of a well-documented spillway failure, as well as several other affected dams.

The reconnaissance activities started on October 28 with a visit to the easternmost region of the island. On October 29, Dr. Juan Bernal from UPRM joined the team leaders for reconnaissance in Aguadilla and Moca. The U.S. mainland-based team members arrived in Mayagüez on October 29, and the bulk of reconnaissance took place from October 30 to November 3. The mainland-based team members began to return to their respective home bases on November 4, 2017, although the team leaders and Dr. Youngjin Park completed a full day of reconnaissance then while returning to San Juan, and Drs. Park and Silva-Tulla were able to visit landslide-affected areas in northeast PR for about a half-day on November 6. Figure 3 shows the tracks of the team's daily reconnaissance activities. This figure also shows (as black diamonds) the locations where LiDAR surveys and photogrammetry using an UAV were performed as part of a second field visit, led by team member Dr. Kayen with the assistance of Drs. Hughes and Morales-Velez. The LiDAR and photogrammetry field activities focused primarily on the Guajataca Dam spillway (January 9, 2018) and two landslide sites (PR-4131 on January 10, 2018, and near PR-9 on January 11, 2019). The PR-4131 debris flow landslide is described later in this paper.

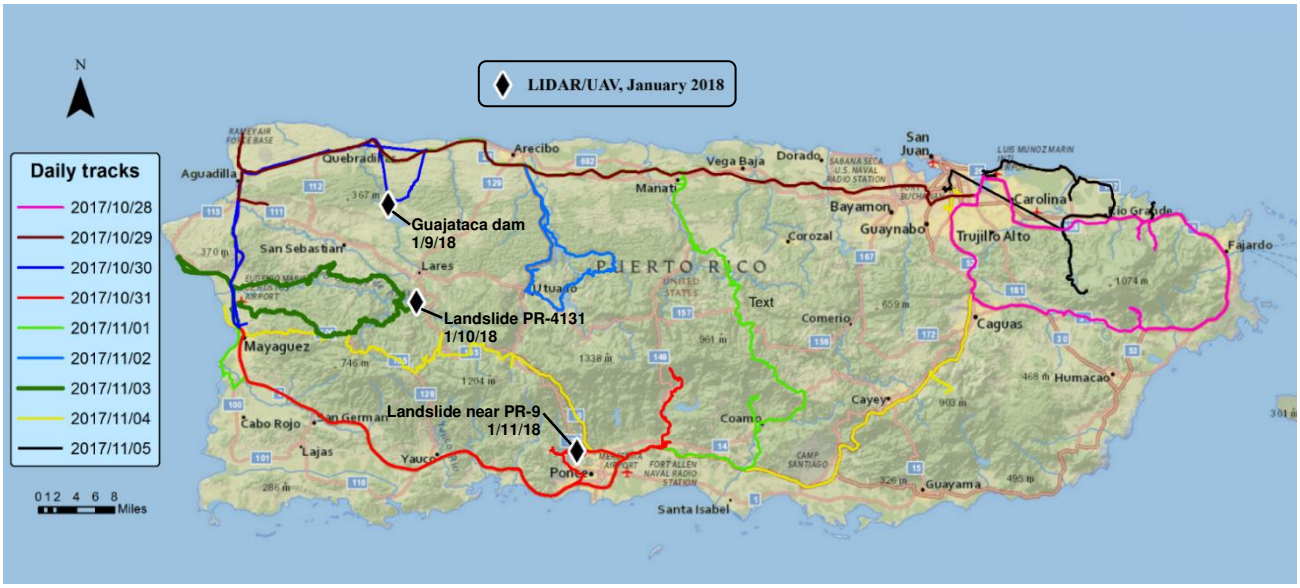


Figure 3. Daily reconnaissance tracks of GEER mission and location of LiDAR scans (Silva-Tulla et al., 2018).

TOPOGRAPHY, GEOLOGY, AND CLIMATE OF PUERTO RICO

The following subsections provide background information for the topography, geology, and climate of Puerto Rico, as they are relevant to many of the observed geotechnical impacts, particularly the rainfall-induced landslides.

Topography

Most of the island of Puerto Rico is mountainous, as shown in Figure 4. The mountain ranges include a central mountain range (the Cordillera Central) that extends across the island from west to southeast with elevations between 330 to 600 m above sea level, and a maximum peak with an elevation of 1,338 m above sea level. The Luquillo Mountains (Sierra de Luquillo), at the northeast portion of the island, have a maximum elevation of 1,074 m. A relatively flat coastal plain, about 8 to 16 km wide, covers most of the perimeter of the island.

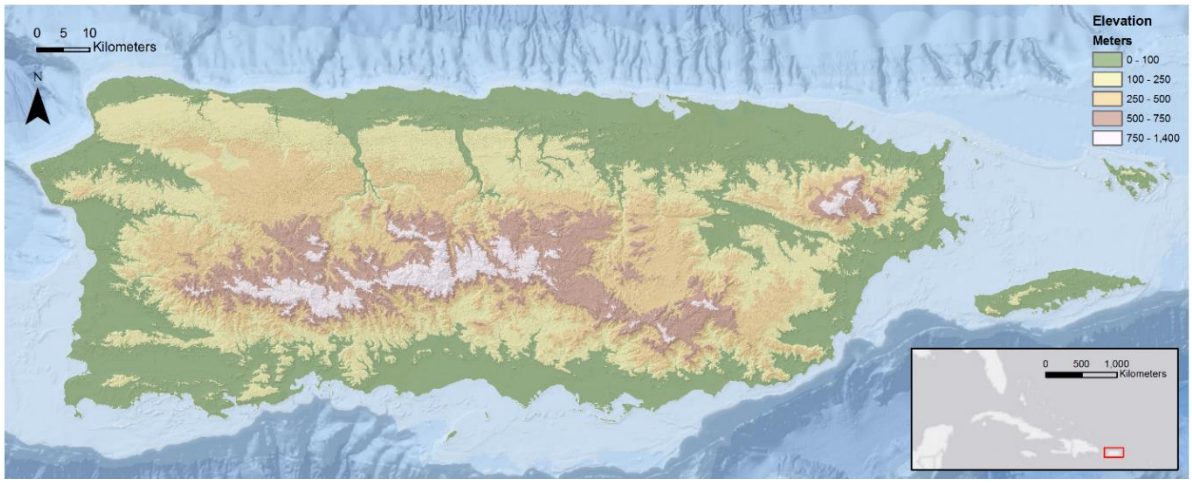


Figure 4. Map of Puerto Rico showing mountainous topography in the central region (Hughes and Morales-Velez, 2017; adapted from Silva-Tulla et al., 2018).

The rugged and steep nature of the topography of the island's interior is illustrated in Figure 5 as a slope map created from a 5 m resolution digital elevation model (DEM) from Puerto Rico's Real Estate Tax Collection Center, or *Centro de Recaudación de Ingresos Municipales* (CRIM) in Spanish (CRIM, 2018). This map shows the majority of the central region

with average slope inclinations with respect to the horizontal ranging from 20° to 30°, and more than 10% of this central PR region as having slope angles of 30° or steeper.

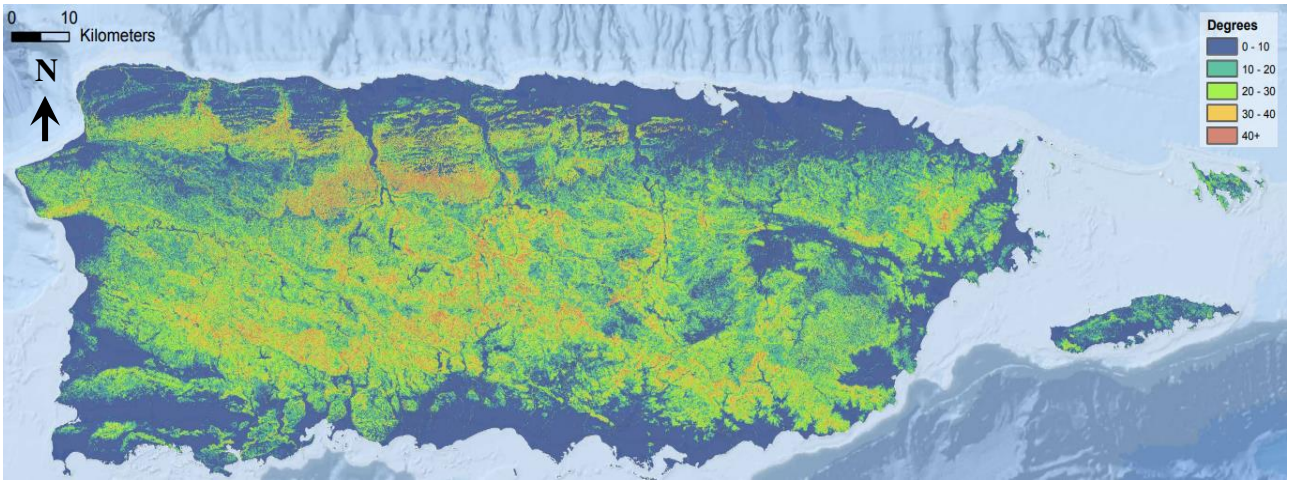


Figure 5. Slope map showing computed average slope inclinations from 5 m resolution DEM (Hughes and Morales-Velez, 2017; adapted from Silva-Tulla et al., 2018).

Geology

The landscape of the island contains an array of landforms that reflect PR's varied geology and climate. Landsliding has been an ever-present factor in shaping the topography. With a high proportion of its land surface having slopes of 20° or steeper, along with geologic settings typically associated with landsliding, all failure modes described in landslide classification schemes occur on the island, including slow- to fast-moving earth slumps, slides, and flows in residual and transported soils. Furthermore, all types of rock failures occur in the steep rocky slopes that are common along coastal cliffs and the drier southern slopes of the Cordillera Central.

The USGS has published preliminary or final 1:20,000-scale geologic maps for 61 of the island's 64 7.5-minute topographic quadrangles. Bawiec (1999) combined the USGS map units into twelve geologic terranes that group units based on similarities in "lithologic rock type, depositional environment, and (or) age of deposition" as shown in Figure 6.

From Figure 6, it can be seen that PR's central mountain range is composed predominantly of volcanic and sedimentary rocks of the Early Cretaceous to Eocene Ages (Briggs and Akers, 1965). The rocks of the Upper Cretaceous Age are comprised of a great variety of pyroclastic, sedimentary, extrusive, and intrusive igneous rocks (Deere, 1955). Because of high moisture and warm temperatures, the bedrock in the Cordillera Central is highly weathered and overlain with an average of 5 to 10 m of saprolite (St. John et al., 1969; Deere and Patton, 1971; Sowers, 1971). The central mountain range is surrounded to the north and south by a belt of middle Tertiary Age limestones, siltstones, and claystones (Briggs and Akers, 1965; Jibson, 1987). Rockfalls from steep cliffs and road cuts originating in colluvial deposits are common in the foothills of the mountains in these sedimentary rocks (Monroe, 1979; Jibson, 1987). The coastal plains are mainly depositional environments composed of sand, gravel, and clay, which form Quaternary beach deposits, swamps, dunes, alluvial plains, and fan deposits (Briggs and Akers, 1965).

Climate

The climate of Puerto Rico varies considerably due to the island's topography and its prevailing north-easterly winds (Boose et al., 2004). The climate is generally humid and tropical in the central mountain range and northern coast, while it's seasonally dry (dry winters, wet summers) along the southern coastal plain (Larsen and Simon, 1993). The levels of mean annual rain in Puerto Rico are shown in Figure 7 (USGS, 2015), which shows that the island's annual precipitation is between 1,500 to 2,000 mm (60 to 80 in) in the northeast part of the island, 762 to 1016 mm (30 to 40 in) in the south of the island, 1,778 – 2,540 mm (71 to 100 in) in the central cordillera, and more than 4,250 mm (170 in) in the Luquillo Mountains (USGS, 2015). The rainy season typically occurs between the months of May and December. Much of the yearly rainfall is delivered by tropical waves, depressions, storms, and hurricanes approaching from the east and southeast (Calvesbert, 1970).

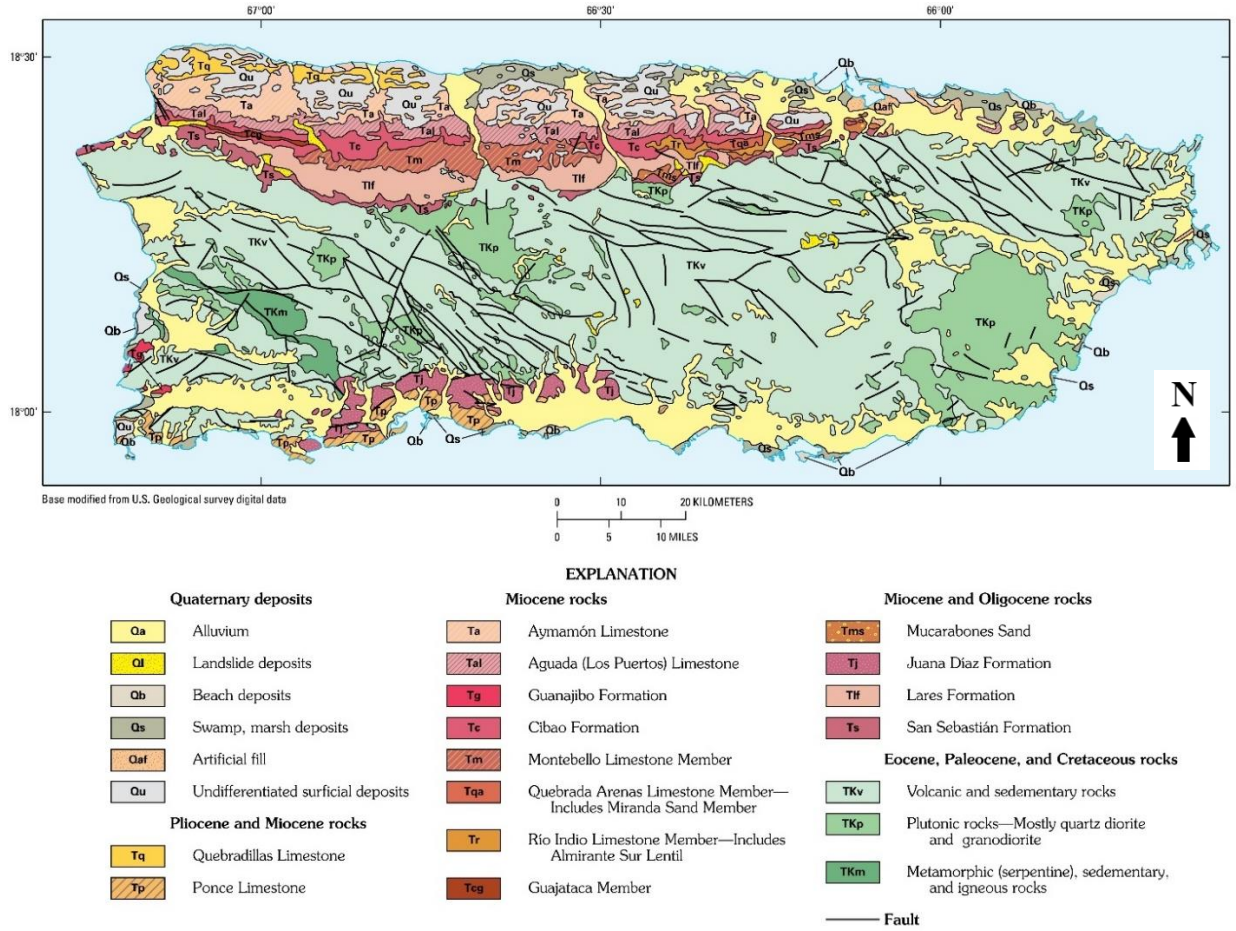
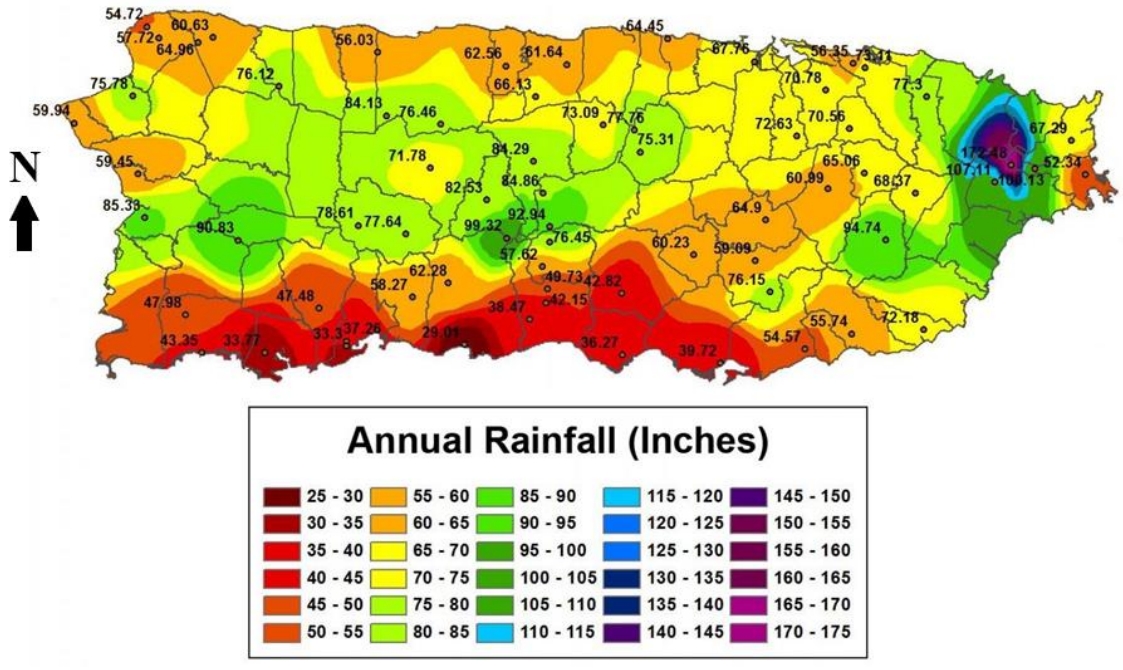


Figure 6. Geology of Puerto Rico (adapted from Bawiec, 1999).



(Note: 1 inch = 25.4 mm)

Figure 7. Mean Annual Rain Distribution in inches for Puerto Rico (Data 1981-2010; USGS, 2015).

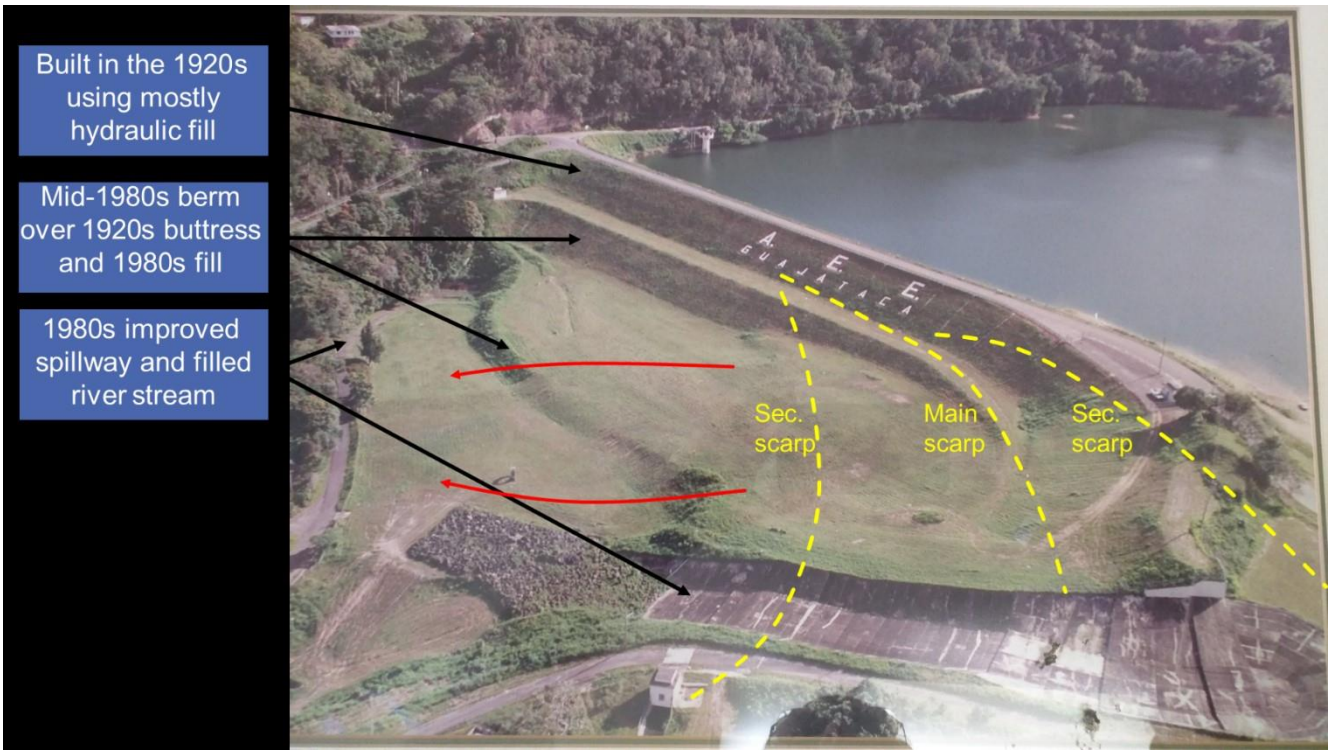
The mean annual temperature varies with the island's elevation and ranges from 23° to 27° Celsius [C] (74° to 81° Fahrenheit [F]) in the foothills and along the coastal plains, and 19° to 23° C (66° to 74° F) in the mountains and highest peaks (Deere, 1955; Calvesbert, 1970).

DAMS

The GEER team visited four concrete dams (Prieto, Dos Bocas, Caonillas, and Guayabal) and one earth dam (Guajataca) during their first reconnaissance visit. Except for the well-publicized failure of a 100-year-old section of the Guajataca Dam spillway due to scour (e.g., NBC, 2017; NPR, 2017; ENR, 2018), dams throughout the island performed remarkably well. None of the 38 dams listed in the National Performance of Dams Program (NPDP) failed. Malfunctions were limited to loss of capacity due to sediment transport and minor landslides or rockfalls near the abutments of several dams. Since Hurricane Maria was preceded by Hurricane Irma, the degree of saturation of many slopes had increased by the time Maria made landfall. Thus, the soil around tree roots was generally wet and soft when the strong winds of Hurricane Maria arrived. The high degree of saturation facilitated tree uprooting, and furthermore enhanced erosion, surficial failures, debris flows, and scour. As a result, reservoirs received large volumes of sediments and debris.

Guajataca Dam

The GEER mission visited Guajataca Dam, where severe damage to the spillway and dam safety concerns prompted the evacuation of about 70,000 downstream residents. Figure 8 shows Guajataca Dam, an earthfill dam built in the 1920s, mostly by hydraulic fill methods, and modified in the 1980s. The dam has a maximum height of about 37 m (121 ft) and a crest 316 m (1,037 ft) long and 9.5 m (31.2 ft) wide, with a "puddle clay" core sloping at about 0.5 to 1 (horizontal to vertical [H:V]). Its upstream and downstream faces slope at ratios of 2:1 H:V or flatter. According to the National Inventory of Dams (USACE, 2016), Guajataca Dam was designed for and owned by the Puerto Rico Electric Power Authority. A detailed description of the history and construction of the dam can be found in USBR (2002).



Note: Figure shows historical and landslide features remediated in the 1980s.

Figure 8. Photo of Guajataca Dam (Lat. +18.397895, Lon. -66.923725), taken a few decades before Hurricane Maria – exact date of photo unknown (adapted from Silva-Tulla et al., 2018).

Figure 9 shows the cross section of Guajataca Dam, as reported by USBR (2002). Available records suggest that a large part of the dam consists of hydraulic fill, but its internal geometry and composition remain unclear. For example, the center of the dam is reported as a "puddle core", but the USBR (2002) report suggests that the hydraulic fill process left the coarsest fill materials near the dam faces and the finest in the core area. The same report indicates that fill placement was changed to "dry" roller compaction in 1927 to address field observations of dam instability. Instability during the initial construction of the dam was reported in February 1927 as cracks, slippage, and other signs of movement, including bulging and settlement of the cofferdams. Reportedly, many locations showed movements on both the dam and the downstream natural ground; maximum movements included a 0.96 m (3.2 ft) downstream horizontal displacement and 1.44 m (4.7 ft) of vertical settlement.

Figure 9 shows the remedial berm constructed on the downstream side of the dam early in 1927 after the reservoir was drained, implemented to stabilize the ongoing sliding in the downstream direction. USBR (2002) also indicates that stabilization measures included the installation of numerous drain holes and replacing the fill placement technique to "dry" roller compaction. As construction of the dam proceeded, new movements of up to 35 cm (14 in) were reported on the upstream face and a heel was installed (location unknown). The USBR (2002) report indicates that in November 1927, as the dam was nearing completion, movements reported as "creep-type" were still observed. To enhance stability, fill was placed at the toe of the dam. The USBR (2002) report indicates that crest movements were measured during the years following the original dam's completion. Movement varied from about 35 cm/yr (13.2 in/yr) between 1927 and 1929 to about 1 cm/yr (0.4 in/yr) between 1942 and 1951. In 1954, about 2,000 m^3 of fill were added to the crest area to restore its original elevation.

In 1971, the USBR was requested to evaluate the dam; in 1977, it recommended various remedial measures, including rebuilding the crest and replacing part of the spillway. During an excavation near the toe of the spillway in 1981, movement of the spillway occurred. The excavation revealed a plastic layer with slickensides, and a subsequent investigation resulted in landslides being mapped under the spillway and dam. To increase the stability, the USBR recommended limiting the elevation of the downstream face berm (Figure 9) and filling or buttressing the river channel area. The work included the placement of a 2.44 m (8 ft) diameter pipeline, completed in 1984, to carry outlet flows.

The river is no longer visible in Figure 8, indicating that the photo was taken after completion of the 1980s improvements. Between 1992 and 1993, instrumentation consisting of seven inclinometers was installed (three along the crest, one over the buttress, and three downstream of the toe). Three of the four inclinometers installed on the buttress and downstream of the dam became inoperable within ten years of their installation due to excessive horizontal movements. Although these inclinometers were not completely sheared by 2002, we understand that they currently are. Movement was reported to our GEER team to have occurred at a depth of about 19 m (elevation 170 m), where a layer of green clay that slopes at an angle of about 4° exists. The appearance of piezometers in the field suggests they are contemporaneous with the slope indicators (i.e., installed in the early 1990s) (Silva-Tulla et al., 2018).

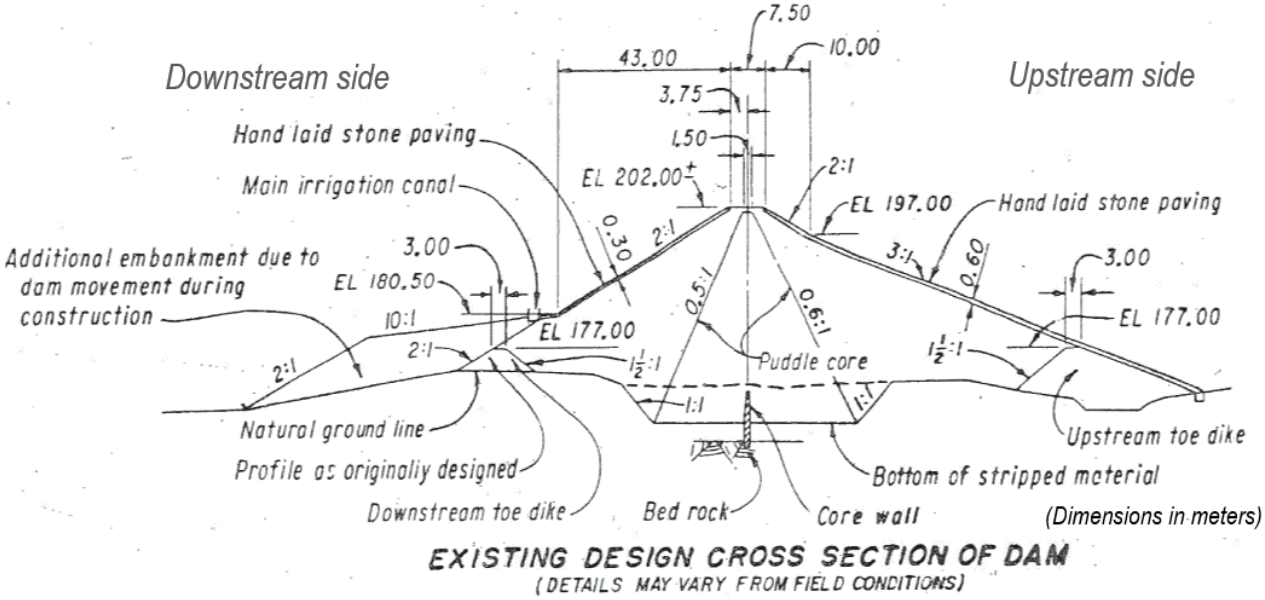


Figure 9. Cross-section of Guajataca Dam from the 1920s (date of drawing is unknown; USBR, 2002).

During Hurricane Maria, scour severely damaged the spillway and siphon at Guajataca Dam, as shown in Figure 10. The siphon, replaced by pumps after the damage from the hurricane, supplied raw water for the Aqueduct and Sewer Authority pump located near the reservoir. Concerns about the dam's stability prompted emergency remedial measures and the evacuation of about 70,000 residents located downstream of the dam. The maximum reservoir elevation that resulted from Hurricane Maria remains unknown.



(Photo location: Lat. +18.39717º Lon. -66.92759º, photo taken 10/30/2017 looking south)

Figure 10. Damaged condition of Guajataca Dam spillway (Silva-Tulla et al., 2018).

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The Google Earth aerial image shown in Figure 11(a) shows the spillway, apparently in good condition in March 2017. In contrast, a Google Earth image from November 2017, shown in Figure 11(b), illustrates significant damage after Hurricane Maria. Figure 11(b) shows that about 100 m (300 ft) of spillway was completely destroyed (roughly 40 m of concrete and 60 m of riprap), and that an additional 25 m of concrete spillway was significantly undermined and displaced. A siphon located under the spillway was also destroyed. Aerial photographs taken during the aftermath of Hurricane Maria show water spilling out of the upstream side of the siphon (on the north side of the spillway), indicating that the siphon was operational during Hurricane Maria. Scour depths below the spillway could not be measured since the area had already been partly filled, but photographs and witness accounts indicate that extensive scour occurred.

What appear to be sand boils along the toe of the earth dam suggest that its foundation materials were also subject to soil transport during Hurricane Maria (Figure 12). The seepage path and source of the eroded materials remain unknown, and considerable uncertainty exists about the origin and nature of the features shown in Figure 12. The GEER team observed water, soil, and other debris in the capped piezometer protective pipes consistent with a recent spike in groundwater pressures. During their visit, the team noted a large void approximately 0.3 m in diameter, located 10 m downstream of the toe and directly downstream of the "A" of the AEE sign on the downstream slope. Excavations, structures, poles, or posts were not reported or visible in aerial photographs near the location of the reported cavity. It seems possible that the void was either created or exacerbated by underseepage resulting from high hydraulic head during Hurricane Maria (Silva-Tulla et al., 2018).



(a) Aerial photograph of dam before Hurricane Maria (March 2017, Source: Google Earth).



(b) Aerial photograph of dam after Hurricane Maria (November 2017, Source: Google Earth).

Figure 11. Comparison of the Guajataca Dam condition between March and November 2017.



Note: Yellow arrows show location of apparent sand boils downstream of the dam toe.

Figure 12. Apparent sand boils downstream of the dam toe (photograph from the Pennsylvania National Guard; figure adapted from Silva-Tulla et al., 2018).

LANDSLIDES

Based on the GEER team observations, slope instability was the most common geotechnical failure mechanism in Puerto Rico during Hurricane Maria. An early USGS count, using satellite and aerial images, reported that Hurricane Maria triggered over 2,000 landslides (Bessette-Kirton et al., 2017). More recently, the USGS and UPRM estimated more than 40,000 landslides and debris flows (Hughes and Morales-Vélez, 2017; Bessette-Kirton et al., 2019). These landslides occurred throughout the island and either damaged or destroyed roads, power transmission lines, water supply pipes, sewer systems, and structures of all types. A common failure mode encountered by the team consisted of scour of highway embankments from overtopping water after debris plugged the pipes and culverts designed to allow streams to flow underneath. This failure mode involved both wind and water forces. Wind toppled trees and other vegetation, creating vast amounts of debris; water carried the debris to the upstream toe of the embankment, where the debris then plugged the drainage facilities.

A rapid identification of landslide density across the island was performed by the USGS (Bessette-Kirton et al., 2017 and 2019) by examining post-hurricane satellite and aerial images (Figure 13). The map was generated analyzing FEMA and DigitalGlobe images collected between September 26 and October 8 in order to estimate the number of landslides inside 2 km x 2 km square cells. The authors warn of limitations of the study related to poor visibility associated with clouds, vegetation, and/or shadows. Further, the authors assumed that the majority of landslides detected were triggered by rainfall from Hurricane Maria, but the effects of antecedent rainfall from Hurricane Irma (September 6, 2017) and heavy rainfall reported in the days after Hurricane Maria may have also triggered landslides.

Despite these constraints, this map is useful in helping to identify the most critical areas of the island affected by landslides, and in aiding response and recovery efforts. The map in Figure 14 shows results of an ongoing investigation at UPRM by Hughes and Morales-Vélez (2017), in which more than 40,000 debris flow landslide sites have been identified across PR. Based on results from these two studies, the municipalities most severely impacted by landslides were Añasco, Mayagüez, Las Marías, Maricao, Lares, Utuado, Adjuntas, Jayuya, Ciales, and Orocovis. Three deaths were attributed directly to one of the landslides in the town of Utuado.

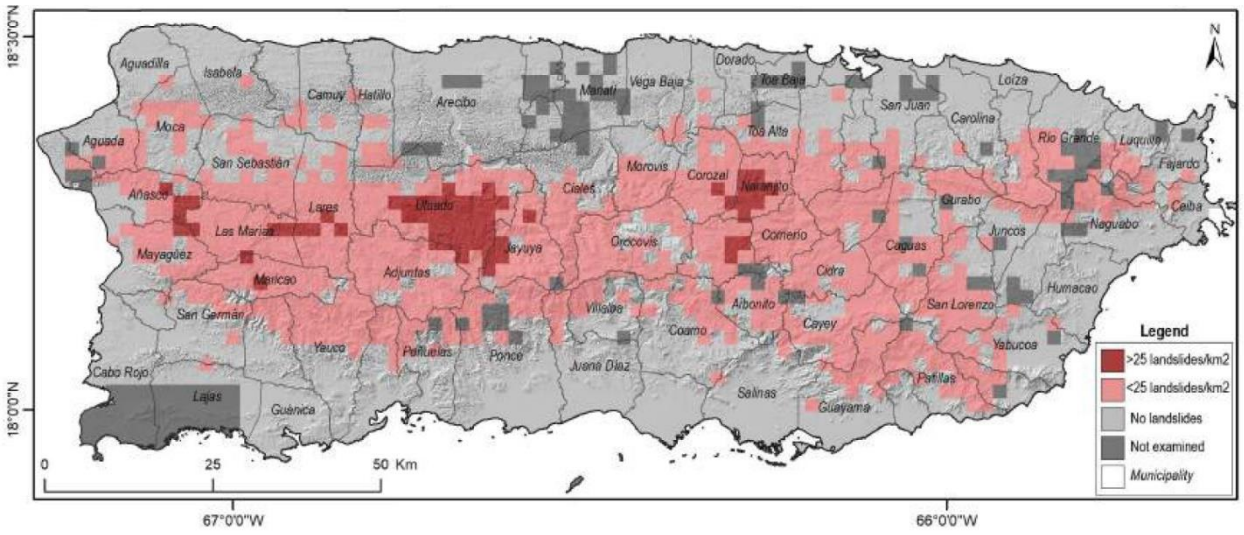


Figure 13. USGS map showing concentration of landslides attributed to Hurricane Maria (Bessette-Kirton et al., 2019).

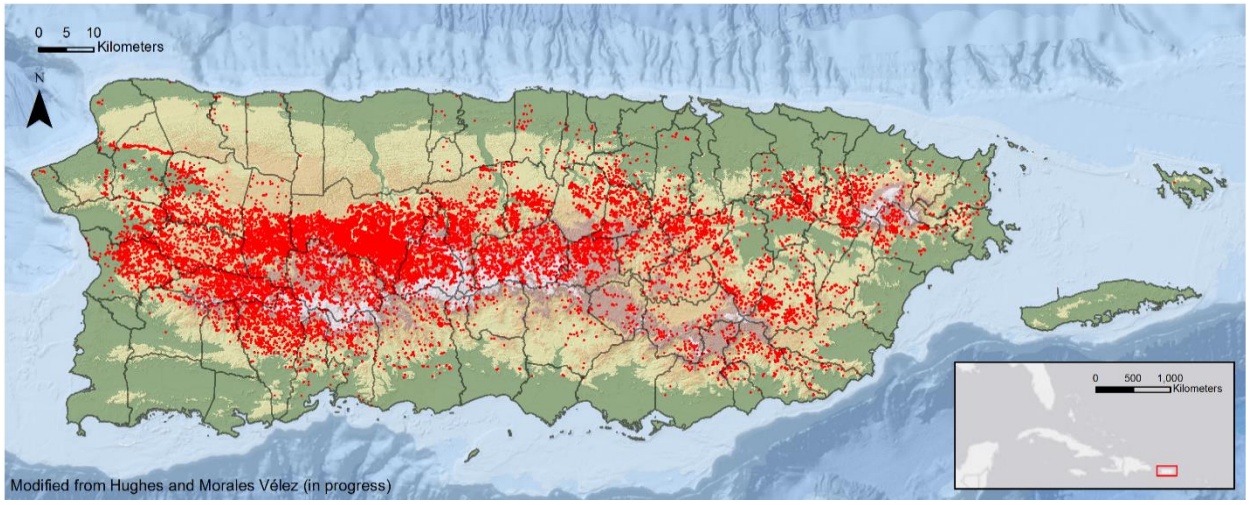


Figure 14. More than 40,000 debris flow sites (shown as red dots) identified across PR by Hughes & Morales-Vélez (2017).

The passing of Hurricane Maria destroyed most rainfall gauges. However, rainfall estimates by NOAA and the National Weather Service for the period of 8:00 AM on September 19 to 8:00 AM on September 21 indicate rainfall ranging between 279 to 559 mm (11 to 22 in) for the municipalities most affected by landslides. For this 48-hour period, the average rainfall intensity would range approximately from about 5.8 to 11.6 mm/hr. Figure 15 shows this estimated range of rainfall intensity for Hurricane Maria, considering a 48-hour duration, together with a preliminary regional landslide rainfall threshold for Puerto Rico by Pando et al. (2005). The estimated rainfall intensity and duration for Hurricane Maria falls above this generalized regional landslide rainfall threshold, consistent with the many documented landslides recorded.

The majority of the slides shown in Figure 14 consisted of shallow debris flows. Figure 16 shows a site, visited by the GEER team, which was affected by some debris flows; this site is located along Puerto Rico State Road 4131 (PR-4131) near the Rio Blanco River in the municipality of Lares. The largest debris flow shown destroyed three homes along the lower road alignment (Silva-Tulla et al., 2018). Luckily, the inhabitants of those homes were not present at the time of the landslide. The debris flow initiated just above the highest road cut on a switchback along PR-4131. The upper area is the primary zone of volume loss, while the lower portion of the road was only covered by debris. The hillslope material slid directly into the river below, which carried much of the small- to medium-sized sediment downstream. Figure 17 shows aerial imagery of the landslide before and after Hurricane Maria.

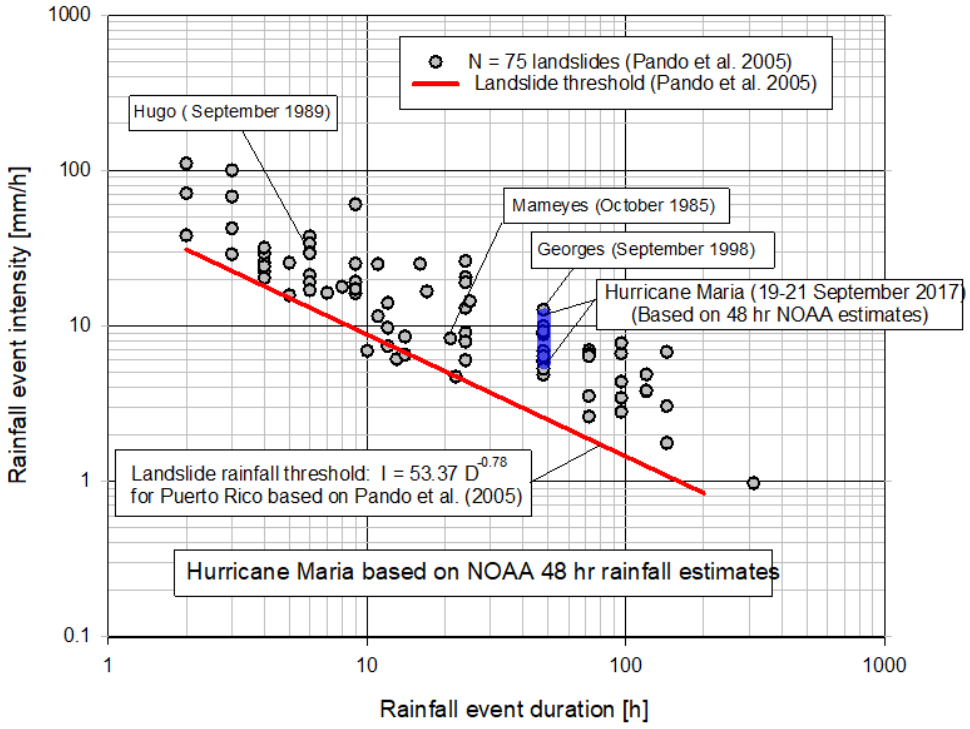


Figure 15. Estimated Hurricane Maria rainfall (blue line) and the Pando et al. (2005) rainfall-induced landslide threshold.



Figure 16. Photo of debris flow above the Rio Blanco River along PR-4131 in Municipality of Lares (photo taken using UAV at location: Lat. +18.250348° Lon. -66.884155°, looking toward the North).



Note: Upper image taken before Hurricane Maria. Lower photo captured by FEMA on October 12, 2017. The white circle with black center dot indicates the location of the TLS Lidar performed in January 2018.

Figure 17. Aerial photos of debris flow site on PR-4131 in central Lares along the Rio Blanco (Silva-Tulla et al., 2018).

COASTAL AND RIVER EROSION AND SCOUR

GEER reconnaissance observations showed ample evidence of coastal erosion and scour where storm waves destroyed or damaged facilities which had been built near (and many in close proximity to) the shoreline. Similarly, river erosion and scour-related damage was also prevalent throughout PR. Much of the river damage was associated with high flows and large accumulations of storm debris. Several critical bridges were destroyed while others were significantly damaged by the

resulting thrust from the debris pushing on their upstream sides. Figure 18 shows the coastal and river scour sites visited by the GEER team. For the sake of brevity, only a couple of these sites are presented herein. A detailed description of all sites shown in this figure appear in the GEER report (Silva-Tulla et al., 2018).



Figure 18. Location of coastal and river scour sites visited by GEER team (Silva-Tulla et al., 2018).

Coastal Scour at Site CE3

Site CE3, located within the Córcega Beach in the municipality of Rincón on the west coast of PR, showed damage at an oceanfront condominium complex consisting of two buildings (Rincón Ocean Club I and II) and a residence (Building A), as shown in the pre-storm aerial image in Figure 19. The beach width before Hurricane Maria at this site was about 6 to 9 m (20 to 30 ft).

After Hurricane Maria, several buildings in the area of Site CE3 suffered severe damage, as shown in Figure 20. This figure shows extensive damage from waves or scour at the three-story Rincón Ocean Club I building, which was supported on shallow footings, and at the common areas of the terrace and swimming pool. A large volume of soil eroded from the front of the buildings and from beneath the swimming pool. Footings and beams supporting the terrace were exposed and sheared off from the building foundation. Part of Building A collapsed into the ocean and what remained standing was severely cracked. The Victoria Del Mar Condominium, the tallest building in this area and located to the north of Rincón Ocean Club I, also suffered extensive damage due to coastal scour. The terrace and swimming pool area of this condominium collapsed thanks to the storm.

The beachfront in the Córcega Beach area suffered extensive coastal scour. The approximately 6 to 9 m (20 to 30 ft) of beachfront shown in the pre-storm photo (Figure 19) was drastically reduced at the time of the site reconnaissance. The GEER Team did not observe sand washout deposits or shoreline erosion protection measures during the field reconnaissance of Site CE3. Unfortunately, there were no storm tide sensors available near Rincón to help assess tidal levels or the magnitude of wave action during this hurricane. However, NOAA (2017) reported highest water levels of 0.3 to 0.6 m (1 to 2 ft) above maximum higher high water (MHHW) for the northwest coastline of PR, where MHHW is defined as the average daily highest tide. This is consistent with a high-water elevation mark data recorded at USGS Stations (Silva-Tulla et al, 2018).



Note: base image from Google Earth, January 27, 2017, accessed June 3, 2018.

Figure 19. Pre-storm aerial image of coastal scour Site CE3 (Silva-Tulla et al., 2018).



(Source: http://www.noticel.com/english/condo-in-rincon-collapses-due-to-hurricane-maria/638463446)

Figure 20. Oceanfront damage in Córcega Beach area (Site CE3; Silva-Tulla et al., 2018).

River Scour at Site RE1

On October 31, 2017, the GEER team observed scour and erosion near the piers and abutments of Highway 52 bridges over the Inabón River at site RE1, just east of the city of Ponce, PR. Figure 21 shows select photos taken during the site visit. The photos show exposed abutment H-piles and ongoing emergency work, including the erection of formwork for abutment repairs and a temporary protective gabion wall. The gabion wall should protect the abutment and reinforced concrete shield under construction in front of the original exposed piles.



Figure 21: Photos of west abutment of westbound Highway 52 Bridge over the Inabón River (October 31, 2017; Silva-Tulla et al., 2018).

ROAD AND BRIDGE FAILURES

Hurricane Maria triggered many road failures and damaged several bridges. This section describes the primary failure modes observed at the sites visited by the GEER Team. Due to page limitations, we show only one representative failure. The GEER report (Silva-Tulla et al., 2018) describes additional road and bridge failure sites.

Many of the road and bridge failures involved the mechanisms described in preceding sections related to scour, as well as the landslides and debris flows triggered by low effective stresses. Numerous landslides in the mountainous central part of the island cut off terrestrial transportation for many residents. If the landslide occurred above the road, covering the pavement with soil and rock, the remedy consisted of partial or total removal of the landslide debris, a time-consuming and costly task but generally within the capabilities of the municipal governments. If the landslide included the road, that meant the water, sewer, electricity, and telecommunications infrastructure was often destroyed along with the road, presenting a much more complicated recovery challenge.

The road and bridge failures observed in the GEER mission were categorized into five different categories: road failures associated with partial or total culvert blockage, road failure sites with downslope slope failures, road failure sites with slope failures on the upslope side (road blockage), road failure sites with complete road failure cut-off, and bridge failures. Most road failures were at locations where the section was built on a fill bench. Some road embankment failures were on the downslope side, other failures were uphill, and some were deep-seated and encompassed both sides of the road. In addition to these failure characteristics, a large number of the road failures involved blockage (total or partial) of a culvert beneath the road (Silva-Tulla et al., 2018).

The GEER team visited several bridge sites and observed damage related to the large hydrodynamic forces from the increased volume and flow speeds associated with Hurricane Maria floods. Figure 22 shows photos from two bridge sites visited by the GEER team; these provide an idea of the magnitude of debris accumulation and the associated large hydrodynamic forces.



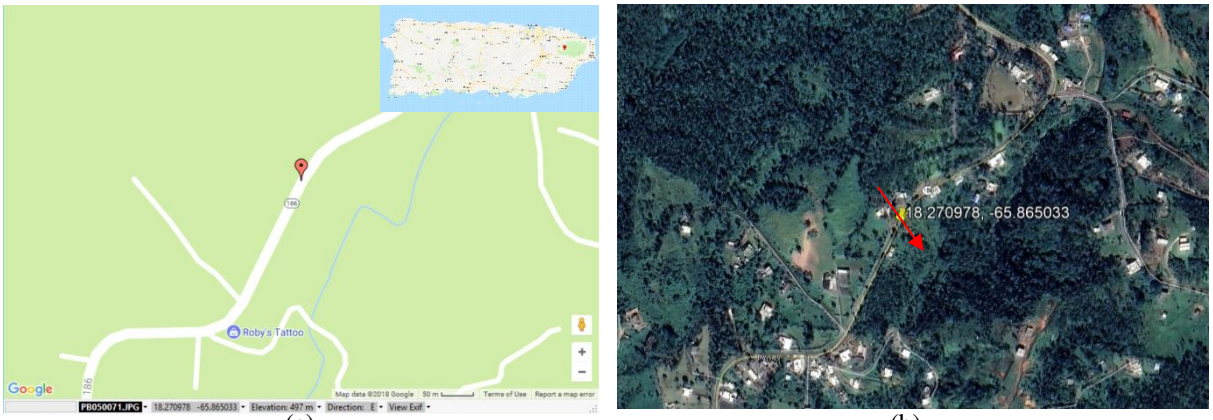
(Lat: +18.301439°, Lon: -66.698319°, 11/02/17)
a) PR-123 bridge failure ("Los Olvidados")

(Lat: +18.28683°, Lon: -67.10610°, 11/03/17)
b) Debris blocked at bridge

Figure 22. Images showing debris accumulation and damage at bridges during Hurricane Maria (Silva-Tulla et al., 2018).

Figure 23(a) shows the location of a road failure on the northeast side of the island near the west boundary of the El Yunque National Rain Forest, along road PR-186. The failure affected the full width of PR-186 and the entrance driveway of a residence on the west side of the road (upslope side). The arrow shown in Figure 23(b) points toward the slope failure direction (southeast). Figure 23(c) shows the upper portion of the failure that resulted in a complete cut-off of PR-186. Figure 23(c)

shows a portion of the concrete pavement driveway of a residence to the left of the image (residence not shown); the final position of the piece of concrete driveway is shown inside the red oval. Additional exemplifying photos are shown in Figures 23 (d), (e), and (f). The arrows in Figure 23(f) point toward the slope failure direction (southeast).



(a) (b)

Note: Lat: +18.270978°, Lon: -65.865033°



(c) (d)

(e) (f)

Figure 23. Road failure affecting PR-186 (GEER mission Site 7; Silva-Tulla et al., 2018).

FOUNDATION FAILURES

Foundation failures observed by the team included lighting towers, electrical transmission poles, and many road sign failures. Some of the road signs simply rotated about the axis of their circular drilled shaft foundation, while others also experienced bearing capacity failures. Although some electrical transmission poles failed from bearing capacity failures, the large number of reinforced concrete poles that had snapped at mid-height provided graphic evidence of the storm power. Figure 24 shows a representative torsional foundation failure of a highway sign structure.



Note: Photo location: Lat: +018.436633°, Lon: -067.147746°; Date: October 30, 2017.

Figure 24. Photo of cantilevered sign foundation failure (GEER Mission Site F2; Silva-Tulla et al. 2018).

SUMMARY AND CONCLUSIONS

Hurricane Maria overwhelmed the natural and constructed facilities in Puerto Rico with its strong winds and intense rainfall. The National Weather Service classified Hurricane Maria as a strong Category 4 hurricane on the Saffir-Simpson hurricane wind scale at the time of its landfall in Yabucoa, Puerto Rico, U.S.A., on September 20, 2017. The immediate aftermath of Hurricane Maria was a devastated island, with several thousand human casualties, severe infrastructure loss, and numerous geotechnical failures related to the intense rainfall and strong winds associated with this extreme event. The passage of Hurricane Maria also triggered thousands of landslides, with the most common type of failure mode consisting of shallow debris flows. Many deeper-seated failures were also observed, typically at sites with a road fill and blocked drainage.

The geotechnical observations presented in this article provide insight to help identify typical modes of failure and to help the engineering community adapt and improve design and construction practices to achieve more resilient infrastructure and lifelines. This case history highlights the importance that antecedent precipitation (in this case, rainfall associated with Hurricane Irma) has on the vulnerability to landslides and debris flows during extreme events such as hurricanes. The combined effects of two high category and near-occuring hurricanes, such as Irma and Maria in PR, have been exceedingly rare historically. The GEER mission to Puerto Rico after Hurricane Maria provided insight on what to expect in landslide-prone areas, especially regarding the need for better predictions of debris flow instability, implementation of mitigation measures (e.g., better/stronger utility poles and their foundations, expanded use of debris basins), and enforcement of zoning regulations to reduce the negative effects of extreme events.

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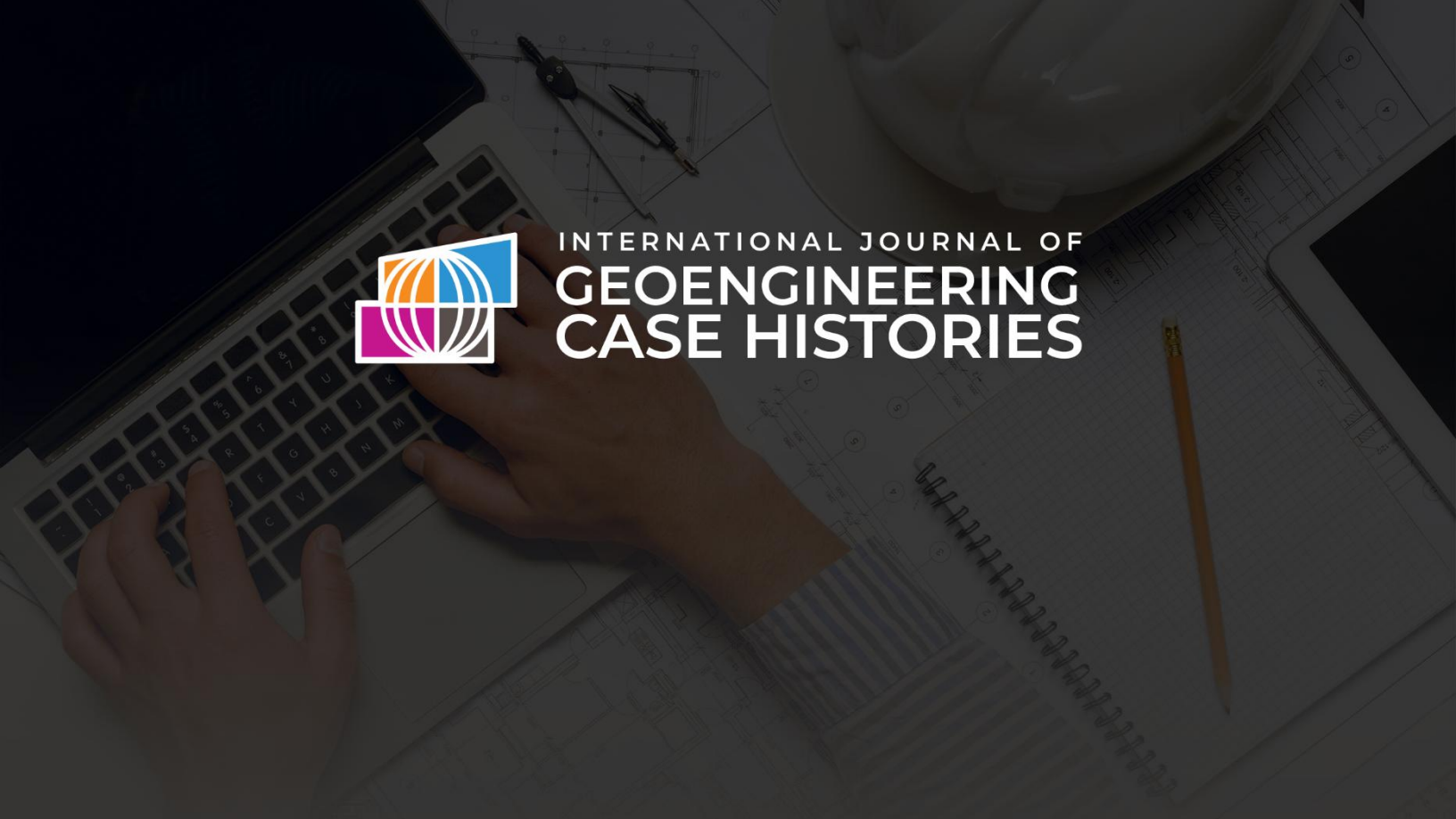
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ACRONYMS

AEE	Electric Power Authority (in Spanish: *Autoridad de Energia Electrica*)
cm	Centimeters
cm/yr	Centimeters per Year
CRIM	*Centro de Recaudación de Impuestos Municipales*
DEM	Digital Elevation Model
FEMA	Federal Emergency Management Agency
ft	Feet
GEER	Geotechnical Extreme Events Reconnaissance
in	Inches
in/yr	Inches per Year
km	Kilometers
LiDAR	Light Detection and Ranging
m	Meters
m/s	Meters per Second
m/yr	Meters per Year
mi	Miles
mm/h	Millimeters per Hour
mph	Miles per Hour
NASA	National Aeronautics and Space Administration
NBC	National Broadcasting Corporation
NID	National Inventory of Dams
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NWS	National Weather Service
PR	Puerto Rico
PRASA	Puerto Rico Aqueduct and Sewer Authority
PREPA	Puerto Rico Electric Power Authority
TLS	Terrestrial Laser Scanning
UAV	Unmanned Aerial Vehicle
UPRM	University of Puerto Rico at Mayaguez
USBR	United States Bureau of Reclamation
USGS	United States Geological Survey
VSABR	Volcano Sedimentary Arc Basement Rocks



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