LANDSLIDE SCIENCE IN PUERTO RICO: PAST, PRESENT, AND FUTURE[1]

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ABSTRACT: This article presents an overview of landslide investigation in Puerto Rico from the time of Spanish control until the present. In addition, a projection for future developments is offered. The island's tectonic and geographic situation combined with a history of intense agriculture practices yield a predisposition of landslide hazard. Mass wasting manifests itself in several modalities with shallow soil failures being most common and deep bedrock slides being most destructive. Movements can be provoked by seismic activity but are regularly triggered by high-intensity rainfall events associated with tropical cyclone systems. Advances in landslides science made during the latter 20th century were made possible by earlier topographic and geologic mapping efforts by the United States Geologic Survey. In the 21st century, instrumentation and monitoring endeavors have been made more effective with the use of emerging technologies. In the near future, advanced real time systems and forecasting programs are possible, and the continued investigation of landslides as principal agents of erosion will lead to a more focused understanding of surficial processes over geologic time. In a landscape faced with natural disasters, it is necessary to meet these phenomena with an adequate level of commitment in order to mold a more resilient society.

Keywords: landslides, Puerto Rico

CIENCIA DE MOVIMIENTOS DE TIERRA EN PUERTO RICO: PASADO, PRESENTE Y FUTURO

RESUMEN: El presente artículo documenta una descripción general de investigación en el tema de derrumbes y deslizamientos de tierra en Puerto Rico desde la época de control español hasta el presente. Además, se ofrece una proyección de desarrollo futuro. La ubicación tectónica y geográfica de la isla combinada con una historia de cultivos intensa ha creado una predisposición de peligro de derrumbes. Movimientos de tierra se muestran en maneras diferentes con derrumbes de suelo superficiales los ejemplos más comunes y deslizamientos profundos siendo los más destructivos. Los movimientos de tierra se pueden desencadenar por lluvias intensas que traen tormentas tropicales y huracanes y por la sismicidad. Logros de la segunda mitad del siglo 20 en el campo de la ciencia de derrumbes y deslizamientos de tierra estuvieron posibles por los previos esfuerzos del Servicio Geológico de los Estados Unidos en trazar la topografía y geología de la isla. En el siglo 21, la instrumentación y el monitoreo han sido hecho más efectivo con el uso de tecnologías emergentes. En un futuro cercano, sistemas avanzados que operan en tiempo real y programas de pronóstico están realmente posible y la seguida investigación de derrumbes como agentes principales de la erosión ayudará en un mejor entender de los procesos superficiales a través de tiempo geológico. En un paisaje que se enfrenta con desastres naturales, es necesario encontrar estos fenómenos con un nivel de compromiso adecuado a fin de que se hace la sociedad más resiliente.

Palabras clave: Puerto Rico, derrumbes, deslizamiento de tierra

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INTRODUCTION

Puerto Rico's vulnerability to mass wasting is a result of the coincidence of multiple factors. Among these are both natural and anthropogenic forcings. No matter the cause, the effects of landsliding are problematic for society as they can cause the loss of life, property, and/or infrastructure. Even landslide sites characterized as merely nuisances can be economically important in the island. As Puerto Rico moves forward from a succession of impactful natural disasters, a focused understanding of the dynamic topographic conditions of the world beneath us are vitally important to ensure the success of current and future endeavors. This article presents a short summary of the historic and contemporary effort to better understand mass wasting across the island.

TECTONICS

Puerto Rico is located along the complicated and diffuse northeastern Caribbean plate boundary zone (Fig. 1). This tectonic setting is a first-order control on the island's topographic state. The oblique collision of the North American and Caribbean plates has been ongoing for millions of years and subduction along this interface is responsible for the genesis of the volcanic arc basement rock units in the island, mostly during the Cretaceous Period. After the cessation of volcanism, vertical subsidence in Puerto Rico was active until about 5 million years ago, marked by the deposition of the north and south coast limestone cover sequences. Since that time, the island has transitioned to a state of tectonic uplift, where rock units that were once located below sea level have been pushed to hundreds of meters above sea level.

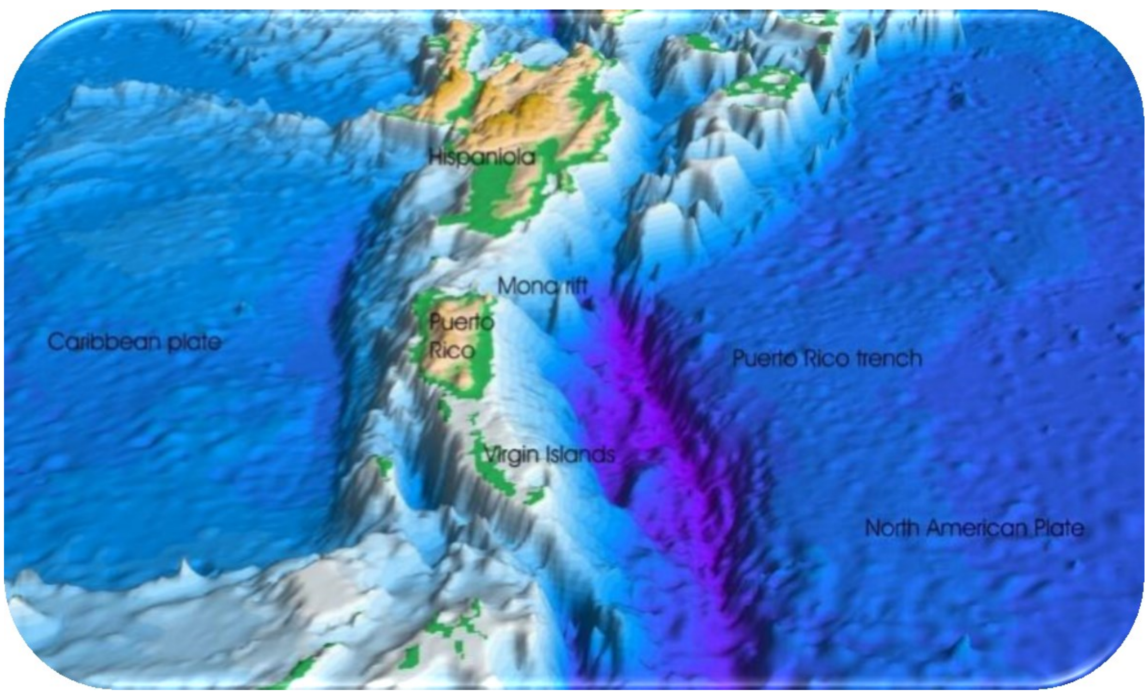

Figure SEQ Figure * ARABIC 1: Topographic relief map of Puerto Rico and vicinity. Modified from Ten Brink et al. (2005).

As the tectonic uplift has progressed, the topographic response has been expectedly delayed, because there is often a lag time between landscape perturbation and eventual landscape change. By chance, we are living in the time of landscape adjustment to this tectonic forcing in Puerto Rico. The principal agent of topographic change is the modification brought about on the vertical position of river channels caused by the relative change in their base level (sea level) upon initiation and continuation of uplift. As the rivers incise from previous vertical positions, the erosional effect moves like a wave headward through the watersheds. As the erosional wave moves up the valleys, the adjacent hillslopes are over-steepened and effectively primed for mass wasting.

Another important topographic detail of Puerto Rico is the total local relief. When the nearby Puerto Rico trench is taken into consideration, the local relief is almost 10 km. The trench is the deepest point in the Atlantic Ocean and reaches more than 8300 m below sea level; only 150 km to the south, the terrain on island is as high as 1300 m. This difference marks one of the highest relief zones on planet Earth. The threat of submarine mass wasting is present, especially along the slope between Puerto Rico and its trench. This slope is marked by large features that resemble large landslide headscarps and are referred to as "ampitheaters". These sites highlight the potential tsunamigenic nature of landslide activity in the region.

A final tectonic-related potential cause of mass wasting is perhaps the most apparent: seismicity. As experienced during the moderate shaking events of 1918 and 2020, ground shaking often results in rock falls (Reid and Taber, 1919; Morales-Vélez et al., 2020). In both events, the rock falls were mostly concentrated in limestone bedrock units, due to the positions of the earthquake foci. Seismic-induced landsliding may be considerable over geologic timespans but is not the primary triggering mechanism for most landslides in Puerto Rico.

CLIMATE

Long term weathering processes and short term weather events both play an important role in the landslide cycle in Puerto Rico. Continuous humid tropical conditions contribute to effective chemical weathering, which is important for bedrock decomposition and soil development. Annual rainfall is greatest when augmented by the orographic effect and not all bedrock units in the island react in the same manner to chemical weathering. The more common example of volcanoclastic bedrock units results in a very plastic cohesive clay regolith soil, that is effective in retaining moisture all year. In contrast, the weathering products in zones underlain by intermediate plutonic bedrock are much sandier as a result of higher quantities of quartz minerals. These soils are much more porous and "flashy" with a much lower level of cohesion, which makes them more sensitive to temporary high intensity rainfall events.

High intensity rainfall events commonly associated with tropical cyclone activity result in positive pore pressure soil conditions that can lead to slope failure. The island's geographic position is especially vulnerable to "Cape Verde" systems that develop during hurricane season. Notable hurricanes that have directly impacted the island include San Ciriaco (1899; Figure 2) and María (2017), among many others. These types of storms usually spawn hundreds to thousands of landslides, usually shallow events that only result in the loss of weathered regolith and soil material above bedrock. The liberated material often moves as debris flows and is usually introduced into the fluvial system and transported downstream. An alternate failure mechanism is the deeper bedrock failure, which is more common in limestone units across the island.

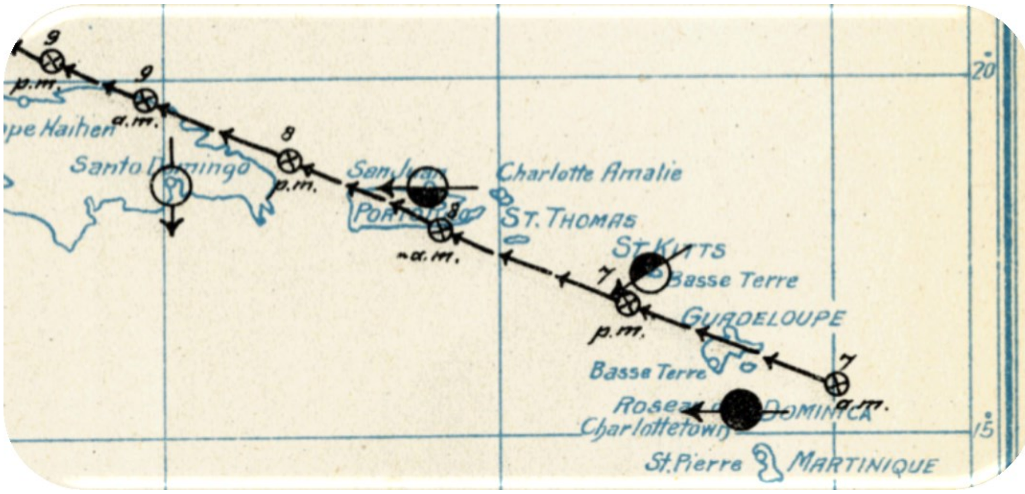

Figure SEQ Figure * ARABIC 2: Track of Hurricane San Ciriaco (1899) across the northeastern Caribbean region. Modified from the U.S. Weather Bureau August 1899 Monthly Weather Review.

HUMANS

Puerto Rico was a Spanish colony from the late 15th century until the turn of the 20th century. During this time and up to the 1940's under United States control, the landscape was extensively and aggressively cultivated with crops such as sugar cane, coffee, plantains, tobacco, and others. At least 90% of the island is estimated to have been deforested through these centuries of agronomy (Figure 3; Larsen and Santiago Román, 2001; Grau et al., 2003). Since the 1940's, the local culture has shifted away from farming and more to urbanized activities due to diverse societal, political, and global factors. However, the topographic legacy of the agricultural practices remain literally imprinted in the landscape. During this agrarian time, not only were forests lost, which resulted in massive soil degradation and erosion, but farmers also cut a very dense improvised and complex system of roads across the countryside. In the early 20th century these roads were described as "many trains which penetrate the island in almost every direction" (Dorsey, 1903) A 21st century analysis shows that these types of trails and roads are the primary sources of day to day erosion and sedimentation in the island's interior province (Ramos-Scharrón and LaFevor, 2016).

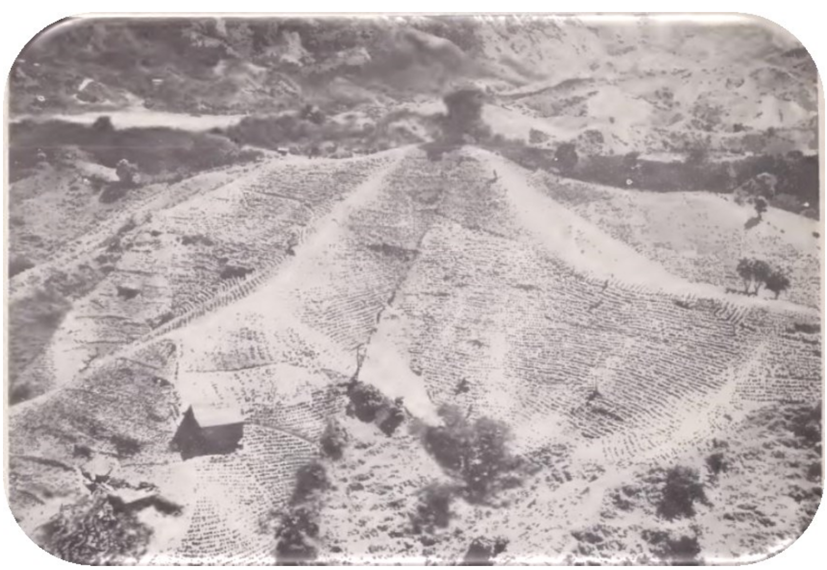

Figure SEQ Figure * ARABIC 3: Deforested tobacco fields in the Rio Caonillas watershed, ca. 1953. Modified from Noll (1953).

LANDSLIDE SCIENCE

Early Days

As early as 1831, de Córdova made reference dangerous mountain roads with cliffs that become impassable during the wet season but no direct mention of landsliding was found in this work. Near the end of the Spanish rule in Puerto Rico, the 1866 work of Abbad Lasierra "*Historia geográfica, civil y natural de la isla de San Juan Bautista de Puerto-Rico*" mentions "*excavaciones ocasionadas por las inundaciones, los terremotos y otros accidentes que trastornan el globo*" in reference to sites where mineral deposits may be found. This is one of the earliest mentions of landsliding in Puerto Rico and is especially remarkable because the author recognizes the variable triggering forces for mass wasting. An 1899 publication "*Puerto Rico: Its Conditions and Possibilities*" by American traveler Dinwiddie described a road between Adjuntas and Yauco that was improved by U.S. troops in the months previous which had then been reduced to "*perilous footpaths, tottering on the edges of drops of five hundred feet deep*" as a result of rainy season landslides in the area. This work was published only a few months before the passage of Hurricane San Ciriaco, which would have certainly caused widespread mass wasting.

One of the initial waves scientific investigation in Puerto Rico produced the 1902 soil survey from Arecibo to Ponce. It includes mention of landslides in Utuado and Adjuntas and highlights the exceptional susceptibility to erosion of the "Utuado sandy loam" soil class (Dorsey, 1903). After the 1918 Mona Passage earthquake just northwest of the island, Reid and Taber's 1919 congressional report mentioned that "*rock falls were common where the [shaking] intensity was above VII*." A few years later, the New York Academy's Scientific Survey of Porto Rico and the Virgin Islands series published "*The Physiography of Porto Rico*" (Lobeck, 1922), which included the declaration that "*it is no uncommon thing to see slumping of the ground even on moderate slopes, and occasionally land slides of really great proportions*."

Mid-20th century

In 1930 and 1931, the U.S. Department of the Navy collected 1:10,000 scale aerial imagery across much of the island of Puerto Rico. Soon after, topographic and later detailed geologic mapping by the United States Geological Survey were undertaken. These operations were pivotal in advancing the study of mass movements in Puerto Rico and the maps remain vital tools for the study of the island. By the 1950s – 1960s, geologist Watson Monroe directed the geologic mapping program in Puerto Rico and was the primary driver of landslide research, mostly focused on the large block landslides along the southern escarpment of the karst region. Prominent landslides along this topographic feature exist at the Lago Guajataca dam site and along PR-10 in Utuado, among many others. Monroe's 1980 work "*Some Tropical Landforms of Puerto Rico*" highlighted many landslide sites across the island and his 1979 publication "*Map Showing Landslides and Areas of Susceptibility to Landsliding in Puerto Rico*" was an important product for highlighting mass wasting potential across the island (Figure 4).

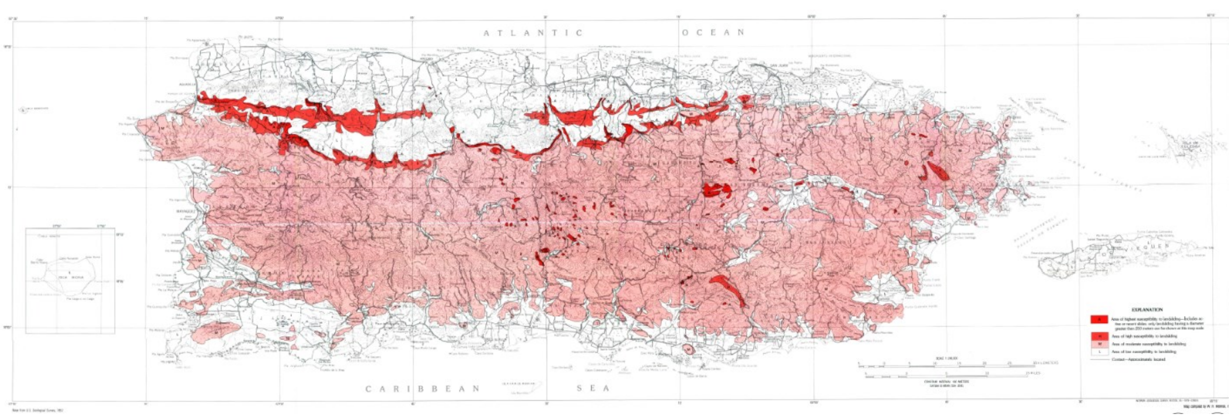

Figure 4: Monroe's (1979) landslide susceptibility map for Puerto Rico. Scale: 1:240,000.

Latter 20th century

The disaster at Barrio Mameyes in 1985 marks a shift towards a modernized and quantitative approach to landslide science in Puerto Rico. The large bedrock block landslide in Ponce remains the deadliest landslide event in any jurisdiction of the United States to date. This event, coupled with the effects of Hurricane Hugo in 1989, highlighted the threat of various types of mass wasting and set the stage for important modern advancements in the coming years. In addition, the local record of events was now sufficient to estimate environmental forcing based upon empirical data. More frequent availability of aerial imagery also made possible the inventory of landslides provoked during certain events (Figure 5). These combined advances, along with emerging geographic information systems (GIS) programs, made possible advanced analyses including the derivation of island-specific rainfall intensity-duration thresholds related to landslide initiation (Figure 6) and more detailed landslide susceptibility products at the municipality scale, where sufficient data was available.

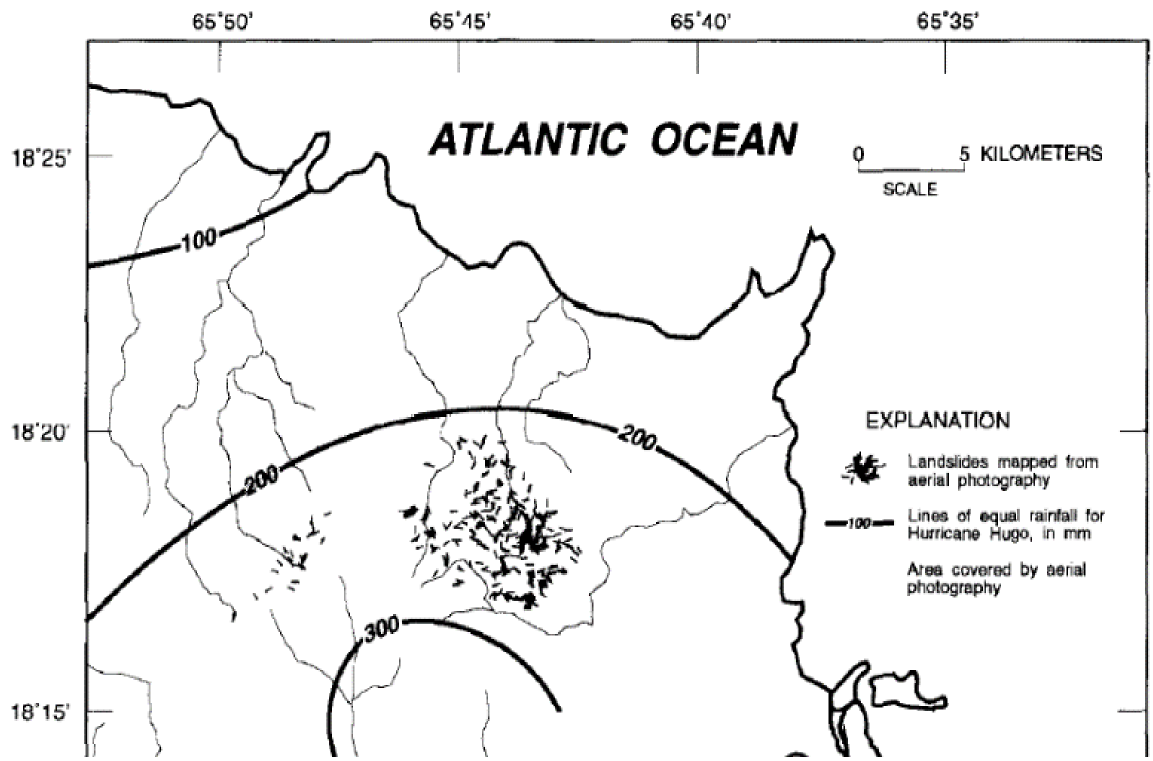

Figure 5: Inventory of landslides triggered by Hurricane Hugo (1989) in eastern Puerto Rico. Aerial imagery and field work were employed to identify landslide locations that were then were plotted on topographic maps. Modified from Larsen and Torres Sánchez (1992).

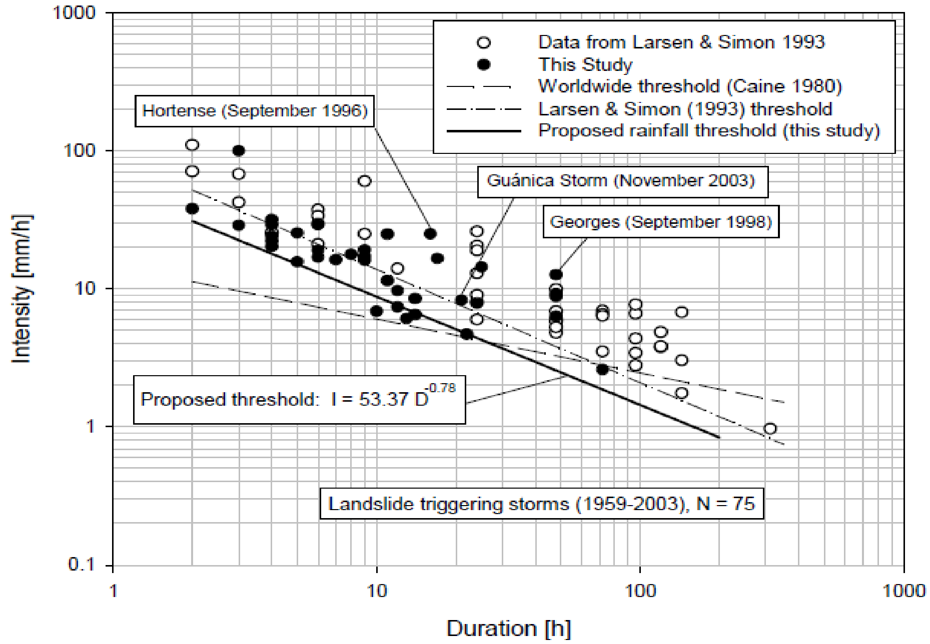

Figure 6: Compilation of landslide generating storm events from 1959-2003 and proposed rainfall intensity-duration thresholds prepared by Larsen and Simon (1993) and Pando et al. (2005).

Instrumentation of mass wasting sites in Puerto Rico was also implemented in this stage of landslide study. The evaluation of important infrastructure sites by engineering firms helped to understand and confirm the hypothesized mechanisms and rates of large block landslide movement (Figure 7). Also, a more academic and less hazard-focused lens was applied to studying mass wasting in the island, especially at the Luquillo Critical Zone Observatory. Landsliding was also recognized as an important erosional process over geologic time in tectonically active regions and with regards to climate dynamics. Many advances in this field of global importance were made in Puerto Rico during this time.

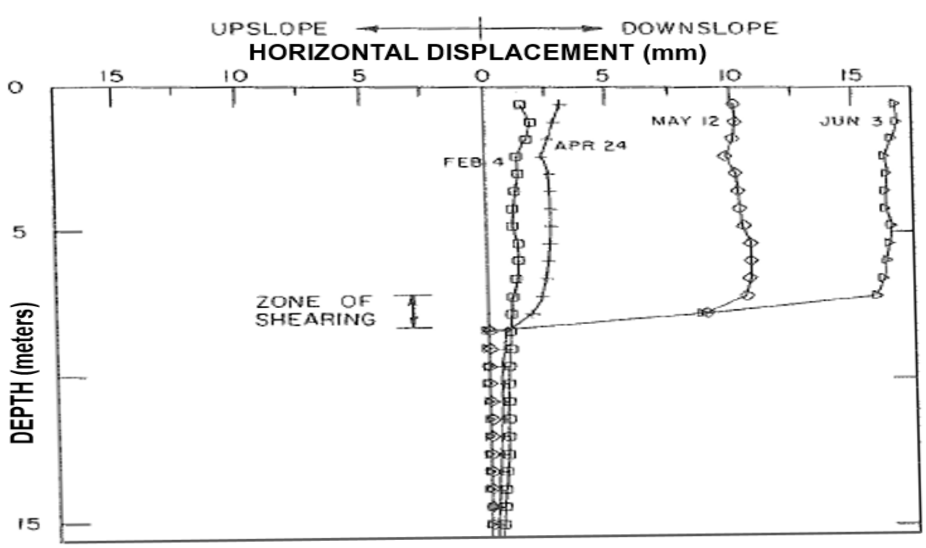

Figure 7: Results from inclinometer measurements in a borehole drilled into a deep seated landslide along the southern karst escarpment during the construction of highway PR-10 in Utuado. The instrumentation shows accelerated movement during times of high precipitation along a failure plane associated with the San Sebastián Formation. Modified from Deere et al. (1989).

The Modern Era

Twenty-first century landslide science in Puerto Rico has benefited from the application of remote sensing, geodetic, and other technological techniques to study mass movements. The installation of semi-permanent GPS antennas in a system of reference and rover networks showed that tracking large, usually slow moving deep bedrock mass movements is possible with centimeter-scale resolution (Figure 8). In addition, georeferenced high-resolution terrestrial and airborne laser (LiDAR) mapping was used as a method to identify and monitor subtle slope movements and to carry out change detection (Figure 9). The use of Structure from Motion (SfM) photogrammetry techniques to create three-dimensional models from unmanned aerial vehicle (UAV, drone) surveys of landslide sites was also introduced and used in harmony with the aforementioned techniques (Figure 10).

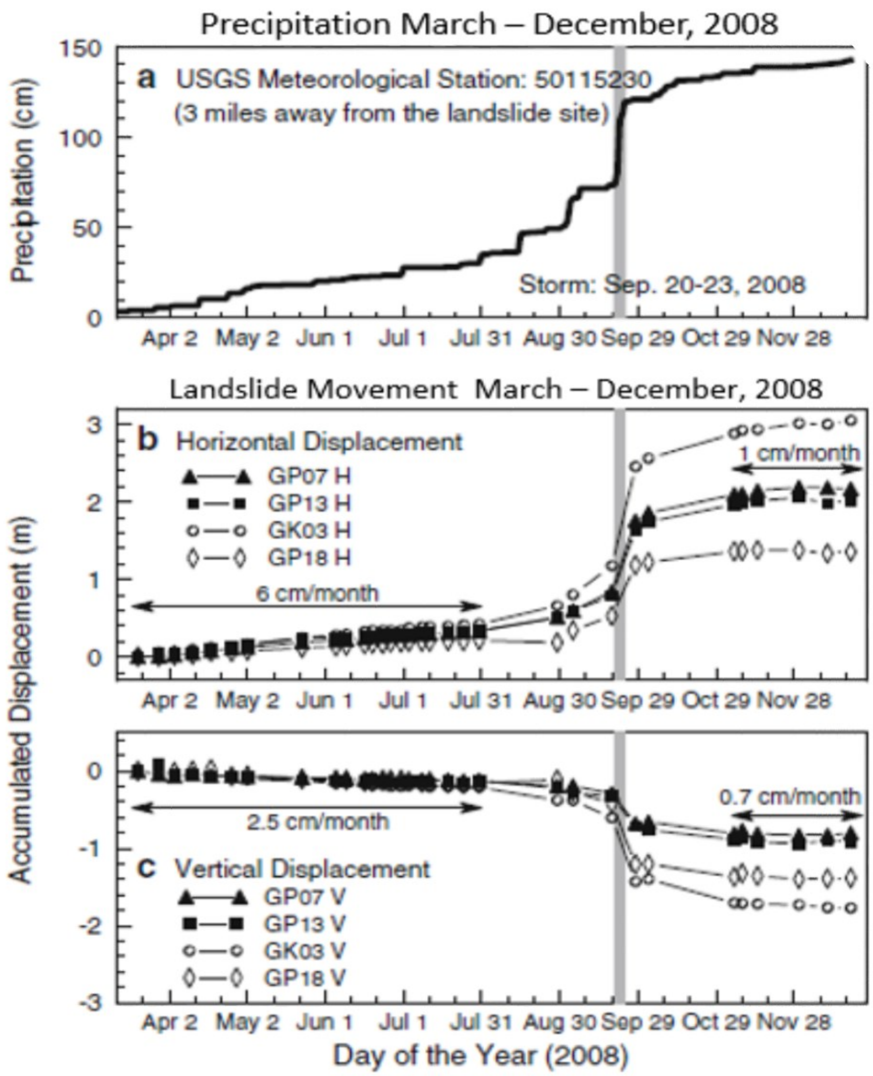

Figure 8: GPS-derived horizontal and vertical motion of the Cerca de Cielo creeping landslide in Ponce in 2008. Accelerated movement of landslide correlated to long duration-high intensity rainfall associated with Tropical Storm Kyle. Modified from Wang et al. (2012).

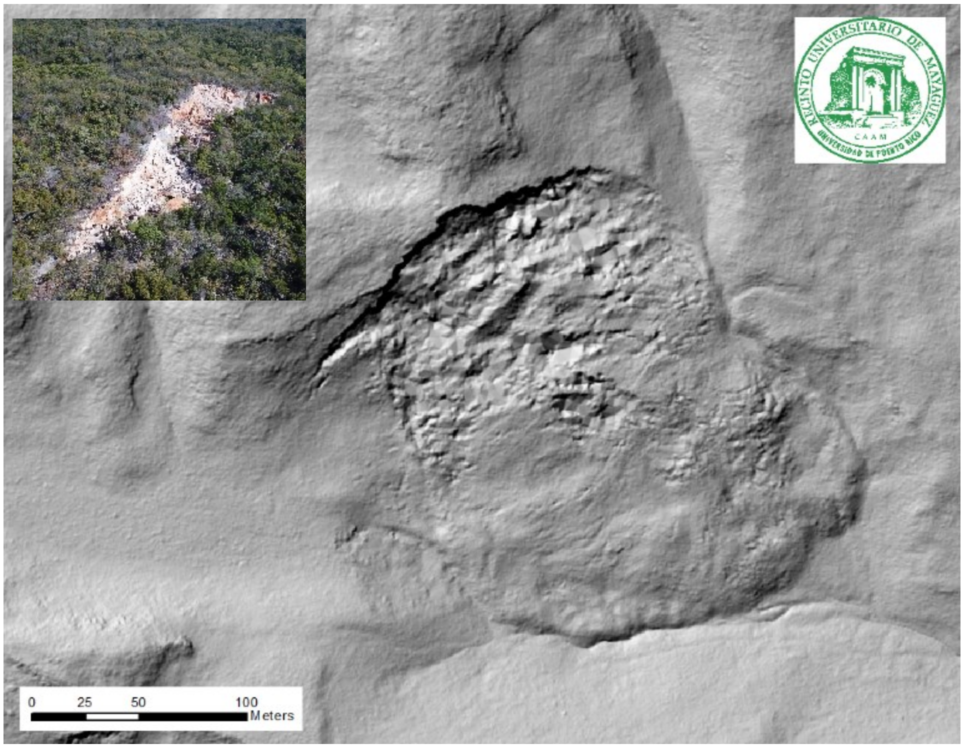

Figure 9: 2018 LiDAR derived hillshade map of a large deep bedrock landslide in Yauco. The landslide body measures 150m wide and 225m long. Photograph inset of headscarp is from 2020. Aerial imagery from 1930 shows that this feature pre-dates that time. Figure prepared for this article by the authors.

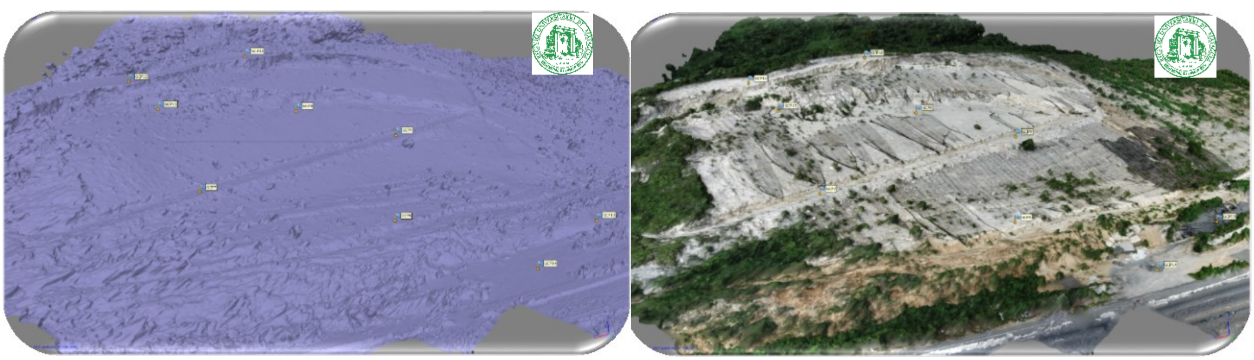

Figure 10: Left: Three-dimensional model of deep bedrock landslide site along PR-9 in Ponce. The model was created with the Structure from Motion (SfM) technique using over 200 high-resolution aerial images captured by unmanned aerial vehicle (UAV, drone) in September of 2018. Right: Same model with orthomosaic image overlaid. Field work and data processing done by UPRM undergraduates Xavier García and Raquel Lugo.

Much like the Mameyes disaster, Hurricane María (2017) stimulated renewed landslide investigation in Puerto Rico. Partnerships between local academics and mainland federal agencies led to the production an unprecedented digital inventory of more than 70,000 landslide sites triggered by Hurricane María and a high-resolution rainfall-induced landslide susceptibility model for the island (Figure 11). Not as devastating, but equally important were the landslides provoked by the M6.4 earthquake and associated seismic sequence in 2020. It was realized that catastrophic widespread landslide-inducing events have both immediate and lingering consequences on the environment and society. Especially important is the legacy of sedimentation related to events that cause widespread landslide activity. As an island that lies along a tectonically active plate boundary and that is annually in the crosshairs of more extreme weather events related to climate change, it is a necessity to forge ahead and build upon the remarkable foundation of landslide science carried out by previous generations in Puerto Rico.

Figure 11: "Map depicting susceptibility to landslides triggered by intense rainfall" of Puerto Rico. Mass wasting susceptibility was modeled at a resolution of 5 meters across the island. From Hughes and Schulz (2020). Online web viewer at: arcg.is/0imC4O.

The (not so distant) Future

Recent advances in hillslope monitoring (Figure 12) and satellite derived estimates of soil moisture make landslide "now" -casting and forecasting a real possibility in the near future in Puerto Rico. Important future work will involve careful scrutiny of environmental parameters that can be used in real time to alert for local, municipality-scale, landslide potential. In addition, the robust river gauge network operated by the USGS makes the island an ideal location on earth to better understand the concept of "source-to-sink" for landslide driven sedimentation and to explore the complicated feedback relationship between chemical and physical weathering. In addition, the diverse geologic and climatic regions of the island make it a unique natural laboratory for these endeavors.

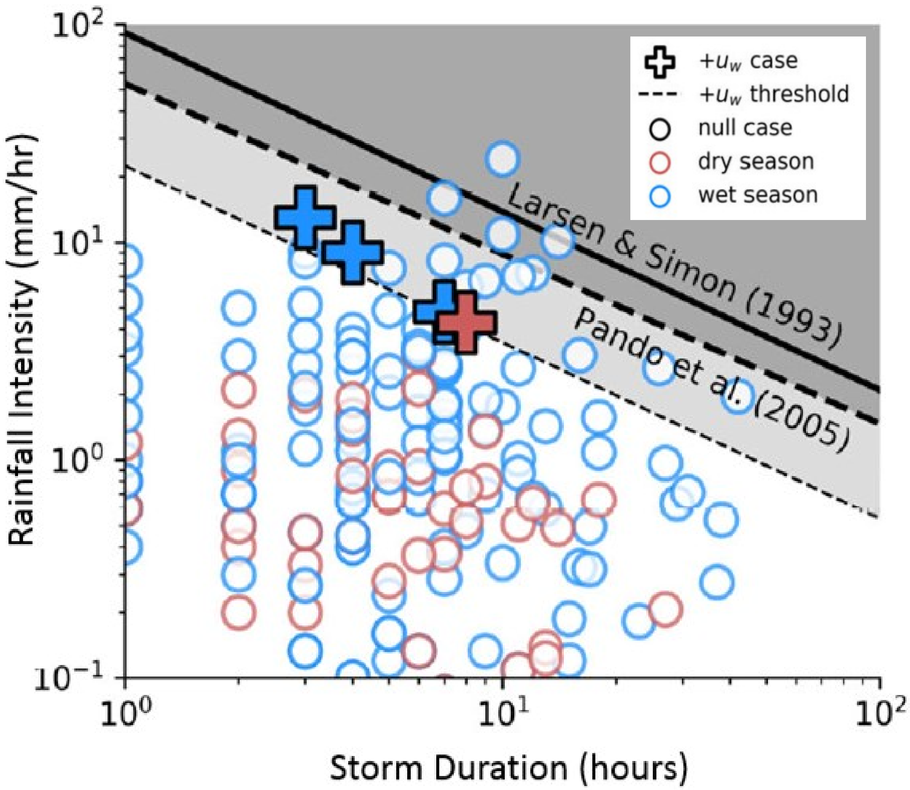

Figure 12: Results of soil moisture monitoring at a site in the Cordillera Central. +u_w indicates positive pore pressure along potential landslide slip surface. Data is from 2018-2019. Modified from Thomas et al. (2020). An expansion of this effort could lead to the development of "watch" and "warning" levels for landslide potential across diverse regions of Puerto Rico.

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