Geotechnical Impacts of Hurricane Fiona in Puerto Rico

Event Date: September 18, 2022

Geotechnical Extreme Events Reconnaissance

Turning Disaster into Knowledge

Sponsored by the National Science Foundation

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GEER Team and Contributors:

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Alesandra Morales[1], Stephen Hughes[1], Karl Lang[2], Frances Rivera-Hernandez[2], Paola Vargas Vargas[2], Jorge Mario Lozano[2], Efstratios Karantanellis[3], Mirna Kassem[4], Drew Gomberg[4], Ries Plescher[3], Edwin Irizarry[1], Estefania Vicens[1], Tania Figueroa[1], Coralis Friedman[1], Kiara Cunillera[1], Anishka Ruiz[1], and Victor Ortega[1]

[1]University of Puerto Rico at Mayagüez
[2]Georgia Institute of Technology
[3]University of Michigan
[4]University of California at Berkeley

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The team leaders are grateful for the collaboration with world class colleagues in the mainland US and their continued partnership.

Executive Summary

Amidst a very active wet season in Puerto Rico, Hurricane Fiona impacted the island on September 28, 2022, bringing over 25 inches of rainfall in some places. The hurricane caused hundreds to thousands of landslides, in addition to extensive flooding and isolated bridge failures. The GEER Hurricane Fiona mission in Puerto Rico was carried out by 13 members during two time periods: 15-19 Oct 2022 and 30-Oct to 08-Nov 2022. The main mission of the two teams was to document and study the geotechnical impacts of Hurricane Fiona and document the induced damages in 50 initial target locations across the island. Instrumentation used in this expedition included GPS trackers, Filio application, and UAVs. Almost exactly 5 years after Hurricane María, we compare the differences and similarities of the two events and the effects on the natural and built landscape. This report includes an appendix with links to over 1,600 images of sites that were visited by our team.

1. INTRODUCTION

1.1. Event Background and Study Area

Comprehensive description of Hurricane Fiona's development and progress has been prepared by the San Juan National Weather Service Office: https://www.weather.gov/sju/fiona2022. Much of the background information below is adapted from this source and the National Hurricane Center archive: https://www.nhc.noaa.gov/archive/2022/FIONA.shtml.

The Atlantic basin's tropical depression #7 formed on 14-Sep-2022 approximately 1300 km east of the Lesser Antilles and became a tropical storm later the same day (Figure 1). At that stage, the storm was not projected to grow into a hurricane. A Tropical Storm Watch was issued for Puerto Rico and the Virgin Islands on 15-Sep-2022, upgraded to a Tropical Storm Warning on 16-Sep-2022.

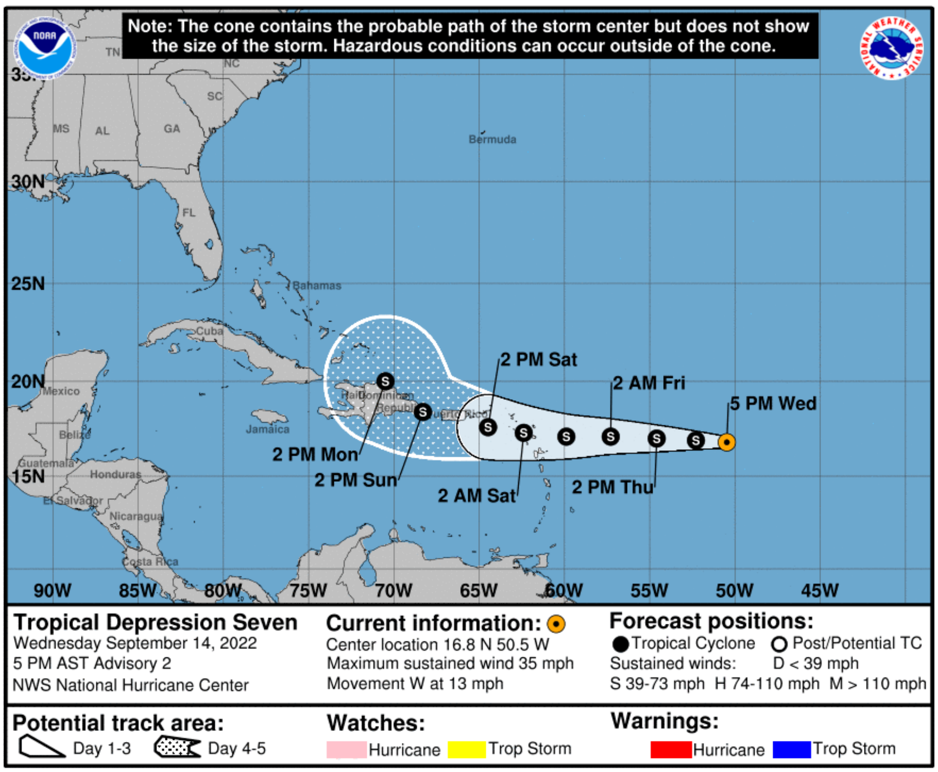


Figure 1: Forecast for Tropical Depression #7 issued at 17:00h AST on 14-Sep 2022 by the National Hurricane Center.

The tropical storm moved across Guadeloupe on 16-17 Sept-2022 with wind gusts of 100+ km/hr, sea swell of 4m, and maximum rainfall intensities up to 150+ mm/hr, 200+ mm/3hr and 300+ mm/6hr; these effects caused flooding and landslides, resulting in around 2 dozen rescues, one death, and damage to infrastructure that led to the declaration of a local state of disaster (Figure 2; https://la1ere.francetvinfo.fr/guadeloupe/tempete-tropicale-fiona-que-d-eau-que-d-eau-1322380.html; https://la1ere.francetvinfo.fr/guadeloupe/tempete-fiona-l-etat-de-catastrophe-naturelle-reconnu-pour-22-communes-de-guadeloupe-1324712.html).

Figure 2: Tropical Storm Fiona damage in Guadaloupe. From: https://la1ere.francetvinfo.fr/guadeloupe/tempete-fiona-l-etat-de-catastrophe-naturelle-reconnu-pour-22-communes-de-guadeloupe-1324712.html

As Tropical Storm Fiona moved past Guadeloupe and into the northeastern Caribbean Sea, a Hurricane Watch was issued for Puerto Rico at 5:00h AST on 17-Sep-2022 (Public Advisory 12) and then upgraded to a Hurricane Warning at 11:00h AST on the same day (Public Advisory 13). In the same 6 hour span, the forecasted event rainfall totals for Puerto Rico increased from 125-250 mm (5-10 in.), locally up to 400 mm (16 in.) to a revised estimate of 300-400 mm (12-16 in.), locally up to 500 mm (20 in.). At 5:00h AST on 18-Sep-2022, the National Hurricane Center located the storm center approximately 240 km southeast of Ponce, Puerto Rico and updated the maximum potential totals of event rainfall for Puerto Rico could be up to 625 mm (25 in.; Public Advisory 15). At 11:00h AST on 18-Sep-2022, with its center located only 80 km south of Ponce, Fiona was upgraded to a hurricane (Public Advisory 17). As the center moved WNW just south of the island, strong rain bands in the hurricane's northern and eastern quadrants affected all of Puerto Rico (Fig 3). The National Hurricane Center reported that the eye of the Hurricane made landfall in southwestern Puerto Rico at 15:20h AST on 18-Sep-2022 (Public Advisory Update, Sept 18).

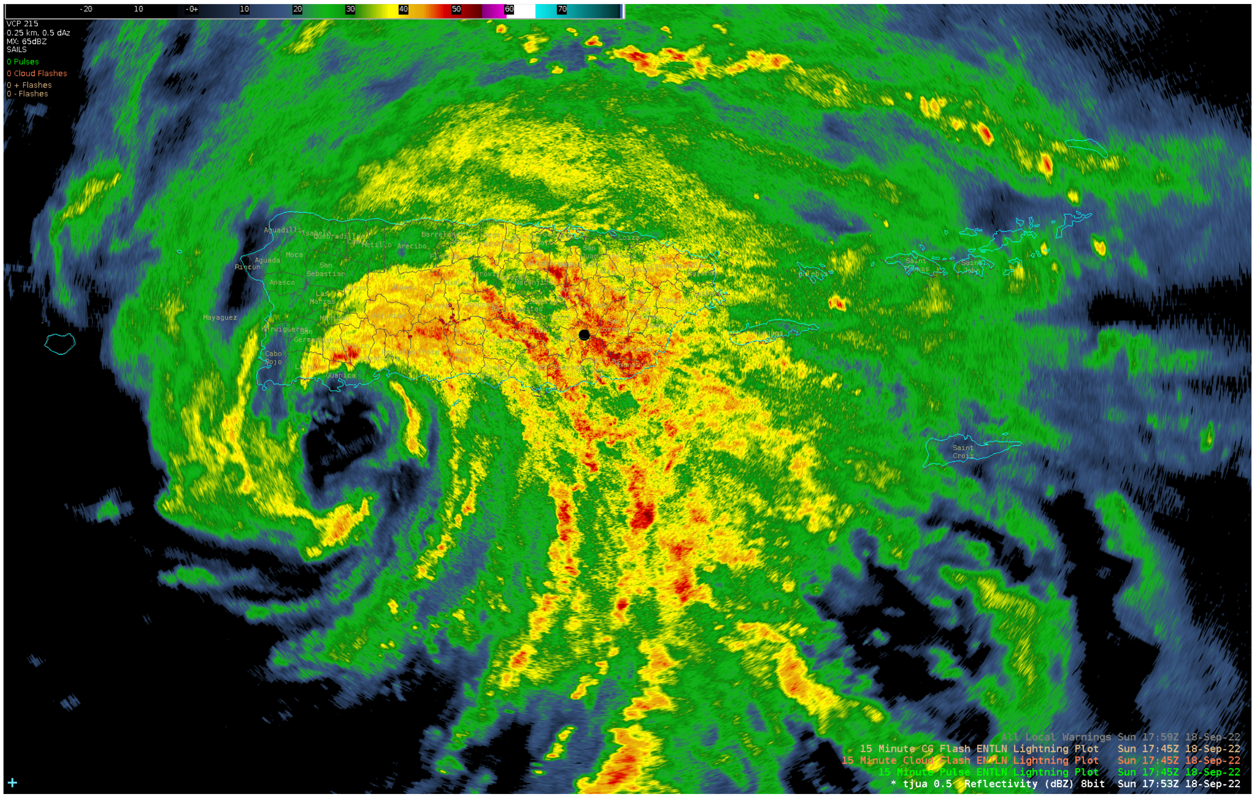


Figure 3: Doppler radar image of Hurricane Fiona as its center of circulation approached southwestern Puerto Rico. Almost all of the intense rain for the cyclone was located to the north and east of the eyewall and crossed over the island of Puerto Rico. Image credit: NOAA/NWS.

The most intense rainfall across Puerto Rico occurred between 12:00h - 23:59h AST on 18-September-2022 (Figure 3). Hourly rainfall amounts of more than 25 mm (1 in.) were very common and over 50 mm (2 in.) were also recorded by rain gauges that are a part of the UPRM-USGS Puerto Rico Landslide Forecasting Network. Event totals for this network of gauges varied from 115 - 664 mm (4.5 - 26.5 in.; Figure 4). The National Weather Service hybrid radar and gauge estimates for the island show event totals of over 625 mm (25 in.; Figure 5). The USGS rain gauge at Lago Cerrillos recorded the maximum for the event at over 800 mm (32 in.).

The National Weather Service and USGS reported that at least 50 of 108 river gauges in Puerto Rico reached flood stage. At least 16 of the gauges reached major flooding levels (Figure 6) and included the Rio Grande de Loiza, Río de La Plata, Rio Cerrillos, Rio Portugues, Rio Gurabo, Rio Grande de Arecibo, Rio Grande de Manati, Rio Grande de Añasco, Rio Guanajibo, and others. Around 50 Flash Flood Warnings and 30 Flood Warnings were issued by the NWS. The storm surge in areas along the southern and eastern coast of the island complicated the river flooding issues as well.

Observed wind velocities at a NOAA Citizen Weather Observer Program station along the coast in Ponce included gusts of up to 103 mph (Figure 7). Most of the island did not experience hurricane force winds, given that the center of circulation passed over the extreme southwestern part of the island.

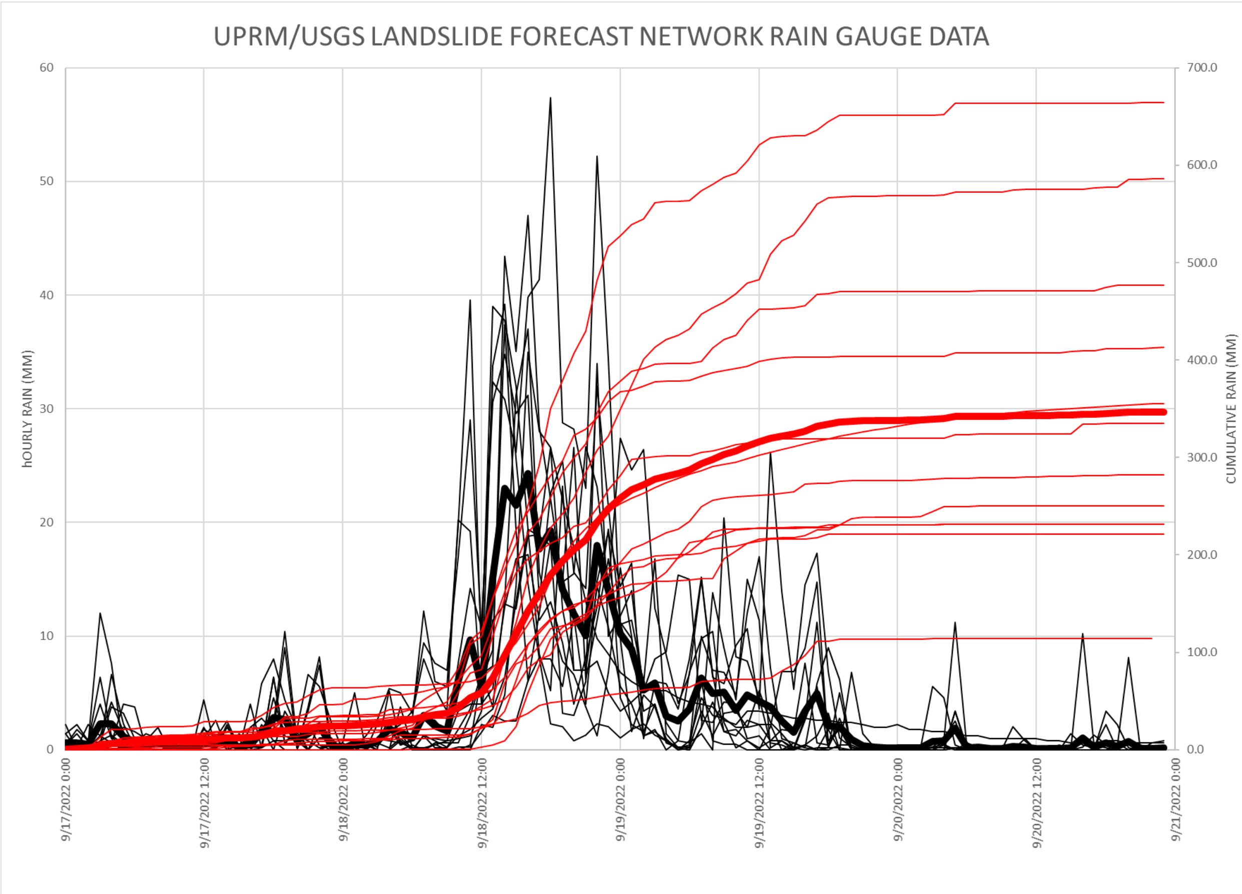


Figure 4: Four-day precipitation data from 12 monitoring stations that are part of the UPRM -USGS Puerto Rico Landslide Forecast Network. Black lines are hourly rainfall and red lines are cumulative rainfall. Thick lines are network averages. Stations are located in Adjuntas, Barranquitas, Cayey, Ciales, Lares, Maricao, Maunabo, Naguabo, Naranjito, San Lorenzo, Toro Negro, and Utuado.

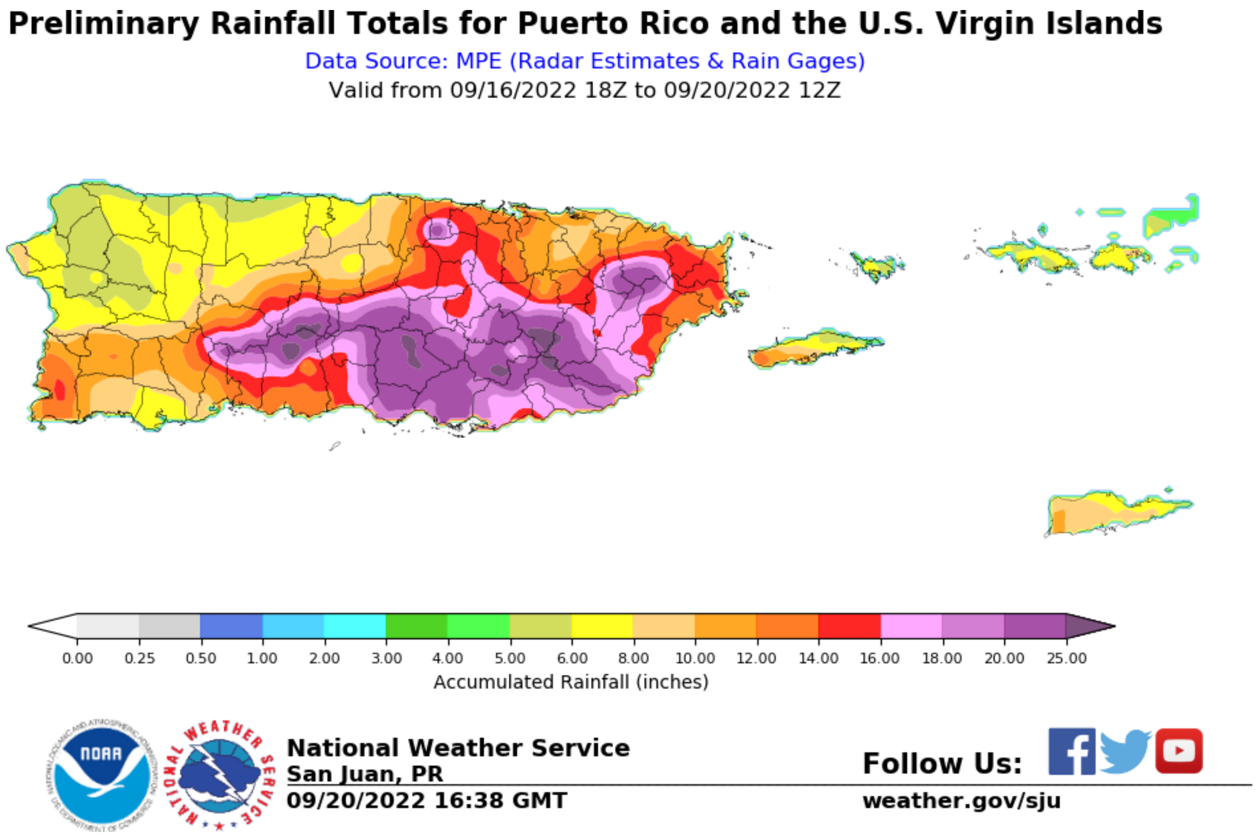


Figure 5: National Weather Service rainfall estimates for Hurricane Fiona in Puerto Rico and the US Virgin Islands

River Sensor	Flood Stage (feet)	Crest (feet)	Date and Time (UTC) of Crest	Flood Category
Rio Grande de Loiza, PR (CAGP4)	16	28.59	9/18/22 20:45	Major
Rio Grande de Loiza, PR (TRUP4)	22	44.65	9/18/22 22:15	Major
Rio Guayanes nr Yabucoa, PR (YBUP4)	21	25.06	9/18/22 19:36	Major
Rio de La Plata, PR (NASP4)	16	35.16	9/19/22 4:30	Major
Rio Cerrillos a, PR (PCEP4)	7	10.37	9/18/22 19:55	Major
Rio Portugues nr Tibes, PR (PRTP4)	14	23.4	9/19/22 5:05	Major
Rio Gurabo at G, PR (GURP4)	20	29.62	9/19/22 7:00	Major
Rio Grande de B, PR (CIEP4)	15	36.84	9/17/22 6:42	Major
Rio La Plata at HWY 2, PR (TOAP4)	16	26.78	9/19/22 5:45	Major
Rio Cibuco at Vega Baja, PR (VGBP4)	15	19.7	9/19/22 8:30	Major
Rio Grande de Arecibo nr San Pedro, PR (AREP4)	14	23.4	9/18/22 22:42	Major
Rio Grande de Manati at Ciales, PR (CIAP4)	10	48.28	9/19/22 13:35	Major
Rio Limon abv Lago Dos Bocas, PR (ARHP4)	14.5	17.81	9/18/22 19:15	Major
Rio Tanama at C, PR (ARDP4)	11	19.96	9/18/22 22:15	Major
Rio Grande de Anasco, PR (SEBP4)	11	26.12	9/18/22 22:45	Major
Rio Guanajibo nr Hormigueros, PR (HORP4)	20	29.21	9/19/22 10:48	Major

Figure 6: Table of flood classification for some rivers in Puerto Rico during Hurricane Fiona. From NWS San Juan

Stn ID	Latitude	Longitude	Time of Max Gust (utc)	Gust (mph)
EW7791	17.960	-66.620	2022-09-18 16:45	103.0
XECY	18.019	-65.857	2022-09-18 14:04	91.3
XMRS	17.929	-66.160	2022-09-18 14:59	81.0
XYTA	18.034	-65.837	2022-09-18 17:52	73.6
XCUL	18.314	-65.227	2022-09-18 15:18	66.7
XJUA	18.455	-66.128	2022-09-18 11:47	66.7
XYAB	18.052	-65.828	2022-09-18 17:42	65.4
XCDP	18.100	-67.189	2022-09-18 20:14	83.7
XBUK	18.278	-64.893	2022-09-18 11:25	60.2
XCRXp	17.678	-64.900	2022-09-18 11:01	59.4
XREY	18.289	-65.632	2022-09-18 14:43	55.2
XBRO	18.343	-64.817	2022-09-18 16:28	50.3
XYMN	18.022	-65.915	2022-09-18 14:07	73.3
XAGU	18.433	-67.157	2022-09-18 20:31	62.4
XGUR	18.256	-65.992	2022-09-18 16:58	52.3

Figure 7: Table of wind observations of Hurricane Fiona in Puerto Rico. From NWS San Juan

The eye of the hurricane traveled northwest and entered the Mona Passage by 17:00h AST (Public Advisory 18). It later passed over Mona around 20:00h AST and then continued towards Hispaniola, making landfall in southeastern Dominican Republic as a Category 1 hurricane around 3:30h AST on 19-Sep-2022. The hurricane moved northwest from Hispaniola into the Atlantic Ocean and eventually northward across the open ocean, reaching category 4 strength on 21-Sep-2022. Later on 24-Sep-2022, the system made landfall in eastern Nova Scotia (Figure 8; NHC Post-Tropical Cyclone Fiona Discussion Number 40).

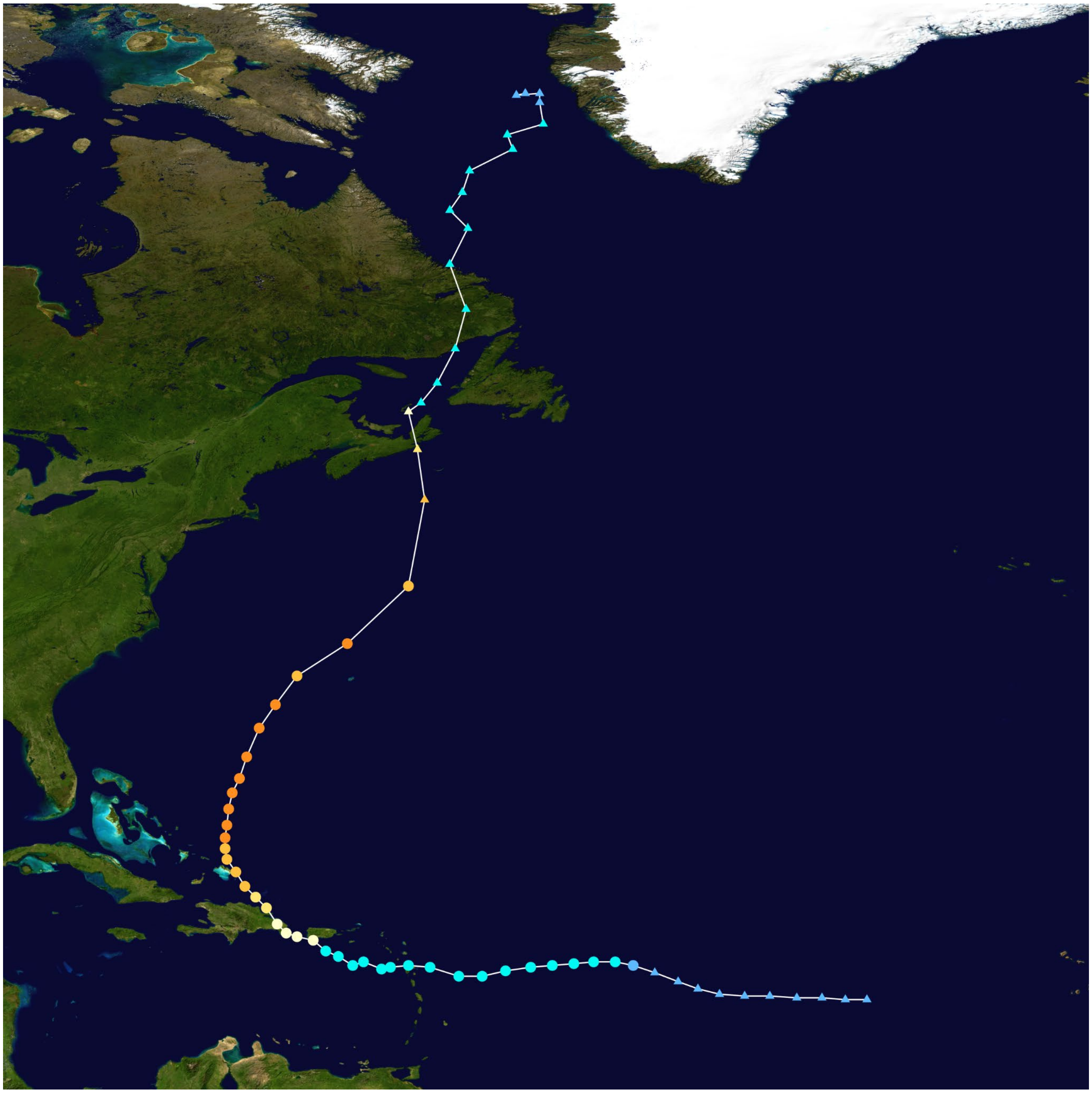


Figure 8: Hurricane Fiona track from wikipedia

1.2. Puerto Rico Landscape and Vulnerability

Puerto Rico is an island that is naturally disposed to landsliding given its tropical climate, tectonic setting, and land use legacy. Events like Hurricane Fiona often lead to flash flooding (a result of the island's dense fluvial network), landsliding, and wind damage.

The island's Cordillera Central rises up to >4,300 ft (>1,300 m) altitude and includes considerable relief in the slopes that descend down to sea level in a very short distance. Most of the island's mountainous regions are adjusting to uplift that was initiated around 4 million years ago and the fluvial network is adjusting to the disequilibrium caused by this movement. Because of this, hillslopes are often oversteepened and frequently slough off soil cover material. The mass movements are typically shallow, up to a few meters deep and commonly transition into debris flows during high-intensity rainfall events in first order channels.

Hurricane Fiona is not the first event to affect Puerto Rico, causing widespread flooding and landsliding. Events like Tropical Storm Isaias (2020), Hurricane María (2017), Hurricane Irma (2017), Hurricane Georges (1998), and several others during the past decades have caused similar destruction. Also, isolated flooding and landsliding associated with regularly tropical downpours are not uncommon in any given rainy season.

1.3. GEER Team

Table 1: GEER team members

Name	Affiliation	GEER Role
Alesandra Morales	University of Puerto Rico Mayagüez	Team Leader
Stephen Hughes	University of Puerto Rico Mayagüez	Team co-Leader
Karl Lang	Georgia Institute of Technology	Member
Frances Rivera-Hernandez	Georgia Institute of Technology	Member
Paola Vargas Vargas	Georgia Institute of Technology	Member
Jorge Mario Lozano	Georgia Institute of Technology	Member
Efstratios Karantanellis	University of Michigan	Team co-Leader
Mirna Kassem	University of California Berkeley	Member
Drew Gomberg	University of California Berkeley	Member
Ries Plescher	University of Michigan	Member
Edwin Irizarry	University of Puerto Rico Mayagüez	Member
Estefania Vicens	University of Puerto Rico Mayagüez	Member
Tania Figueroa	University of Puerto Rico Mayagüez	Member
Coralis Friedman	University of Puerto Rico Mayagüez	Member
Kiara Cunillera	University of Puerto Rico Mayagüez	Member
Anishka Ruiz	University of Puerto Rico Mayagüez	Member
Victor Ortega	University of Puerto Rico Mayagüez	Member

Figure 9: Some members of the GEER team at a landslide site in Las Marías in October 2022

2. METHODS AND INSTRUMENTATION

2.1. Reconnaissance planning

The GEER Hurricane Fiona mission in Puerto Rico was carried out during two phases. In the weeks following the Hurricane, team members at UPR-Mayagüez and Georgia Tech organized a catalog of target sites throughout the island based on information from federal and local government agencies in addition to local news reports, social media reports. The target sites list included over 50 locations and were organized with location information (municipality, road, kilometer marker, latitude and longitude), type of geotechnical failure, source of information, and then each was assigned a priority value on a scale from 1 to 3, with 1 being highest priority (Appendix A). These targets were incorporated into an interactive map platform (ArcGIS Online) that was easily accessible while we were in the field (Figure 10). The initial map was modified frequently to add or remove target points. The first group carried out reconnaissance during 15-19 Oct 2022 and the second group was organized from 30-Oct through 08-Nov 2022.

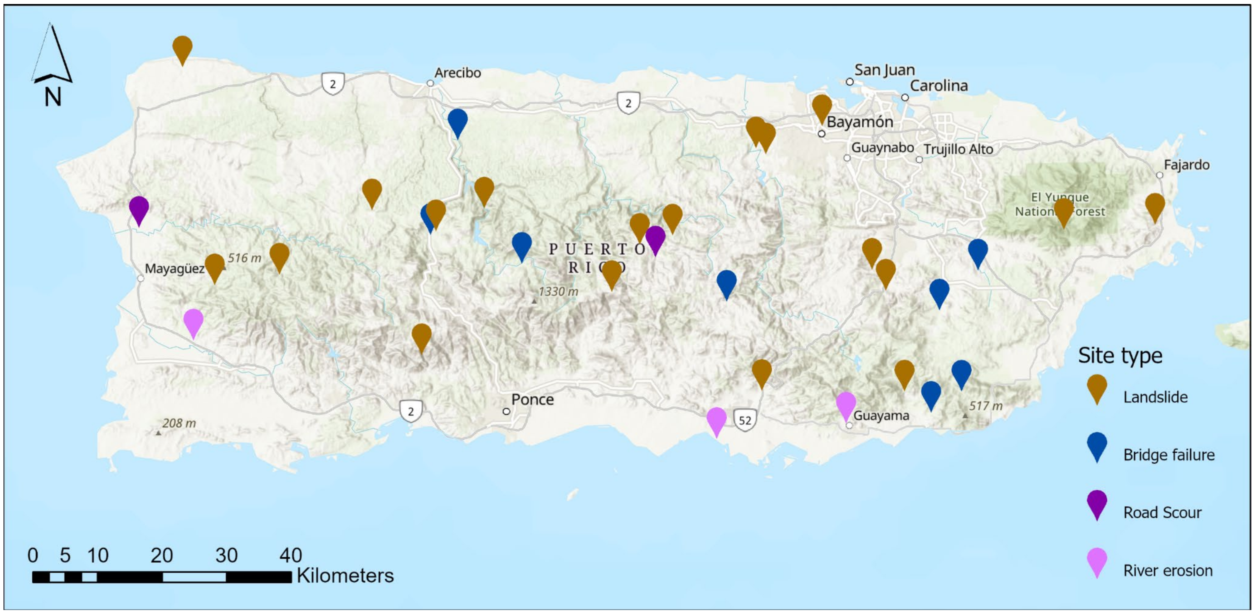


Figure 10: Pre-deployment target sites identified

2.2. Reconnaissance routes

Using handheld GPX trackers we recorded the routes taken by the team members. Figures 11 and 12 show the routes examined during the different phases of the mission.

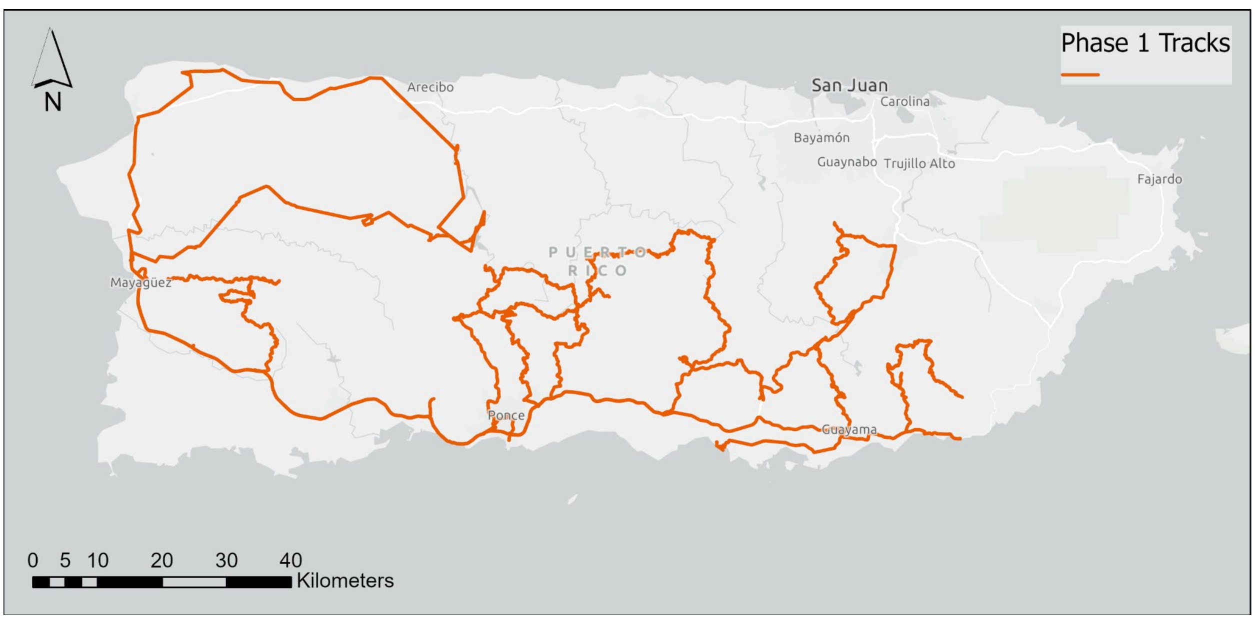


Figure 11: Reconnaissance tracks from Phase 1 (10/15 to 10/19)

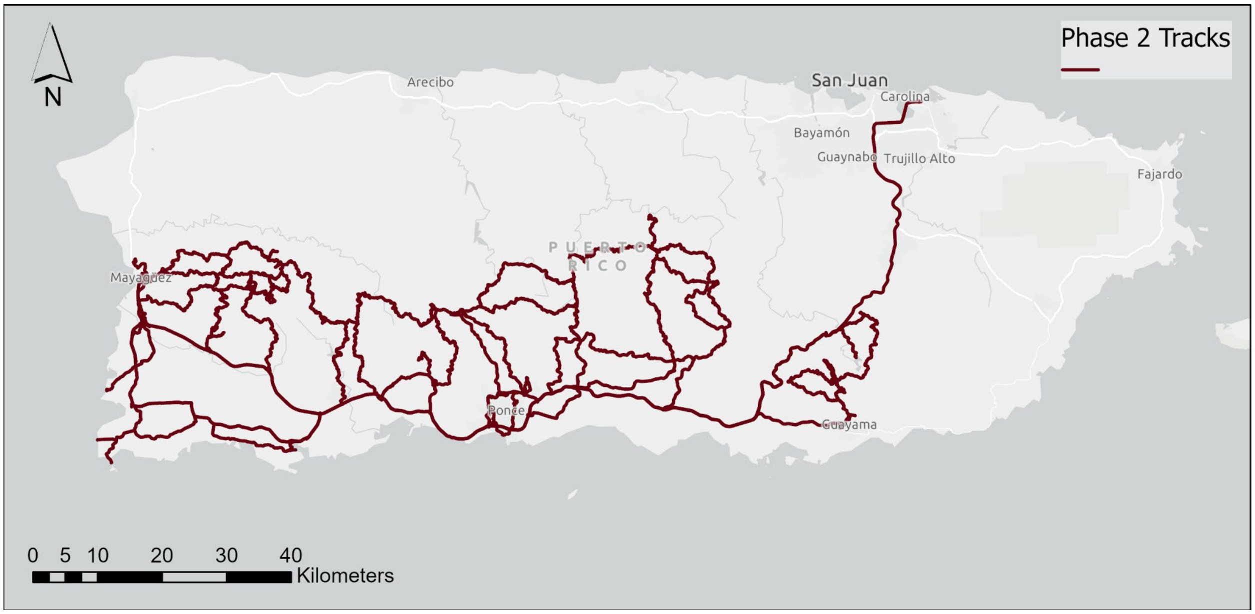


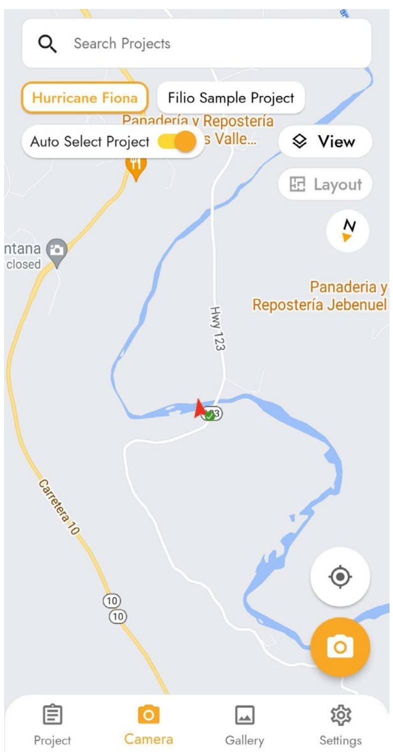
Figure 12: Reconnaissance tracks from Phase 2 (10/30 to 11/9)

2.3. Instrumentation

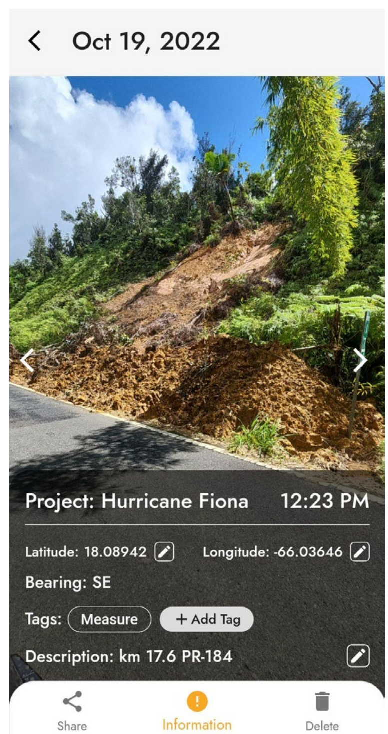
2.3.1. Filio Application Media Collector

We used the application “Filio” to collect around 1000 photos and videos of landslides, damaged roads and other damaged infrastructure that we encountered in the studied area as part of the documentation. When a picture was taken from within the application, Filio automatically collected the GPS coordinates, date taken, and the direction that the picture-taking device was facing. “Filio” also allowed us to write notes about the landslides in each image and thus keep track of any observations or specifics about the location (e.g highway number and mile marker). “Filio” also allows for voice notes to be added to images instead of written notes, though the team did not use this feature for this project.

The application added the point to a map of the project in the form of an arrow, as shown in Figure 13 (a). When selected, the photo and accompanying metadata are displayed, as shown in Figure 13 (b)



(a)



(b)

Figure 13. a) FIlio project map with arrow indicating the location where a picture was taken b)

Different “Filio” projects collected by several members of the team were joined together into one project that will be shared using a link to the public as part of this expedition. One of the limitations associated with “Filio” is that we were not able to extract the photos taken by “Filio” with the same resolution. The map below (Figure 14) and Appendix A shows the locations of all of our observations across the island during the 2-phased mission.

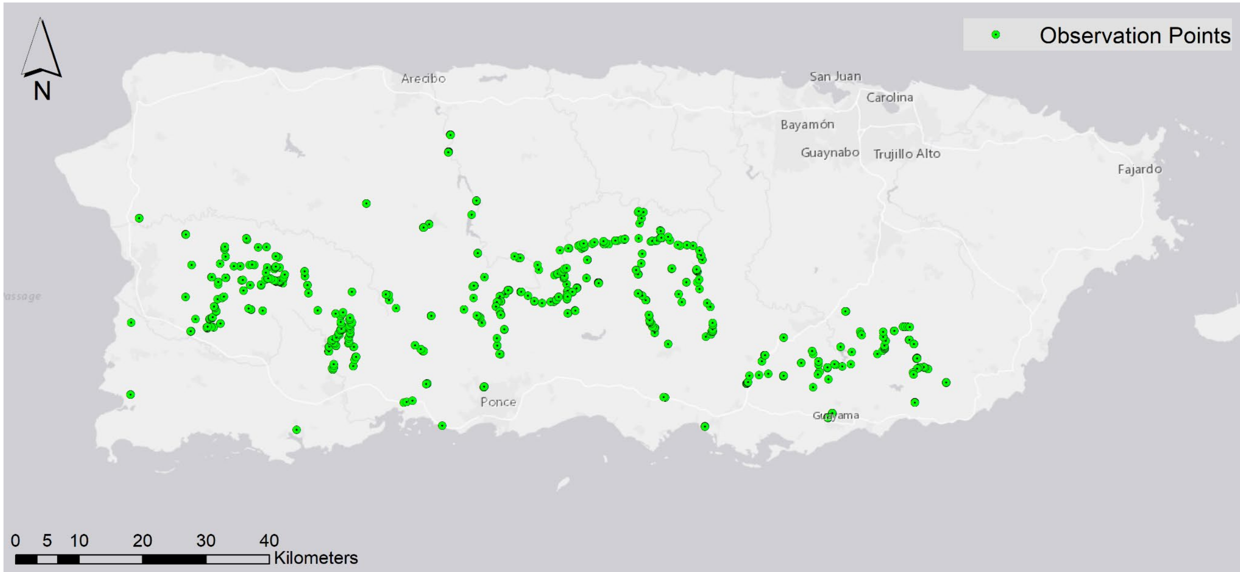


Figure 14: Map of over 1,600 observation points recorded during the GEER Hurricane Fiona mission in Puerto Rico in 2022. Details for each point are in Appendix A.

2.3.2. Drones

DJI AIR S2, DJI PHANTOM 4 RTK, and ANAFI Parrot UAVs were used to collect digital photo inventories necessary for Structure from Motion photogrammetry 3D modeling and orthomosaic imagery. The sites chosen for these types of surveys were those that were generally larger and included visible runout and deposition areas. One of these types of photos is used as the report cover photo.

3. LANDSLIDES

3.1. Background and general observations

Landslide susceptibility in Puerto Rico is high and landslides occur frequently during the most intense part of the yearly rainy season (Aug-Nov; Hughes and Schulz, 2020). Hundreds to thousands of annual shallow soil and regolith landslides generally affect roadways, utilities infrastructure, homes, and other infrastructure. Less common bedrock failures in the island are usually much larger and can be more devastating and/or move for years to decades at a time. In 2017, precipitation from Hurricane María triggered tens of thousands of shallow landslides (Hughes et al., 2019). Almost exactly 5 years later, Hurricane Fiona brought a very similar amount of rainfall to the island, but the magnitude of landslide sites was not equally as severe. While we do not have a complete Hurricane Fiona inventory at the moment (the Hurricane María inventory benefited from very high resolution FEMA aerial imagery and no equivalent data set was collected after Hurricane Fiona), it is easily recognizable that there are an order of magnitude less landslide sites related to the more recent hurricane. Important factors that account for this difference include the specific locations that received maximum event rainfall, the influence of Hurricane Irma on antecedent soil moisture conditions 2 weeks before Hurricane María, and the relative paucity of easily mobilized hillslope material after Hurricane María.

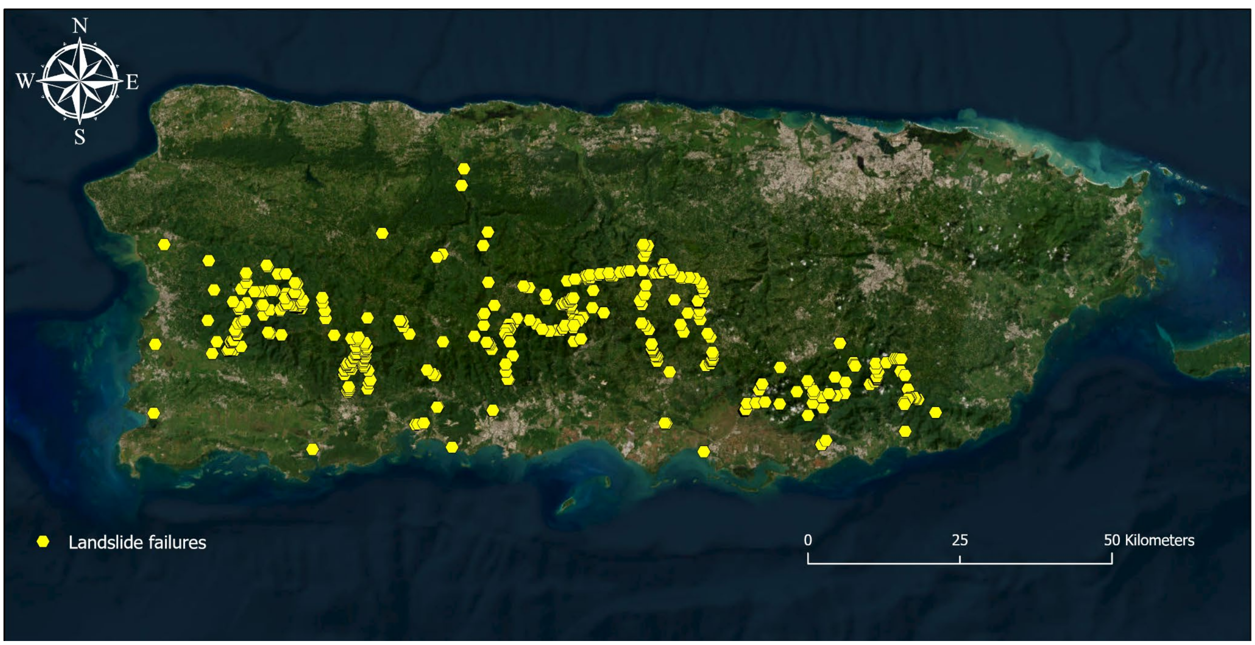


Figure 15: Map illustrating the locations of observed landslide failures after Fiona hurricane. Landslides were spanning from meter-scale to large slope failures with the majority to be shallow slumps on the surficial soil layer.

Geological formation	**Number of landslides**

Andesite/Basalt/Dacite	173
Serpentinite/Amphibolite	20
Volcaniclastic with mixture of sedimentary	716
Mudstone	120
Siltstone, claystone; sandstone, limestone, and conglomerate	64
Limestone	173
Plutonic batholith	53

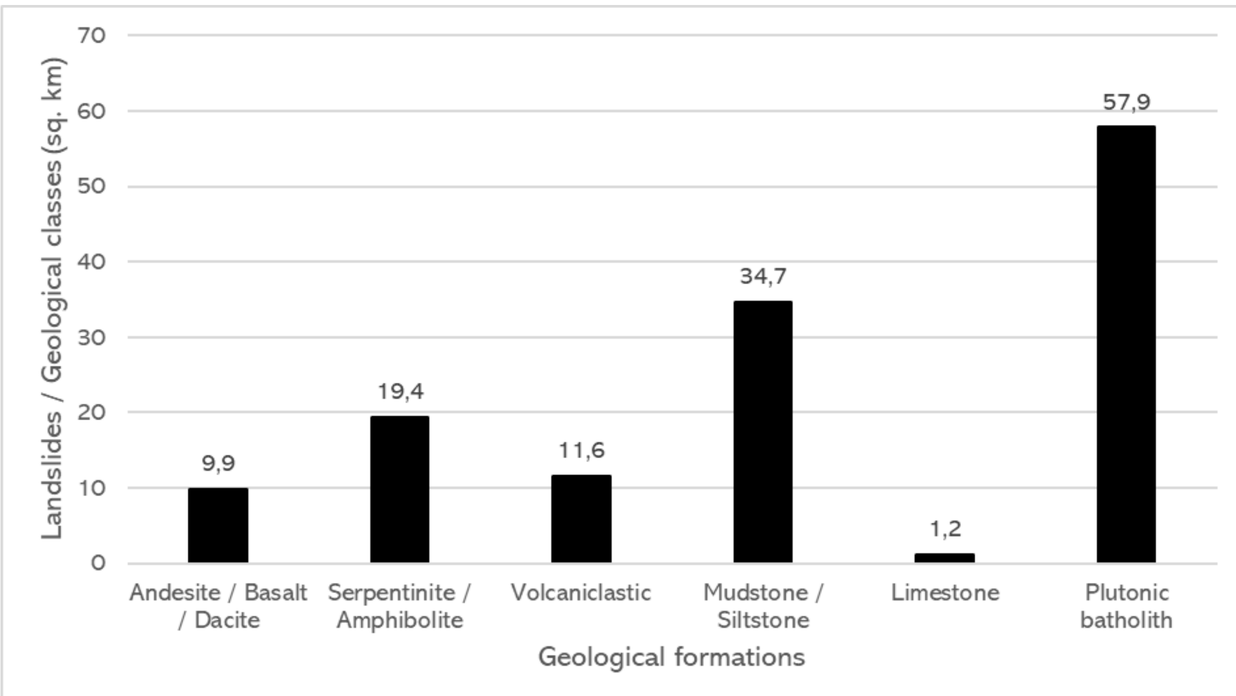


Figure 16: Number of landslide failures per square kilometer for the distinct geological formations in Puerto Rico

3.2. Landslide failure mechanisms

While the degree of landsliding in the two hurricane events is dissimilar, the dominant mechanism of slope failure is identical. The majority of the observed landslide sites are small and shallow rather than bedrock failures, with a few notable exceptions occurring at select large failures across the island. The vast majority of slides encountered during reconnaissance were small: on the order of several tens of square meters. Typical shallow translational failure mechanisms induced by Hurricane Fiona are shown in Figure 17. The failures that occur in first order channel hollows very often transitioned into debris flows (Figure 19).

The failure plane is most often located at the boundary between soil/regolith and less weathered bedrock material (often saprolite) as shown in Figure 18. These slopes were initially stable given the matric suction in the unsaturated zone that translated into significant effective stress values.

Typical landslide depths were less than ten meters. Select failures, such as the pre-existing PR-9 Ponce landslide (section 3.6 below), are much larger and extend for a couple hundred meters. It is important to recognize that there is bias in the distribution of landslides reported here as observations were constrained to the road network. Because this network features steep and relatively short slopes, this likely has influence on the type of landslides encountered.

Figure 17: Typical shallow landslide induced by Hurricane Fiona along PR-52 (18.09637, -66.18862). Photo taken on 04-Nov 2022.

Figure 18: Failure plane at the boundary of soil/regolith and less weathered bedrock material along PR-128 in Rio Yauco (18.05961, -66.86041). Photo taken on 07-Nov 2022.

3.3. PR-712 Debris Flow in Salinas (18.04221, -66.18957):

At this site, we encountered a long debris flow runout that had covered the road at some point (Figure 19). We were not able to access the initiation point, but the feature was at least 200 meters long. As seen in pre-event LiDAR (Figure 20), it appears that the site may be a reactivation from a previous mass movement. The road was not damaged, only temporarily covered.

Figure 19: Aerial imagery of shallow debris flow site along PR-712 in Salinas (18.04221, -66.18957). Pickup truck for scale. Photo taken on 30-Oct 2022 and the view is looking generally south.

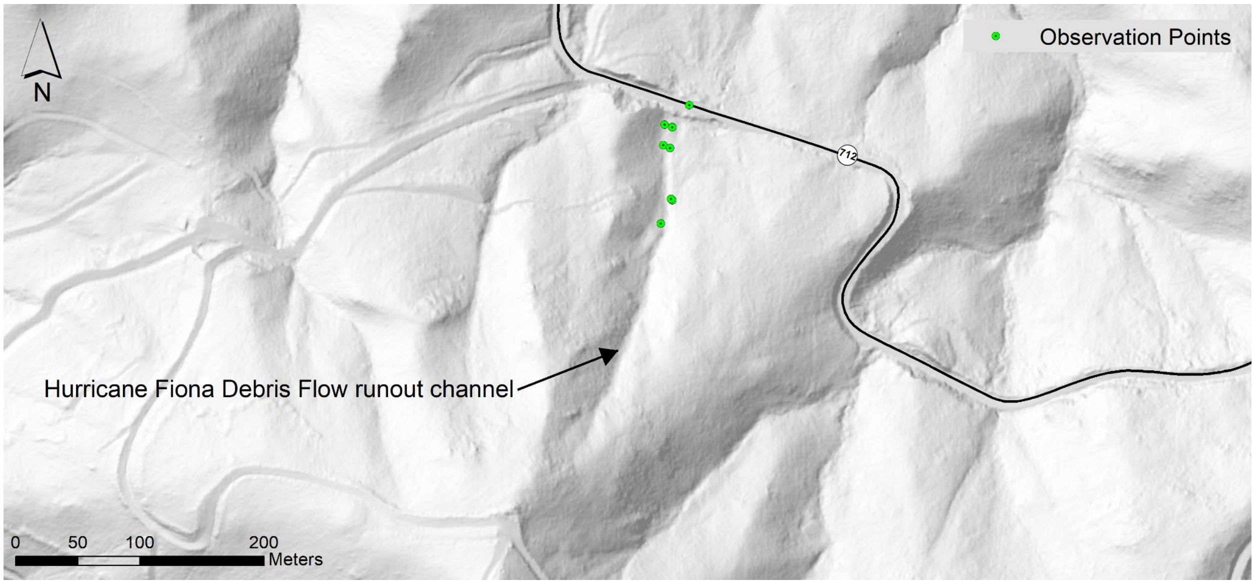


Figure 20: 2016 1m resolution LiDAR derived hillshade map of the PR-712 site in Salinas (18.04221, -66.18957)

3.4. PR-52 Rockfall in Salinas (18.0711, -66.2172):

This landslide was not triggered during Fiona, but several weeks later during our 2nd phase of reconnaissance on 06-Nov 2022. In the entire month after Hurricane Fiona, tropical rains continued. In early November, one event included an additional 5-8" of precipitation over 48 hours (NWS San Juan). The excess rainfall on already saturated hillslopes caused frequent new landslides across many parts of the island, so much so that at several sites we were unable to recognize if the failure was directly related to Hurricane Fiona, some time after, or both. The site on PR-52 is especially important because it blocked one complete direction of travel along the main expressway that connects the San Juan metropolitan area to the south coast of the island (Figure 21). From pre-event LiDAR derived digital elevation data, it is evident that the site is a large benched cut slope that was engineered during the construction of the freeway (Figure 22).

Figure 21: Rockfall along PR-52 in Salinas, near the border with Cayey (18.0711, -66.2172). Photo is from https://www.primerahora.com/noticias/puerto-rico/fotogalerias/fotos-graves-danos-a-carreteras-a-causa-de-las-fuertes-lluvias

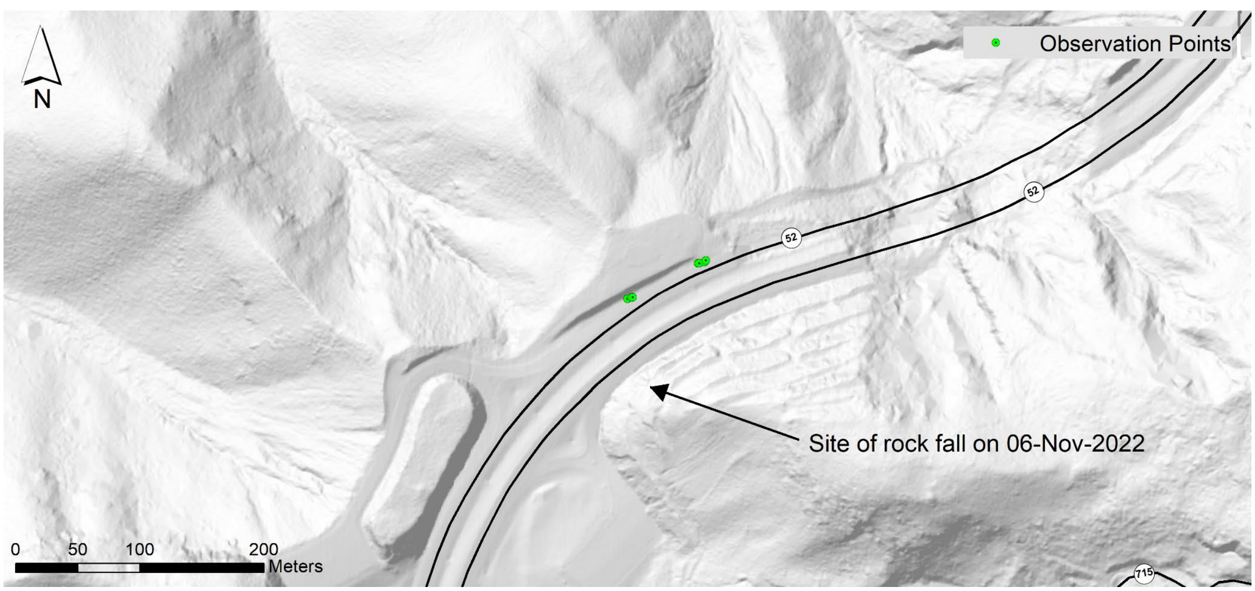


Figure 22: 2016 1m resolution LiDAR derived hillshade map of the PR-52 site in Salinas (18.0711, -66.2172)

3.5. PR-409 Landslide in Las Marías (18.2061, -66.94397):

This is one of the larger sites that we documented after Hurricane Fiona. The site is a rotational slump landslide that covered the road in ~10m of weathered regolith material and also introduced a small landslide dam in the creek below (Figure 23). Back rotated trees were very evident along the slide body (Figure 24) and based on an analysis of pre-event LiDAR digital elevation data, the site is considered a new failure (Figure 25).

Figure 23: Photo mosaic of over 250 aerial photographs of a large rotational slump landslide along PR-409 in Las Marías (18.2061, -66.94397). Vehicles at the right center of the photo for scale.

Figure 24: View of the headscarp of the PR-409 landslide standing on the toe material that covered the road. Note the deep weathering profile.

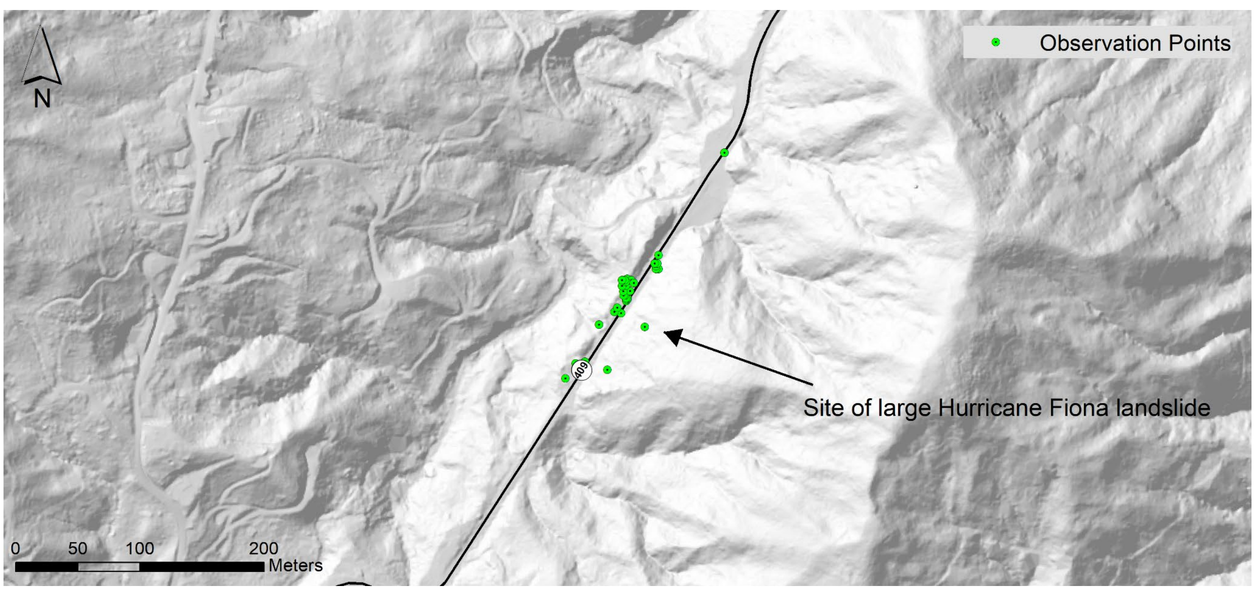


Figure 25: 2016 1m resolution LiDAR derived hillshade map of the PR-409 site in Las Marías (18.2061, -66.94397)

3.6. PR-9 Landslide in Ponce (18.03192, -66.63573)

A large bedrock landslide along PR-9 to the North of the city of Ponce initiated well before Hurricane Maria (2017). This landslide is located in the Juana Diaz Formation which was the geological unit that experienced large failures during the nearby Mameyes landslide disaster of 1985. The geology at the site consists of basal gravel to conglomerate overlain by chalky limestone. No observable changes in the landslide site were noticed with respect to the pre-hurricane Maria as reported by the GEER team that visited the site before Hurricane Maria (June 2017) and after the hurricane (October 2017). Changes were documented related to the 2020 Puerto Rico M6.4 earthquake. Hurricane Fiona; however, has reactivated the landslide at this site. Cracks at the site induced by previous failures were expanded amid hurricane Fiona. Figure 26 shows a differencing model between May 2022 and November 2022 at the Ponce landslide site.

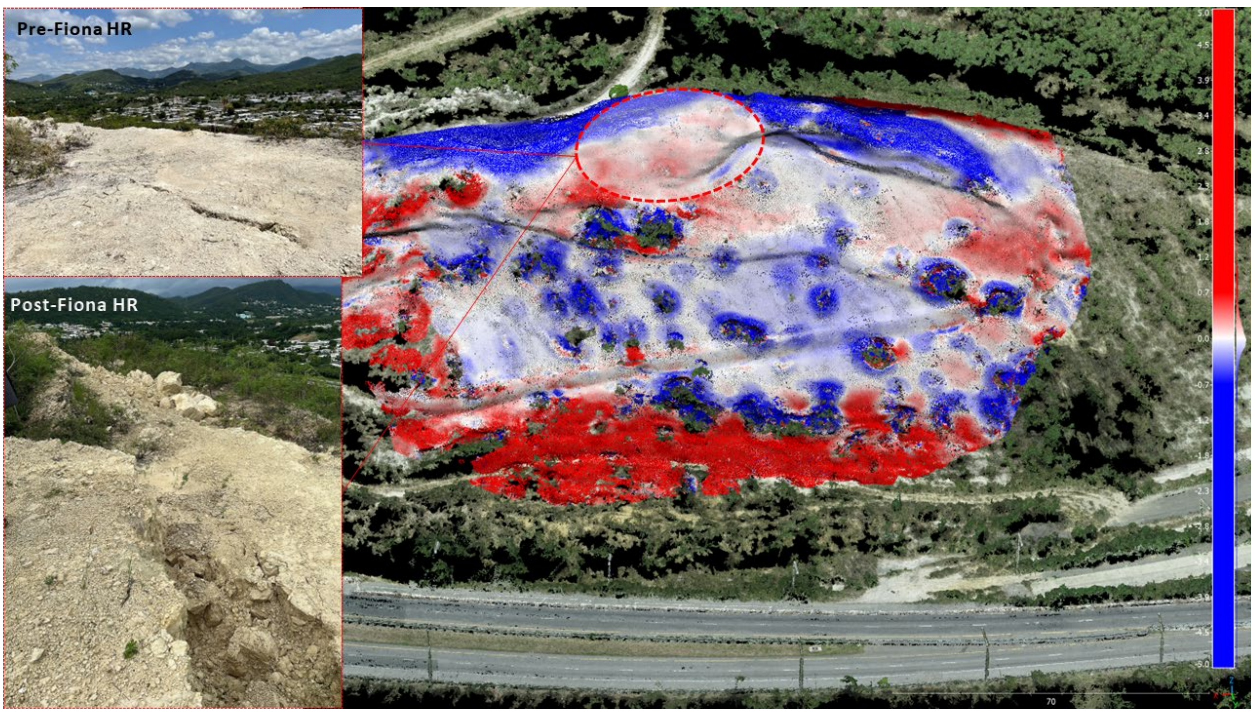


Figure 26. Differencing model between May 2022 and November 2022 from Ponce landslide.

Figure 27. Aerial photos of the Ponce landslide indicating the landslide failures.

3.7. PR-339 Landslide in Mayagüez (18.19312, -67.03934)

This landslide cut through the PR-339 road resulting in a road closure of the area. The landslide was roughly 20 meter wide and extended into a debris flow. Our reconnaissance took place after barriers had been set up but from the geometry of the failure it appears to have been between the soil and regolith similar to the majority of the failures in the area. Debris from the slide continued nearly 50 meters away from the head scarp at the road. This landslide was one of the select areas we surveyed that damaged existing infrastructure and prevented travel.

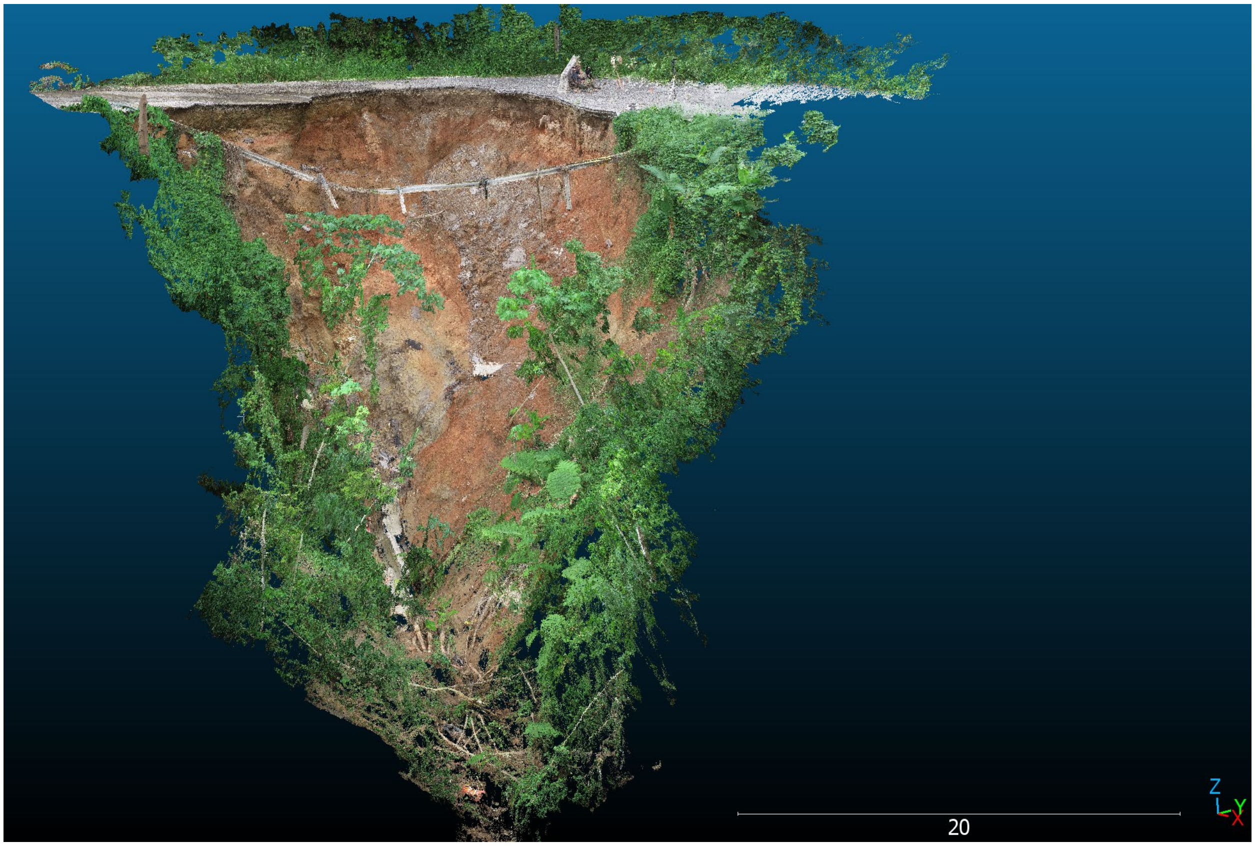


Figure 28: Structure from motion model of landslide and road failure on PR-339

3.8. PR-143 Landslide in Ponce (18.160905, -66.609789)

This pair of landslides were above the Ruta Panoramica and were relatively surficial, on the order of a meter or two deep. During our reconnaissance, some of the slide debris had been cleaned off the road and there was not visible damage to the adjacent power lines. These landslides were typical of the smaller near surface failures that were documented across the island from heaving rains during Fiona.

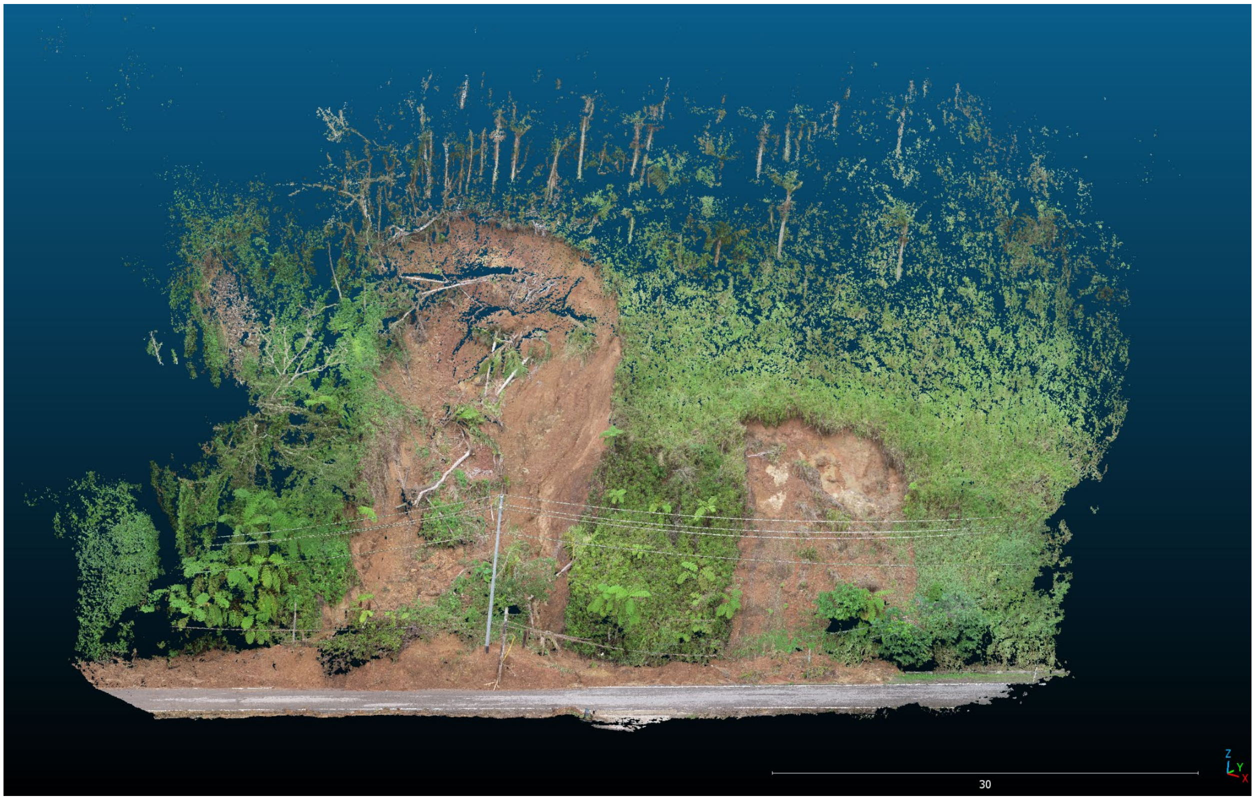


Figure 29: Structure from motion model of landslide adjacent to road on PR-143

4. BRIDGE FAILURES

After Hurricane María in 2017, several bridges that were destroyed were replaced by temporary bridges that were then taken out by Hurricane Fiona. Below are two examples. These types of structures cannot withstand the drag of floodwaters and abundant debris that are loaded onto their upstream side during extreme precipitation events. Our observations show that the simple hardware that bolts the bridge structure to concrete abutments is not sufficient.

4.1. Temporary bridge site in Utuado (18.2600, -66.7225)

Figure 30: Aerial photograph looking south at the location where a temporary bridge structure across the Río Grande de Arecibo in Utuado was washed away during Hurricane Fiona. Video of bridge failure here: https://www.telemundopr.com/noticias/puerto-rico/colapsa-puente-en-utuado/2394672/

Figure 31: Aerial view of the western abutment of the temporary bridge in Utuado that was washed away

Figure 32: Destroyed concrete structure with rebar (deflected in downstream direction) on the western abutment of the temporary bridge in Utuado that was washed away during Hurricane Fiona

4.2. Temporary bridge in Arecibo (18.3917, -66.6805)

Figure 33: Aerial view of a temporary bridge failure along the Río Grande de Arecibo in Arecibo (18.3917, -66.6805). View is looking North. Note large amounts of vegetation that was caught by the bridge and the section of bridge washed away at the left center of the photo. Humans on bridge for scale

Figure 34: Horizontal separation of bridge segments along the Rio Grande de Arecibo bridge failure site in Arecibo. Separation is wider on the upstream side of the structure, indicating downstream rotational movement.

Figure 35: View of the missing segment of the temporary bridge of Rio Grande de Arecibo in Arecibo. Note the sheared rebar at center left of the photo that was used to anchor the temporary segment.

5. SCOURING AND UNDERMINING

5.1. Background and general observations

Several other bridges were left unusable after Hurricane Fiona not because of bridge failure, but because of the erosion of the structural abutments of earthen material. Some typical examples are described below.

5.2. Erosion in Arecibo PR-123 bridge (18.368, -66.684)

Figure 36: PR-123 bridge over the Rio Grande de Arecibo in Arecibo (18.368, -66.684). This bridge did not fail during Hurricane Fiona but the approaching abutments on either side had to be rebuilt following the storm. View is looking Northwest.

Figure 37: Aerial view of pieces of PR-123 approach segments that were washed downstream by the Rio Grande de Arecibo (18.368, -66.684). View is looking north.

5.3. Erosion in PR-358 San Germán Bridge

Figure 38: Aerial view of the PR-358 bridge over the Rio Hoconuco in San Germán (18.116, -67.071). The bridge structure did not fail, however, the abutments on both sides partially failed due to high discharge over and around the bridge during Hurricane Fiona.

5.4. Bank erosion in Sector La Escuelita (PR-759-Int) Maunabo (18.0289, -65.9475)

Figure 39: Example of bank erosion along the abutment of a small bridge over the Rio Maunabo in Maunabo (18.0289, -65.9475). The bridge did not suffer but the complete abutment and river bank was washed away. The area washed out was replaced with fill material to provide access to residents of a small isolated community beyond the bridge crossing.

6. Conclusions

Almost exactly 5 years after Hurricane María, Hurricane Fiona in September of 2022 reminded those in Puerto Rico of the devastating effects related to tropical cyclones in the Caribbean region. The island's topography, population density, and other factors make it especially vulnerable to flooding, landsliding, and other direct and long-term impacts related to extreme weather events. May this report, our team's findings, and ongoing collaborative endeavors help to advance our society's resilience and capacity to withstand these types of events in the future.