WIDESPREAD SHALLOW MASS WASTING DURING HURRICANE MARIA: LONG-TERM SIGNIFICANCE OF SEDIMENTATION IN THE TROPICS[1]

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ABSTRACT: Hurricane María was an extreme atmospheric event that impacted Puerto Rico in 2017. As a result of the passage of hurricane María over the island more than 70,000 landslides were triggered, with the highest density of mass wasting found in the mountainous center of the island. This area is highly susceptible to slope failure given the local soils that form as a result of continuous tropical chemical weathering of the bedrock material. Copious amounts of sediment from these soils were mobilized and transported by the landslide-triggering event. The results of our study reveal the soil types that are most susceptible to mass wasting loss in order to better understand their susceptibility to failure and contribution to sedimentation across the rugged interior of the island. A preliminary analysis of area volume scaling statistics for thousands of landslide sites in the important Lago Dos Bocas basin reveals that Hurricane María likely liberated at least 1.7 million cubic meters of mostly superficial sediment in the lake's contributing area (not including the Caonillas sub-basin). In an effort to determine the efficiency of the fluvial system to transport these sediments during and after the catastrophic hurricane event, bathymetric surveying was carried out in Lago Dos Bocas, where much of the sediment is hypothesized to have been deposited. This reservoir is a vital piece of infrastructure in the island as it supplies water to the San Juan metropolitan area. Based on the 2021 bathymetric survey and the historical data, the excess sediment deposition to the reservoir related to Hurricane María is estimated at approximately 2.1 million cubic meters. When compared with data from 1999-2010, this volume represents the equivalent of 18 years of background sedimentation. At present, the reservoir capacity loss since construction is at 64%. These analyses are pertinent to understand how the local sediment budget has been affected and to re-calculate the useful life of the reservoir and highlight the vulnerability of Caribbean infrastructure systems, given the forecasted likelihood of increased tropical cyclone activity in the years to come.

Keywords: landslides, hurricane María, bathymetry, soil, sedimentation, Caribbean

EXTENSOS DESLIZAMIENTOS SUPERFICIALES DEL HURACÁN MARÍA: LA IMPORTANCIA DE LA SEDIMENTACIÓN EN EL TRÓPICO A LARGO PLAZO

RESUMEN: El huracán María fue un evento atmosférico extremo que impactó a Puerto Rico en el 2017. A raíz del paso del huracán María sobre la isla más de 70,000 deslizamientos de tierra se desencadenaron con una mayor concentración en la parte central montañosa de la isla. Esta región es altamente susceptible a deslizamientos de tierra por los suelos que se forman como resultado de la continua meteorización química tropical del material parental. Este evento, desencadenante de deslizamientos de tierra, movilizó y transportó abundantes cantidades de sedimentos provenientes de estos suelos. Los resultados de este estudio nos permiten determinar que suelos son más susceptibles a deslizamientos para entender su susceptibilidad y su contribución a la sedimentación a través del interior montañosa de la isla. Un estudio estadístico preliminar de factores de escala de área y volumen en la importante cuenca del Lago Dos Bocas mostró que el huracán María probablemente liberó al menos 1.7 millones de metros cúbicos de sedimento mayormente superficial en el área alrededor del lago (sin incluir la sub-cuenca de Caonillas). Se realizó una evaluación batimétrica en el Lago Dos Bocas, donde se entiende que se depositó una gran parte del sedimento, con el propósito de determinar cuán eficaz fue el sistema fluvial

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transportando estos sedimentos durante y después de este catastrófico huracán. Se escogió dicho embalse por ser una infraestructura de vital importancia para suplir agua al área metropolitana de San Juan. En base a los resultados batimétricos del 2021 y datos históricos, se estima que el exceso de sedimentos depositados en el embalse relacionados al huracán María es de aproximadamente 2.1 millones de metros cúbicos. Al comparar los datos con los de estudios batimétricos del 1999-2010, este volumen representa un equivalente de 18 años de sedimentación. Estos resultados nos indican que, desde su construcción, el embalse ha perdido un 64% de su capacidad original. Es pertinente realizar estos análisis para entender cómo se ha afectado la cantidad de sedimento local, recalcular la vida útil del embalse y destacar la vulnerabilidad de los sistemas de infraestructura Caribeña, dado el pronosticado aumento en actividad ciclónica tropical en el futuro cercano.

Palabras claves: deslizamientos de tierra, huracán María, batimetría, suelo, sedimentación, Caribe

INTRODUCTION

It has been estimated that 0.5 to 1% of global fresh water reservoir storage is lost annually as a result of sedimentation (Basson, 2009). Tropical regions are more at risk of sedimentation, due to higher rates of erosion and the impact of atmospheric events (Nagle *et al.,* 1999). Caribbean islands are especially vulnerable to the occurrence of landslides in these storms, which have been determined to account for a large portion of the sediment supply in fluvial systems, particularly bedload (Ahmad *et al.,* 1993). Puerto Rico is located along an active tectonic boundary and in the path of tropical cyclone systems; both circumstances contribute to the susceptibility of landsliding on the island. Episodes of magmatic activity, erosion, subsidence, carbonate deposition, and uplift over the past tens of millions of years have resulted in a rugged mountainous interior, characterized by active and adjusting topography. The highest peaks on the ~9,000 km^2 Caribbean island are more than 1,300 meters (m) altitude and lie within only a few tens of km from the coast. Pockets of relatively low-relief upland plateau are remnants of a relict landscape that existed before uplift initiated around 4 Ma, and continues to the present (Brocard *et al.,* 2016; Taggart & Joyce, 1989). These upland surfaces have largely been dissected by fluvial processes that have incised channel beds and over-steepened hillslopes in order to adjust to the relative base level change. It is in the zones of adjusting hillslopes that landslides are most common on the island. The most common mass wasting style is shallow debris flow, where soil and regolith material are mobilized as a result of over saturation in the overburden material, commonly associated with high intensity precipitation from tropical cyclone systems. These shallow failures often deliver sediment slurry directly to the fluvial system in Puerto Rico, with about half of all landslide-mobilized material estimated to be introduced to downslope channels in one local study (Ramos-Scharrón *et al.,* 2021). After transport to the stream network, the sediment is carried according to limitations defined by sediment size and stream flow metrics. The large amount of landslide material introduced to the fluvial network converts into a large component of the sedimentation problem that is widespread across Puerto Rico, notably in the freshwater reservoirs of the island.

Long-term weathering and short-term weather events are both important to consider for landslides in Puerto Rico. Chemical weathering and development of the critical zone (saprolite, regolith, and soil) in the island is accelerated because of the convergence of high annual rainfall, active biological processes, and year-round warm temperatures (Dosseto *et al.,* 2012; Ferrier *et al.,* 2010; White *et al.,* 1998; White & Blum, 1995). The chemically weathered material can locally be up to tens of meters thick and is the principal zone where shallow mass wasting occurs (Simon *et al.,* 1990).

Tropical cyclone systems that affect Puerto Rico generally form near the Cape Verde islands and move westward across the Atlantic Basin towards the Caribbean archipelago. Both tropical storms and hurricanes can bring intense rainfall capable of triggering landslides across the island. In addition, some local heavy precipitation events that are not associated with tropical cyclones often exceed global and island-specific empirical rainfall intensity-duration landslide provoking thresholds (Caine, 1980; Díaz Sosa, 2021; Larsen & Simon, 1993; Pando *et al.,* 2005). Hurricane María crossed Puerto Rico on September 20, 2017 and caused widespread landsliding. Over 70,000 headscarp sites were documented across the island (Hughes *et al.,* 2019; Figure 1) and caused damage to infrastructure, destruction of homes, loss of cultivated crops, deaths, and resulted in long-term sedimentation at offshore coral reef sites (Bessette-Kirton *et al.,* 2019; Ramos-Scharrón *et al.,* 2021; Takesue *et al.,* 2021). Precipitation estimates were as high as 950 mm for parts of the mountainous interior for the duration of the storm (Pasch *et al.,* 2018) and exceeded the intensity-duration thresholds for landslide triggering almost everywhere across the island. Landslides were most abundant in the municipalities on the northern flank of the east-west trending Cordillera Central and in the Río Grande de Arecibo and Río Grande de Añasco watersheds.

Figure 1: Location of the landslides triggered by Hurricane María in 2017. Note: There were more than 70,000 landslides identified throughout the island, the majority located in the north central region (Hughes *et al.*, 2019).

STUDY AREA

The Lago Dos Bocas reservoir is part of the 615 km^2 Río Grande de Arecibo basin, one of Puerto Rico's largest watersheds and located in the north central portion of the island (Gómez-Gómez *et al.,* 2014; Fig. 2). During Hurricane María, the Río Grande de Arecibo basin had the highest landslide density among National Hydrography Dataset level 10 watersheds at 30 landslides per km^2 and its sub basins also had the highest density at 50 landslides per km^2. The soil orders in this basin are predominantly Ultisols, Oxisols, and Inceptisols and include 35 soil series (Sotomayor-Ramírez *et al.,* 2010). Many of these soils originate from plutonic bedrock material and have a high sand content and low cohesion when chemically weathered (Hughes & Schulz, 2020). The sandy texture of the soil units in this watershed is one of the principal reasons why it was the most affected by the landslides triggered by Hurricane María. Because of the impact that landslides have on the Río Grande de Arecibo basin, the Lago Dos Bocas reservoir was selected to assess the sediment transportation efficiency, connectivity, and deposition related to a widespread landslide triggering event. One of two main reservoirs in the basin, Lago Dos Bocas, was built in 1942 and had an original storage capacity of 37.5 million cubic meters (Mm^3) and a drainage area of 440 km^2 (Sheda & James, 1968). It is an important reservoir in the North Coast Superaqueduct Project, estimated to supply approximately 350,000 cubic meters per day (m^3/d) of water to communities along the north and northeast coast of the island as of 2005. It can be divided into two principal sub-basins: the 205 km^2 Río Grande de Arecibo watershed and the 105 km^2 Río Caonillas-Río Limón catchment area (Soler-López, 2007).

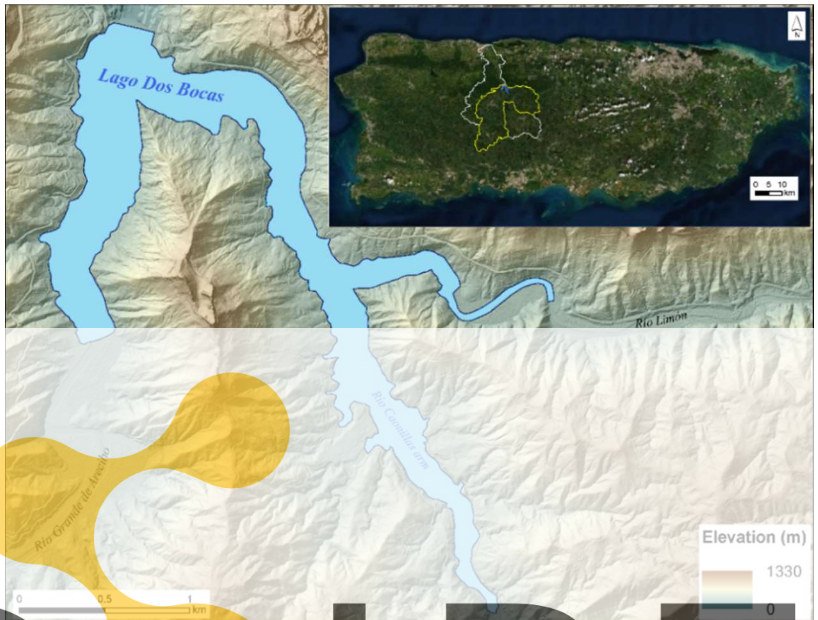

Figure 2: Lago Dos Bocas in central Puerto Rico (18.333, -66.666). The inset map of Puerto Rico shows the greater Río Grande de Arecibo watershed in white and the Lago Dos Bocas contributing area in yellow.

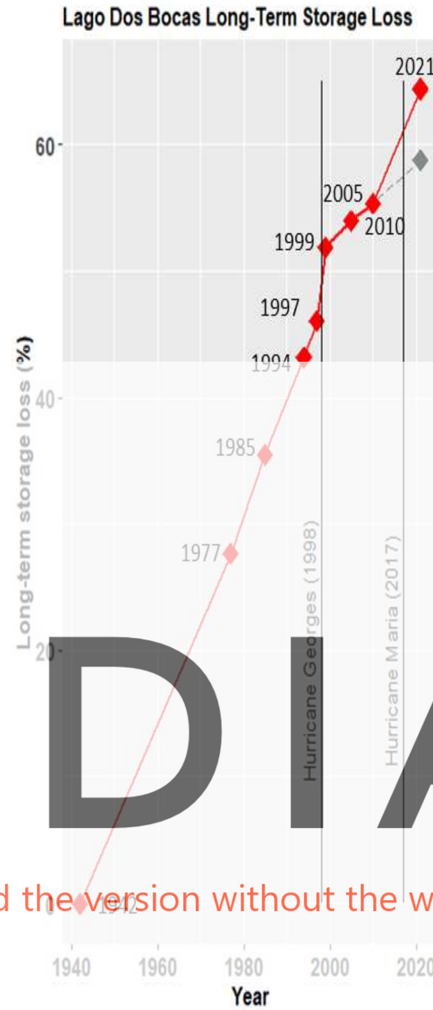

Figure 3: Long-term storage capacity loss of Lago Dos Bocas reservoir from 1942 to 2021. Red line connects bathymetric survey data. Dashed gray line shows a hypothetical "post-Georges" increase in storage loss that could have been expected if Hurricane María did not impact the island.

Lago Dos Bocas has been affected by sedimentation since its construction, accounted by surveys by the United States Geological Survey (USGS) from 1942 to 2010. During this period, the USGS performed 7 surveys in the reservoir (Table 1; Quiñones *et al.,* 1989; Soler-López, 2001, 2007, 2014; Soler-López & Webb, 1998; Webb & Gómez-Gómez, 1996). The last survey in 2010 indicates that the reservoir's storage capacity had decreased by 55% since 1942, equivalent to a storage capacity of around 16.75 Mm^3 (Fig. 3). Surveys in 1997 and 1999 that bracketed Hurricane Georges in 1998 demonstrated a large pulse in sedimentation compared to years prior, but surveys in 2005 and 2010 showed considerably lower sedimentation rates during that decade compared to pre-Georges surveys. A potential explanation for this observation is that the high flows caused by Hurricane Georges could have flushed all available material accumulated over decades and stored in channels of the fluvial network to the reservoir, reducing the amount of sediment that could be transported into the reservoir in following years (Soler-López, 2007, 2014).

Table 1: Lago Dos Bocas bathymetric survey data from 1942 to 2021. Source: USGS and this study.

Year	1942	1977	1985	1994	1997	1999	2005	2010	2021
Capacity (Mm^3)	37.5	27.14	24.2	21.31	20.23	18.04	17.26	16.74	13.35
Live storage (Mm^3)	29.47	23.13	--	19.15	18.68	17.06	16.5	16.30	13.35
Dead storage (Mm^3)	7.83	4.01	--	2.16	1.55	0.98	0.76	0.44	0
Years since construction	0	35	43	52	55	57	63	68	79
Sediment accumulated (Mm^3)	--	10.36	13.3	16.19	17.27	19.46	20.24	20.76	24.15
Inter-survey sediment accumulation (Mm^3)	--	10.36	2.94	2.89	1.08	2.19	0.78	0.52	3.39
Long-term storage loss (%)	--	27.6	35.5	43.2	46.1	51.9	54.0	55.4	64.4
Inter-survey loss of capacity (Mm^3/yr)	--	0.296	0.368	0.321	0.367	1.09	0.13	0.104	0.29

METHODS

Soils

The Lago Dos Bocas and Lago Caonillas sub basins include 87 mapped unique soil map units (NRCS SSURGO) out of around 700 total soil map units throughout Puerto Rico (Fig. 4). The soils mostly formed above either volcaniclastic and granodioritic bedrock, where the volcaniclastic soils are more clay rich and the granodioritic soils are sandier. These soil units were used in an analysis of landslides triggered by Hurricane María to rank each unit's affinity for shallow mass wasting. The Frequency Ratio (FR) technique was used and employed as an important contributing factor in a revised high-resolution landslide susceptibility map for Puerto Rico (Hughes & Schulz, 2020). An FR score is calculated as the ratio between the numbers of events (landslides in this case) that fall in a certain bin (unique soil map units in this case) divided by the abundance of that condition throughout the study area:

$$FR_{fi} = \frac{N_{Lfi}/N_L}{A_{fi}/A} \quad (1)$$

Where:

FR_{fi}: frequency-ratio value for each soil map unit

N_{Lfi}/N_L: ratio of the number of landslides in a soil map unit to the total number of landslides in the inventory

A_{fi}/A: ratio of the aerial extent of the soil unit to the total study area. An FR score of <1 reflects a negative correlation, while FR values >1 indicate positive correlation.

In addition to FR analysis the outline of thousands of shallow mass wasting sites in the Lago Dos Bocas and Lago Caonillas basins were digitized using high resolution aerial imagery captured in the months immediately following Hurricane María. The area of each polygon was calculated in GIS and a volume estimate was generated with shallow mass wasting scaling factors shown in the following equation, modified from Larsen *et al.* (2010) and Ramos-Scharrón *et al.* (2021):

$$V = \alpha A^{\gamma} \quad (2)$$

Where:

V: landslide volume

A: landslide area

α and γ: power law scaling factors.

This approach is simplistic because it assumes landslides in diverse regolith material all fail to a similar depth. However, it provides an acceptable first order estimate of volume per area for this study.

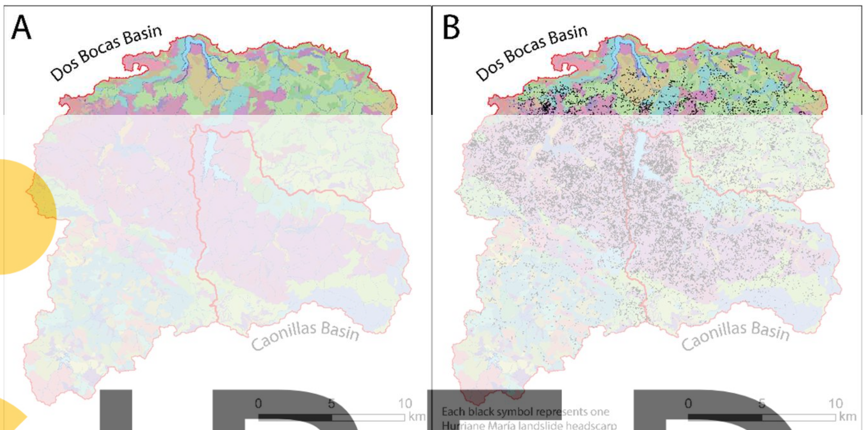

Figure 4: A) Distribution of soil map units in the Lago Dos Bocas and Caonillas watersheds. Colors are randomly assigned to each unique soil map unit. B) Hurricane María landslide headscarp represented by each black symbol. The Lago Dos Bocas basin includes 13,390 sites whereas the Caonillas basin includes 8,617 sites. Note concentration in soil units colored in purple trending NW-SE.

Bathymetric Survey

A bathymetric survey was conducted in Lago Dos Bocas reservoir on March 3, 2021 using a Humminbird HELIX 7 CHIRP GPS G3N depth sounder (broadband frequency: 180 to 240 kHz) on a motor-powered boat (Fig. 5A). An Emlid REACH RS2 and RS RTK GPS antennas were used to later compare the location. This survey approach is similar to that published by USDA NRCS (Huscher & Griffith, 2015). To obtain a dense array of survey points, a series of transects following a "zig-zag" pattern oriented perpendicular to the lake channel orientation were completed. Survey points were collected as far upstream as feasible, given the water depth. Periodically, depth measurements were made with a demarcated rope and anchor to assess the accuracy of the depth sounder recordings. While conducting the survey and navigating the transects, the data string from the depth sounder was streamed via modified output cable to a laptop running a Tera Term terminal, stored as a National Marine Electronics Association (NMEA) message text file (Fig. 5B, 5C). The NMEA data stream was updated every second and stored in a text file containing depth, water temperature, time and date, and multiple positioning sentences, among other information. A code was prepared using the R programming language to extract and organize the target data strings and export them to a CSV file (Fig. 5D).

The depth data were corrected relative to the Normal Operation Level of the USGS station number 50027100 "Lago Dos Bocas at Damsite Near Utuado Puerto Rico," which is 89.92 m (295 ft) above sea level. The lake level during the start and majority of the survey was consistent at 88.65 m elevation, incrementing through the day. By the end of the survey the lake level had increased by approximately 20 centimeters (waterdata.usgs.gov, last accessed 13-sept-2021). After correcting the depth values, the data was imported to ArcMap as a table, and then converted to a point shapefile. Erroneous data points, which included recordings affected by increased boat speed, obstacles in the water impacting the depth sounder (such as tree branches or other debris), and incomplete depth measurements, were removed from the dataset. The outline of the Lago Dos Bocas reservoir was digitized from historical aerial imagery and was used as the bathymetric survey's interpolation limit with a value of 0 m depth incorporated into the model. The data points were interpolated, and a triangulated irregular network (TIN) dataset was generated using the Create TIN ArcMap tool. The resulting file was converted to a raster format using the TIN to Raster tool. The Extract by Mask tool was used with the digitized lake outline shapefile to remove any excess raster data interpolated outside of the lake boundary.

The 2010 bathymetric dataset (J. Gómez-Fragoso, pers. comm., 2020) was compared with the 2021 survey to determine increases or decreases in depth along sections of the reservoir. This differencing was carried out using the Raster Calculator in ArcMap. Considerations of future sedimentation for the Lago Dos Bocas were made using historical data, our new survey data, and hypothetical future extreme event scenarios.

Figure 5: (A) Lago Dos Bocas at the time of the 2021 bathymetric survey. (B) NMEA data stream on the Tera Term terminal during the survey. (C) Depth sounder monitor, battery, and computer. (D) Segment of the NMEA message recorded during the field survey with red outline of the sample measurements selected, extracted depth ($GPDPT) and position ($GPGLL) sentences, and final CSV with the data organized in single row.

RESULTS

Soils

Soil map units in the Dos Bocas and Caonillas basins are among the most susceptible to shallow mass wasting in Puerto Rico. Based on the analysis of over 70,000 Hurricane María shallow mass wasting sites, the Pellejas clay loam and Lirios clay loam units that are prevalent in these catchments cover only 1.8% of the Puerto Rican landscape but suffered 23% of the event landslides (Hughes & Schulz, 2020; Table 2). These two units are seen as the NW-SE swath of map units in Fig. 4B and developed above the Utuado granodiorite bedrock unit.

Table 2: FR values of the two most affected soil units in the catchment areas.

Soil Map Unit	MUKEY	FR Score	Area (km^2)	Area (%)	Landslides	Landslides (%)
Pellejas clay loam, 40 to 60 percent slopes	326463	14.0	98.9	1.1	8524	15.9
Lirios clay loam, 40 to 60 percent slopes, eroded	326445	10.5	59.1	0.7	3802	7.1

Specifically, within the Lago Dos Bocas contributing area, more than 13,000 Hurricane María landslide headscarp points were inventoried (Hughes *et al.,* 2019) and 8,100 individual landslide areas were digitized as polygons in a related effort. After calculating the area of each polygon and using the Puerto Rico-specific shallow mass wasting scaling factors empirically derived by Ramos-Scharrón et al. (2021; α=0.254, γ=1.152) an approximate mobilized volume of 1.70 Mm^3 of sediment was arrived. Given that this total was derived from an incomplete polygon inventory, this volume of 1.70 Mm^3 should be considered a *minimum* estimate for landslide mobilized sediment during Hurricane María, which likely exceeded 2 Mm^3.

Bathymetric Survey

After parsing the dataset for inaccurate depths or locations, 4,749 data points from 172 transects (Fig. 6a) were used to create the bathymetric model (Fig. 6b). After interpolating all the data points, the resulting raster had a 13.86 m spatial resolution. The maximum depth is 18.9 m and the average depth is 8.5 m. The deepest area of the lake is in the Río Limón / Río Caonillas arm. The surface area of the lake at normal operating level is 1.5 km^2 or slightly less.

The calculated water capacity at normal operating level for the present survey (2021), is 13.35 Mm^3. One-hundred percent of this amount is considered "live-storage" as there is no depth greater than the level of the reservoir's underwater intake structure (located at 18.4 - 21.2 m deep [Soler-López, 2007]). This would indicate a storage capacity decrease of 24.15 Mm^3 or 64.4% from the original 37.5 Mm^3 at the time of construction in 1942.

Between 2010 and 2021, there was a calculated sediment accumulation increase of 3.39 Mm^3. Most of the increase in sediment occurred in the Río Grande de Arecibo arm of the reservoir, a well-documented trend observed for decades (Fig. 6c). The 3.39 Mm^3 inter-survey loss of capacity accounts for the complete time period between the last two surveys and represents a period-average annual increase of 0.308 Mm^3 during the decade. To estimate how much of the increase from 2010-2021 can be attributed to Hurricane María driven sedimentation, the average infilling rate from 3 bathymetric surveys (1999, 2005, and 2010) after Hurricane Georges was used. The average post-Georges rate of 0.117 Mm^3/yr was projected from 2010 to 2021, resulting in an estimated hypothetical water storage capacity of 15.45 Mm^3 (see gray dashed line in Figure 3). This storage capacity was then subtracted from the true measured storage capacity in this 2021 study (13.35 Mm^3), resulting in a difference of 2.1 Mm^3. This volume of 2.1 Mm^3 (or 5.6% of the original reservoir capacity) is potentially representative of the excess sedimentation to Lago Dos Bocas reservoir that can be attributed to Hurricane María. Compared to the steady post-Georges sedimentation rate, the calculated Hurricane María excess amount represents approximately 18 years of accumulation.

DISCUSSION

Our estimate of at least 1.7 Mm^3 of liberated sediment at landslide sites triggered by Hurricane María in the Lago Dos Bocas contributing area and a similar value of 2.1 Mm^3 of excess sediment deposited in the reservoir, sometime between 2010 and 2021, are important to better understand the source to sink dynamics for the system. Widespread mass wasting appears to be a significant and primary contributor to downstream sedimentation for this case study and should be included in sedimentation modeling efforts. Specific soil units that are comprised of low cohesive sandy material in rugged terrain are key in this integrated relationship.

In the first decade of the 21st century the sedimentation rate in Lago Dos Bocas was approximately 3 times lower as compared with the 20th century, with an average interannual storage capacity loss of 0.117 Mm^3 in the period of 1999-2010 compared to an average of 0.338 Mm^3 loss from 1942-1997. This drastic inflection point in sedimentation rates is marked by the passage of Hurricane Georges in 1998. USGS bathymetric surveyor Soler-López (2007, 2012) speculated that the flooding associated with Hurricane Georges drastically "*depleted erodible and transportable bed sediments within the tributaries of Lago Dos Bocas reducing the readily available sediments, thus, reducing its storage capacity loss rate.*" Another more gradual contributor to decreased sedimentation in the watershed is the decades-long abandonment of cultivated lands as more residents move towards urban centers or out of Puerto Rico. This trend away from agriculture decreases the immediate effect of sediment runoff from farming activities.

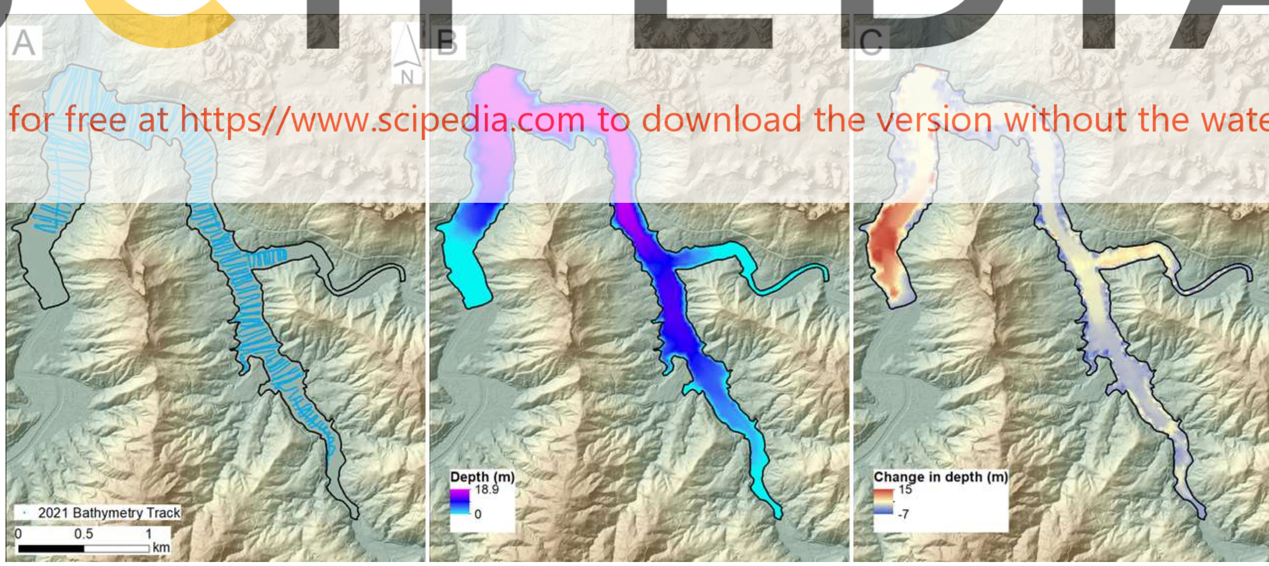

Figure 6: (A) Transects of the 2021 bathymetric survey in the reservoir. (B) 2021 bathymetric survey interpolated raster. (C) Difference of the 2010 survey and 2021 survey rasters. Positive numbers indicate a decrease in water depth (i.e. increase in sediment accumulation). Note most dramatic infilling in the Rio Grande de Arecibo arm.

Projecting a useful lifespan for the reservoir is complicated by these sedimentation rate changes over time and the forecasted likelihood of more frequent extreme atmospheric events in the future. After the 2010 survey, the estimated date of the lake being 100% infilled was calculated at 2065 using the long-term (1942-2010) annual capacity loss rate. If the post-Georges rates are only considered, this date would be a century longer, until the year 2173. This post-Georges rate was used above to estimate the Hurricane María contribution, and it is unknown how much transportable sediment was accumulated between 2010 and 2017. Given the unlikely scenario that channels in the Lago Dos Bocas contributing area were effectively stocked with sediment to pre-Georges conditions in these 7 years, the Hurricane María associated sedimentation estimated at 5.6% or 2.1 Mm^3 is all the more impressive and we conclude that it is mostly related to the mobilization of sediment from the hillslope. If Hurricane María effectively "flushed" transportable sediment from the system in a manner similar to, or more so than, Hurricane Georges, then the buildup of sediment in the fluvial network was essentially reset to zero in 2017 and it could be assumed that the next decade or longer will have relatively low sedimentation rates if no extreme atmospheric events cause widespread landsliding during that period.

A pertinent unknown factor is the time required to once again buildup transportable sediment in the local fluvial network, such that the interannual sedimentation in non-catastrophic event years would return to pre-Georges rates. This further complicates an estimate of the usable life of the reservoir. Future bathymetric surveys are needed to carefully estimate a longer term post-María rate and will benefit from the survey results described herein. Reasonable estimates for the complete infilling of Lago Dos Bocas without additional extreme atmospheric event driven sedimentation could range from 2060 – 2100, depending on the time needed to build-up enough fluvial channel sediment to return to a background interannual capacity loss rate of approximately 0.3 Mm^3. If events of the magnitude of Hurricanes Georges and María occur more frequently, the reservoir could become useless earlier than 2060.

CONCLUSION

Sedimentation is a severe problem in Puerto Rico and other vulnerable sites worldwide. Sediments mobilized during extreme events can fill important freshwater reservoirs and also affect water quality of both rivers and offshore sites. Distinct low cohesion sandy soil units throughout the Lago Dos Bocas contributing area contribute to this area being extremely susceptible to shallow mass wasting during high-intensity rainfall events. Sediments liberated at these landslide sites are mobilized by high-flow in first order tributary networks and are easily incorporated into the larger fluvial network and transported downstream.

The combination of sedimentation-inducing characteristics for the Lago Dos Bocas and nearby Lago Caonillas basins are exceptionally effective in impacting the reservoirs, especially after widespread landslide generating events such as Hurricane María. Sedimentation related to Hurricane María appears to have filled approximately 5.6% (2.1 Mm^3) of the original capacity of Lago Dos Bocas and represents nearly two decades of background 21st century sedimentation. The sediment delivered to the reservoir is comparable to a preliminary estimate of the material that was mobilized at landslide sites.

Ongoing work with high-resolution LiDAR data will assist researchers in the process of refining the understanding of sediment and source to sink connectivity on the short- and long-term scales, especially in the Caribbean and other tropical regions.

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