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Debris-flow growth in Puerto Rico during Hurricane Maria: Preliminary results from analyses of pre- and post-event lidar data

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Abstract

On September 20, 2017, Hurricane Maria triggered widespread debris flows in Puerto Rico. We used field observations and pre- and post-Maria lidar to study the volumetric growth of long-travelled (>400 m) debris flows in four basins. We found overall growth rates that ranged from 0.7 to 30.4 m³ per meter of channel length. We partitioned the rates into two growth mechanisms, aggregation of multiple landslides, or erosion and entrainment of channel sediment. In three basins, landslides accounted for more than 80% of the total debris-flow volumes. In one basin, entrainment accounted for 96% of the volume. These results indicate that forecasting volumes for regional debris-flow inundation modeling is more complicated than estimating the number and volume of contributing landslide source areas, although this task is difficult by itself. In this preliminary analysis, we did not find geologic, topographic, or morphometric variables that correlated with the growth observations. We suspect that the observed growth rates were heavily influenced by local variations in environmental conditions, including antecedent soil moisture conditions, duration and intensity of rainfall, and availability of channel material. Given these considerations, regional debris-flow inundation modeling may be best achieved by using a suite of scenarios that capture possible mechanisms of debris-flow growth.

1 INTRODUCTION

Volumetric growth of debris flows as they move downslope and downstream can increase flow mobility, and therefore the hazard and risk to people and infrastructure (e.g., Guadagno and Revellino, 2005). Growth can occur by a variety of mechanisms, including the aggregation of multiple landslide sources, erosion and entrainment of channel sediment, incorporation of channel bank failures, and the merging of multiple debris flows (e.g., Reid et al., 2016). Multiple growth mechanisms often occur in single flows, but determining the volumetric contributions from these mechanisms is difficult, and therefore the varying contributions are often poorly known. In areas where overall rates of growth (also known as bulking rates, erosion rates, or yield rates, which are typically from entrainment of channel material) have been quantified, they vary widely, from negligible entrainment up to 300 m³

per meter of channel length (e.g., Hungr et al., 2005; Reid et al., 2016).

The timing of debris-flow growth is also difficult to reconstruct without eyewitness accounts or in-situ instrumental monitoring data. For example, during individual triggering events, there can be single or multiple debris flows that can create the overall spatial patterns of erosion and deposition measured by forensic investigations. Throughout this paper, we use the term “growth rate” when describing the volume of sediment per meter of channel length required to account for the total volume of material removed from drainage basins by debris flows during a hurricane. However, by using this term, we are not implying that we know the timing or number of debris flows that created the measured patterns of erosion and deposition used to estimate the growth rates. When growth rate is used in this way, it is a proxy for the maximum possible spatial growth rate affecting a single debris flow,

whereas in reality, the erosion and entrainment responsible for determining the rate could have been from multiple flow events.

Because growth rates can strongly influence flow mobility, knowledge of net rates from all sources, including landslides, is critical for local and regional debris-flow inundation modeling efforts. In tropical areas such as Puerto Rico, an understanding of debris-flow growth is especially important because of the common presence of wet soils and channel sediments, and thus the possibility for elevated positive-pore pressures which can enhance growth, particularly by entrainment (Iverson et al., 2011).

Widespread debris flows triggered by Hurricane Maria in Puerto Rico (Bessette-Kirton et al., 2019a; Bessette-Kirton, 2019b; Hughes et al., 2019; Schulz et al., 2019) provide an opportunity to examine debris-flow growth rates in a tropical area with a large population exposed to landslide hazards. Hurricane Maria struck Puerto Rico on September 20, 2017 and triggered tens of thousands of debris flows in at least three-fourths of Puerto Rico's 78 municipalities (Bessette-Kirton et al, 2019a). Bessette-Kirton et al. (in press) showed that debris-flow height/length (H/L) ratios ranged from 0.1 to 1.9 and that mobility was positively correlated with the number of landslides contributing to the flows (i.e., H/L decreased as the number of landslides increased). However, Bessette-Kirton et al. (in press) did not have adequate data to determine if the observed increase in mobility was strictly due to the aggregation of landslides, or if entrainment of channel material or the merging of multiple flows also contributed.

In this paper, we explore debris-flow growth during Hurricane Maria at four study sites in Puerto Rico (Fig. 1) using field observations and pre- and post-event lidar data to estimate debris-flow erosion and deposition. We focus on results from lidar analyses, and also describe field observations where needed to support or enhance the lidar analyses. We differentiate the volumetric contributions from landslides and channel entrainment and discuss possible topographic, geologic, morphometric, and environmental controls on the observed growth patterns.

2 STUDY SITES

During the fall and winter of 2017-2018, we identified long-traveled (> 400 m long) debris flows triggered by Maria from ~0.15 m-resolution digital aerial imagery collected between 9-15

October 2017 (Quantum Spatial, Inc. 2017). In the spring and summer of 2018, we made field observations of debris flows at 11 of the identified sites in the Naranjito, Corozal, Barranquitas, Utuado, Lares, and Las Marias municipalities of Puerto Rico. In this paper, we focus on four sites in the Naranjito and Utuado municipalities (Four Car, Twenty Headed, DOG, and Hook, Figs. 1 and 2). These sites are located where pre- and post-Maria lidar data are currently (as of October 2019) available. We informally named the sites after characteristics observed in the field. For example, "Twenty Headed" is named after the 20 separate landslides that supplied material to the debris flow(s) in the basin. The Four Car and Twenty Headed sites are underlain by basaltic tuff of the Cretaceous Los Negros Formation (Nelson, 1967a), whereas the DOG and Hook sites are underlain by granodiorite of the Cretaceous Utuado batholith (Nelson, 1967b). The drainage basins that include the debris-flow sites (see Fig. 2) are small (<300,000 m² (<0.3 km²)) and steep (mean slopes $\geq 28^\circ$, see Table 1).

3 METHODS

We made field observations at the study sites by hiking up or down channels affected by debris flows. Bedrock cliffs and thick vegetation prevented us from accessing some channels, but we were able to collect data at observation locations either in, or just downstream from all of the study sites (Fig. 2). At each observation location, we recorded an autonomous GPS location, measured channel cross-sections and channel slope gradients using a laser rangefinder with inclinometer, estimated the approximate depth of flow erosion or deposition, and noted the type of deposits (debris flow, water-dominated flood, or mixed deposits). We identified debris-flow deposits as unsorted, matrix-supported deposits that contained randomly oriented clasts (cobbles and boulders). In contrast, flood deposits were sorted, contained distinct bedding, and were generally finer grained than debris-flow deposits.

We used a difference of DEMs (DoD) created from pre- and post-Maria lidar data to assess net elevation changes (erosion, transport, or deposition) caused by debris flows. Lidar data were acquired by the U.S. Geological Survey (USGS) in 2015 and 2016 (pre-Maria) and in mid-to-late 2018 (post-Maria). The data sets were acquired to meet "quality level 2" (QL2, pre-Maria) and "quality level 1" (QL1, post-Maria) specifications which state that elevations in



Figure 1. Map showing the location of the four study sites (Four Car, Twenty Headed, DOG, and Hook) in the Utuado and Naranjito municipalities (shaded in light gray) in central Puerto Rico. Thin, light gray lines show municipality boundaries.

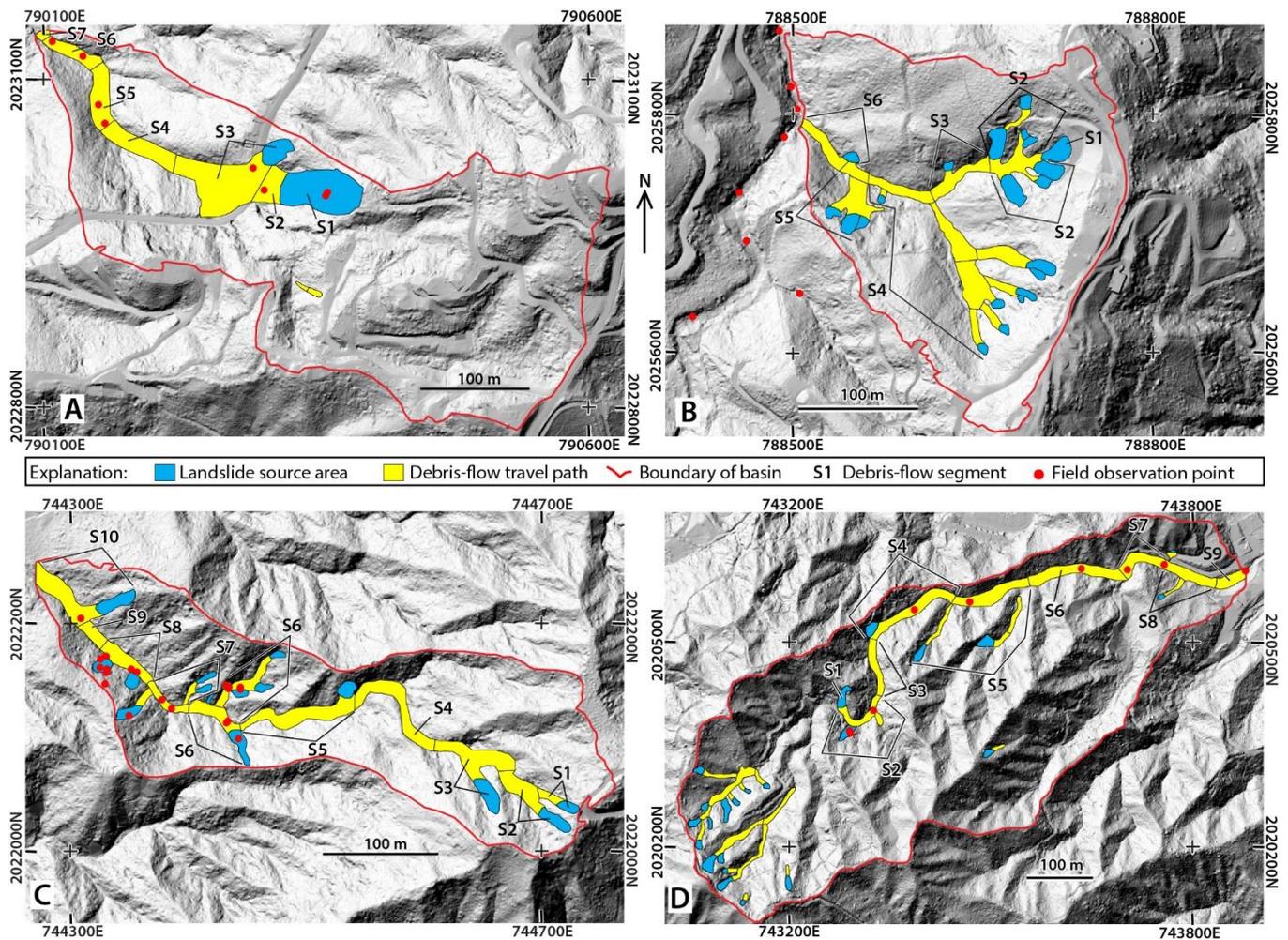


Figure 2. Maps showing debris flows in the four study areas, A) Four Car, B) Twenty Headed, C) DOG, D) Hook. Shaded-relief base maps are from 2018 (post-Maria) 0.5-m lidar data. Debris flows are divided into landslide source areas (blue polygons) and travel paths (yellow polygons). Landslides and paths at the upper end of the basin at Hook, which are disconnected from the main debris flow path, were not used to determine growth rates. Black lines within source areas and travel paths are polygon boundaries used to subdivide areas and volumes for growth estimates. Segments are labeled S1, S2, etc. Red lines show drainage-basin boundaries. Coordinates shown are UTM zone 19. Note that the individual maps are different scales.

Table 1. Geologic, morphometric, and topographic characteristics of study basins shown in Figure 2. Basin height is the elevation difference (relief) from the highest point in the basin to the outlet of the basin. Mean slope is calculated from all 1-m DEM cells in the basin (from pre-Maria lidar). Melton's number is a dimensionless measure of basin ruggedness defined as basin height/basin area^{0.5} (Melton, 1965). Column 3 is U in equation 3 of Reid et al. (2016).

Site name	Underlying geologic unit	Basin area, U (m ²)	Basin height (relief, m)	Melton's number	Mean slope (degrees)	Percentage of basin with slopes > 30 degrees
Four Car	Basaltic tuff	94,750	258	0.83	28	62
Twenty Headed	Basaltic tuff	60,070	130	0.53	28	54
DOG	Granodiorite	63,620	220	0.87	38	58
Hook	Granodiorite	255,560	213	0.42	33	59

vegetated areas (i.e., most of Puerto Rico) were accurate to within a two-standard deviation (2σ) value of ± 0.3 m (Heidemann, 2018, p. 24). We used bare-earth DEMs from the two data sets to create the DoD by subtracting the pre-Maria DEM from the post-Maria DEM. The pre-event and post-event bare-earth DEMs had cell resolutions of 1 m and 0.5 m, respectively. The DoD had a resolution of 1 m. Application of the law of propagation of errors (DoD accuracy = $\sqrt{0.3^2 + 0.3^2}$) indicates that the DoD had an accuracy of ± 0.42 m.

We used a Geographic Information System to assist in mapping debris flows at the four study sites using the rectified, high resolution imagery acquired immediately following Maria in October 2017, as well as the previously mentioned DoD. We used polygons to outline areas impacted by the flows, and defined the polygons as either landslide-source areas or debris-flow travel paths (Fig. 2). We delineated landslide-source areas as topographic depressions in the DoD created by mobilization and evacuation of the landslides. Downslope deposits and debris-flow channels were included in the debris-flow travel paths. We stopped mapping travel paths at the mouths of the study basins where debris flows began mixing with flood water. Channel-bank failures were mapped as landslides if they created a distinct depression in the DoD, and were included with travel-path polygons if they did not. This method allowed us to differentiate volumes of material contributed by landslide sources and entrainment of channel sediment.

In addition to source areas and travel paths, we divided each flow into segments to better track changes in debris-flow growth and contributions during downslope and downstream movement (Fig. 2). Segments ranged from about 50 to 150 m in length and were strategically selected to capture important changes in contributing source areas or travel paths. For example, at Twenty Headed, the three main clusters of landslide-source areas and their adjacent downslope travel paths, were divided into separate segments (Fig. 2B).

For each polygon and segment, we mapped the curvilinear length of flow path contained in the polygon, determined the area of the polygon, and extracted the mean elevation change from the DoD. As an example, Figure 3 shows elevation changes in the DoD at Four Car. Mean values in each polygon and segment were multiplied by areas to calculate volumes. Negative volumes indicated erosion, and positive volumes indicated deposition. Growth rates, expressed as m^3/m , were determined for each polygon by dividing the volume by the length of the flow path within the polygon (Table 2). For each segment, growth rates were calculated separately for landslide source areas, travel paths, and combined landslide sources and travel paths (Table 2 and Fig. 4). Some travel paths were impacted by both entrainment and deposition. Overall growth rates for each basin were determined by dividing the total volume of material removed from the basin by the cumulative length of source areas and flow paths (Table 2 and Fig. 4).

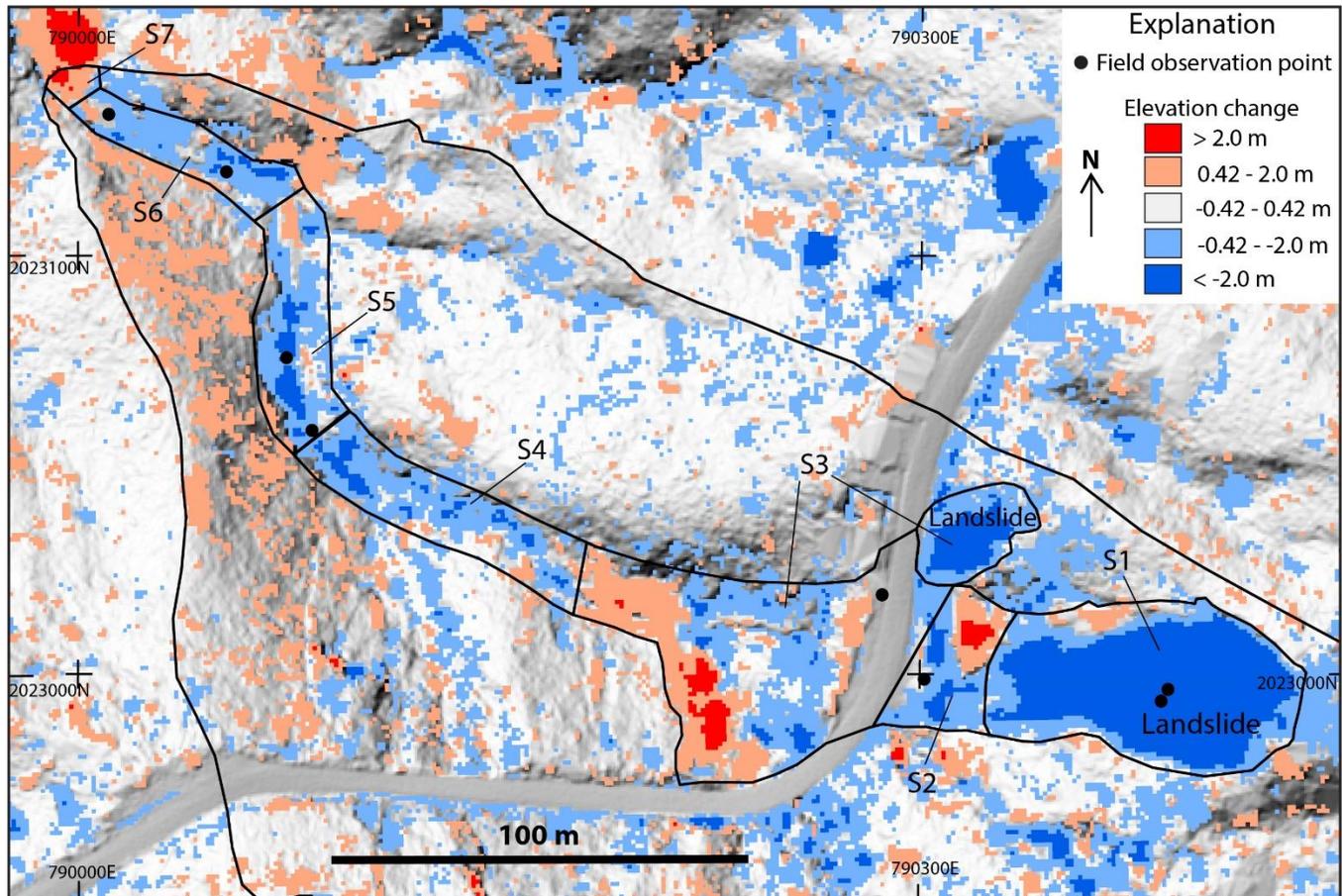


Figure 3. Map showing elevation changes from landslide and debris-flow activity at the Four Car study site obtained from a difference of DEMs (DoD) created by subtracting 2016 (pre-event) lidar DEM from 2018 (post-event) lidar DEM. Segments as shown in Figures 2A and 4A are labeled S1, S2, etc. Coordinates shown are UTM zone 19.

4 RESULTS

Overall debris-flow growth rates at the four sites spanned about 1.5 orders of magnitude (Fig. 4 and Table 2). Rates at Twenty Headed, DOG, and Hook were similar, ranging from 0.7 to 3.0 m^3/m . The rate at Four Car was 30.4 m^3/m . Landslides were responsible for more than 80% of growth at Four Car, Twenty Headed, and DOG. At Hook, channel entrainment accounted for 96% of volume growth (Fig. 4, Table 2). Debris flows at Four Car and Twenty Headed consistently grew along their travel paths, whereas DOG and Hook alternated between growth and deposition along their travel paths (Fig. 4).

The sizes of landslides that contributed to debris-flow growth spanned almost three orders of magnitude in volume. At Twenty Headed, DOG, and Hook, many landslides likely contributed to the resultant debris flows, but the slides were small and thin (<0.9 m), with areas less than 400 m^2 and volumes less than 500 m^3 . At Four Car, there were only two landslides, but both were large and thick (>1.9 m), with areas of

2450 m^2 and 490 m^2 , and volumes of 9460 m^3 and 930 m^3 , respectively. Slopes greater than 30° accounted for 96% of our mapped landslides, which is consistent with field observations of Baum et al. (2018).

Field observations identified two broad types of flows in the basins (i.e., debris flows or floods), as well as the locations where transitions occurred between the two types of flows. Our observations indicated all four of the study basins were dominated by debris flows, but flooding dominated areas downstream from the mouths of these basins. All debris flows traveled out of the study basins, but we could not accurately determine their downstream extent because their downstream deposits were cross cut, reworked, and redistributed by flood waters. We also observed locations where debris-flow deposits were intact and partially blocked downstream channels. Together, these observations indicated that debris flows occurred before, during, and after flooding. The largest of our study basins was small, with an area of 255,560 m^2 (0.26 km^2),

Table 2. Sediment volumes and growth rates for debris flows in the four study sites. Positive values indicate growth (erosion) and negative values indicate deposition. See Table 1 for basin size used to calculate the last column. Using symbols from growth equations 3 and 4 of Reid et al. (2016), column 2 is L, column 3 is V, column 4 is c2, and column 9 is c1. Two standard deviation (2σ) volumetric errors estimates use the 0.42 m 2σ value for the DoD with Equation 5 of Coe et al. (1997). Error estimates assume that errors in the DoD are random (i.e., no systematic errors are present) and do not account for elevation errors from inaccurate bare-earth DEMs caused by standing or downed trees.

Site Name	Cumulative length, L, of contributing channel network (m)	Total volume, V, of sediment removed from basin, (m ³)	Total growth rate, c2 (m ³ /m)	Volume of sediment contributed by landslides (m ³)	Growth rate from landslides (m ³ /m)	Volume of sediment contributed by entrainment (m ³)	Growth rate from entrainment (m ³ /m)	Total amount of lowering within the basin, c1 (m ³ /m ²)
Four Car	420	12,770 +/-40	30.4 +/- 0.1	10,410 +/- 20	24.8 <+/-0.1	2,360 +/- 30	5.6 < +/-0.1	0.13
Twenty Headed	1,060	3,220 +/-40	3.0 <+/-0.1	2,530 +/-20	2.4 <+/-0.1	690 +/-30	0.7 < +/-0.1	0.05
DOG	1,130	840 +/-40	0.7 <+/-0.1	1,370 +/-20	1.2 <+/-0.1	-530 +/-40	-0.5 <+/-0.1	0.01
Hook	1,080	3,070 +/-50	2.8 <+/-0.1	120 +/-20	0.1 <+/-0.1	2,950 +/-50	2.7 <+/-0.1	0.01

indicating that flooding occurred very high in the drainage network during Hurricane Maria.

Because GPS locations of our field observation points were only accurate to about 10 m, we could not directly compare our field-measured cross sections and estimates of erosion and deposition to elevation changes at specific 1-m pixels in the DoD. However, our cross-section profiles and field observations of erosion or deposition were generally consistent with elevation changes in the DoD. Exceptions were noted in some areas where we observed deposition in the field, but the DoD showed that erosion had occurred. Both observations might be correct if extensive erosion occurred first, followed by deposition of relatively thin deposits later in the flow sequence. The net effect of this situation would be a signature of overall erosion in the DoD. Additionally, our observations along channels showed that growth (erosion) transitioned to deposition at channel slopes between 3 and 8°.

5 DISCUSSION

Our results show wide spatial variations in debris-flow growth rates, as well as large differences in the contributions from landslides and channel entrainment. These variations occur both between debris flows in different basins and within individual debris flows. Our results

indicate that forecasting volumes for regional debris-flow inundation modeling may be more complicated than simply estimating the number and volume of landslide source areas, although this task by itself is difficult. Despite the observed variability, a logical question is: are there any geologic, topographic, or morphometric variables that could be used to forecast growth rates and debris-flow volumes during triggering events? To address this question, we statistically compared our debris-flow growth rates with different geologic, morphometric, and topographic variables (given in Table 1) including geologic units, basin ruggedness (Melton's number, basin height/basin area^{0.5}, as defined by Melton, 1965), and topographic slope, but did not find a variable or variables that would accurately forecast debris-flow growth and volumes at the four sites. For example, an evaluation of geologic units with respect to growth rates suggests that underlying rock type did not control the observed variability in growth rate or the mechanism of growth (landslides or entrainment). The rock type is the same at DOG and Hook in Utuado municipality, but the site responses were very different. At DOG, more than 80% of debris-flow growth was dominated by landslides, with predominantly deposition, rather than entrainment, occurring along the travel path. At Hook, entrainment of

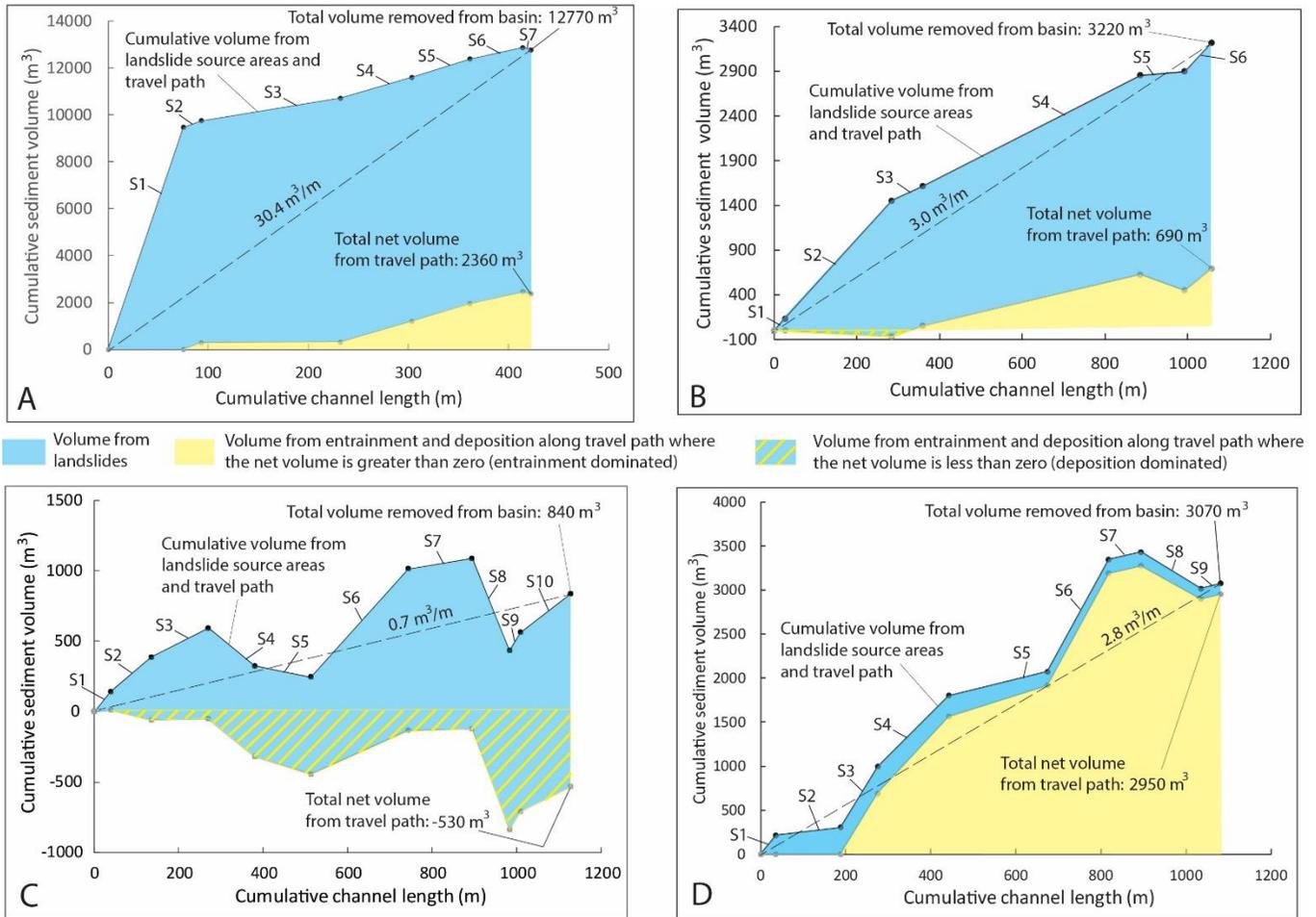


Figure 4. Diagrams showing debris-flow growth estimated from elevation changes at each study site, A) Four Car, B) Twenty Headed, C) DOG, D) Hook. Segments from Figure 2 are labeled, S1, S2, etc. Upward trending lines indicate volumetric growth, whereas downward trending lines indicate deposition. The dashed black line indicates the overall growth rate. Blue and yellow colors correspond volumes from landslide source areas and debris-flow travel paths, respectively as shown in Figure 2. Blue-colored swaths show the volume contributed by landslides for each segment. Solid yellow swaths show the volume along the travel path where the net volume is greater than zero (i.e., entainment dominated over deposition). Hatched yellow lines show the volume from entainment and deposition along the travel path where the net volume is less than zero (i.e., deposition dominated). Wide blue swaths indicate that growth was dominated by landslides and narrow blue swaths indicate that growth was dominated by channel entainment. Cumulative channel lengths terminate at the mouths of study basins where debris flows merged with contemporaneously occurring floods from other basins.

channel material accounted for 96% of growth. A comparison of growth with basin ruggedness shows that the most rugged basins (DOG and Four Car), having nearly identical Melton’s numbers of 0.87 and 0.83 (Table 1), yielded the lowest and highest growth rates, respectively (Fig. 4 and Table 2). Although our initial comparison of growth with geologically related factors is not encouraging based on four sites, data from our additional, currently unanalyzed, sites may reveal useful patterns in the future.

The apparent lack of correlations with geologic and topographic factors suggests that growth rates during Hurricane Maria may have been controlled by environmental factors. Three likely important factors include antecedent soil moisture

conditions, rainfall duration and/or intensity, and availability of channel material. The first two factors would influence both the number and size of landslides as well as the probability of downstream entainment. Unfortunately, local variations in these two factors were difficult to constrain during Maria (Bessette-Kirton et al., 2019a) and will likely be poorly defined in future hurricanes. The third factor is dependent on variations in human activity that generates fill material, and the production of sediment versus the frequency and magnitude of events that remove sediment from individual basins (e.g., Cerovski-Darriau et al., 2019). The distribution of fill is poorly known, and although the relation between sediment production and removal can sometimes be estimated at specific sites, its spatial

variation is rarely well known. Given these considerations, we suspect that the best approach for regional debris-flow modeling would be to use a suite of growth-rate scenarios to span the observed range of debris-flow volumes.

6 CONCLUSIONS

We used multi-temporal lidar data to determine debris-flow growth rates at four basins in Puerto Rico that were impacted by Hurricane Maria in September 2017. Growth rates ranged from 0.7 to 30.4 m³ per meter of channel length. At three sites, growth was controlled by sediment from landslides. At one site, growth was dominated by entrainment of channel sediment. We suspect that growth rates were likely controlled by variations in antecedent moisture conditions, rainfall duration and intensity, and availability of artificial fill and channel sediment.

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