Portraying runout and inundation from hurricane-induced landslides in Puerto Rico

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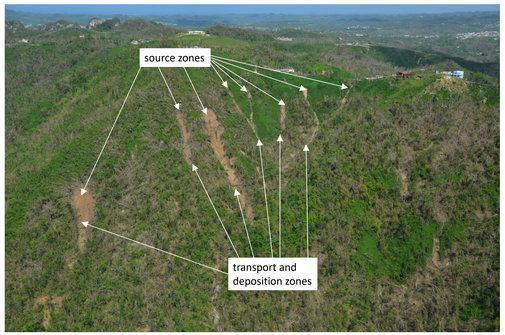
USGS science for a changing world

1) Motivations

- In September 2017, Hurricane Maria induced more than 70,000 landslides in Puerto Rico. Most landslides originated as shallow failures on steep slopes. After initiation, these landslides mobilized to varying degrees – some slides only traveled partway downslope, whereas others reached drainages and mobilized into long traveled debris flows. These moderate to high mobility landslides were likely to block roads, thereby disrupting access to medical services and electricity.
- As demonstrated by Hurricane Maria, forecasting potential landslide runout zones is critical; however, many landslide susceptibility maps do not identify areas vulnerable to landslide runout.



Ciales, Puerto Rico, photo by Jason Kean

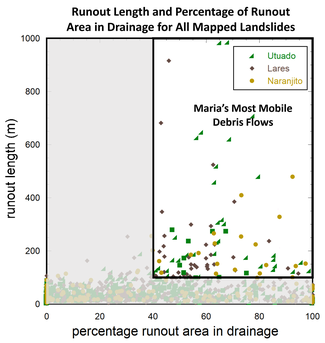
2) Methods

- We developed tools to identify areas susceptible to hazard from landslides over a spectrum of mobility
- Our methodology integrates A) user-provided potential landslide source zones with two methods to identify areas susceptible to landslide runout :
- B) For moderate mobility slides, we define potential runout zones by minimum angle of reach (tan(height/length)) from the source. B provides a methodology to: 1) estimate runout in open-slope topographies where channels are not present or 2) provide a transition from source zones to the channel.
- C) For channelized debris flows, we identify potential inundation zones using empirical volume-area relations in concert with empirical debris-flow growth factors. Our growth factors integrate growth over a drainage network and are defined as a function of potential upstream contributing landslide source areas.

landslide process	type of model	model for Puerto Rico	relative mobility
A) initiation	source zone	regolith+TRIGRS (Baum et. al., this poster session)	
B) transport, and deposition	H/L runout	Grfin Tools* H/L (TauDEM AvalancheRunout)	moderate
C) growth, transport, and deposition	debris flow inundation	Grfin Tools inundation empirical growth factors + empirical V/A	high

*Grfin (pronounced griffin; growth-gr, flow-f, inundation-in) Tools is a toolset under development by the USGS.

3) Maria's Most Mobile Debris flows (MMM)



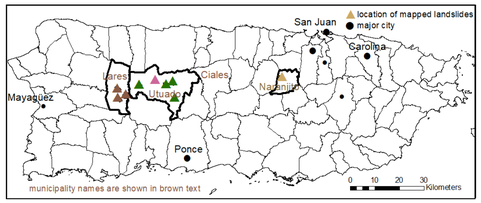
From eight study areas, we extracted the subset of mapped landslides representative of the most mobile channelized debris flows, identified by two characteristics :

1. **>40% of runout zone in the channel, and**
2. **>100 m runout length**

This data-set provides :

1. Characteristics of debris-flow inundation zones, and
2. Runout areas for comparison with Grfin Tools inundation results

	maximum Strahler stream order			mean stream slope (degrees)			mean planform curvature (1/m)			mean source area ratio (SR)		
percent exceeding criteria	Lares	Utuado	Naranjito	Lares	Utuado	Naranjito	Lares	Utuado	Naranjito	Lares	Utuado	Naranjito
50	2	3	2	15.9	9.8	15.0	0.03	0.03	0.03	0.85	0.79	0.58
25	3	3	3	11.2	7.0	11.2	0.02	0.02	0.02	0.77	0.65	0.42
10	4	4	4	8.2	4.8	8.8	0.02	0.01	0.01	0.62	0.55	0.20
0	5	5	4	3.1	1.1	7.0	0.01	0.01	0.01	0.33	0.29	0.09
# of debris flow inundation zones	44	49	19	Characteristics of 112 debris-flow inundation zones for Maria's most mobile debris flows, including zones of growth, transport, and deposition.								



Locations of eight areas with detailed landslide mapping (landslide affected areas, including source, transport, and runout zones) of >2000 landslides in Lares, Utuado, and Naranjito (Baxstrom et al., 2021; Bessette-Kirton et al., 2019; Einbund et al., 2021).

$$SR = \frac{\text{contributing area susceptible to shallow landslides}}{\text{contributing area}}$$

Observations

- Channelized debris flows are a minority of landslides but are present across dissected and upland terranes in volcaniclastic, granitoid, and non-limey sedimentary geologic terranes
- The percentage of the channel with zones of debris-flow inundation is higher in segments of the channel with high source area ratio (SR)

4) Evaluation of Predictive Success for Debris-Flow Inundation Scenarios

We evaluated eight debris-flow inundation scenarios, constrained by:

- Statistics for stream order, curvature, and source area ratio from Maria's most mobile debris flows
- Field measurements of stream slopes where growth transitioned to deposition (3 to 8 degrees) (Coe et al., 2021)
- Debris flow volumes estimates, using empirical growth factors (c_1) as a function of upslope contributing area susceptible to shallow landslides, where $V=c_1 U_{src}$
- Volume estimates from Hurricane Maria debris flows (used to restrict maximum volumes (V_{max}))

Volumes and Empirical Growth factors from Hurricane Maria debris flows (Coe et al., 2021)

range of c_1 values	0.01 - 0.13 m^3/m^2
range of c_1 values, normalized to percentage of area with slopes >30 degrees	0.02 - 0.21 m^3/m^2
range of volumes	840 - 12,770 m^3

most likely ----------> least likely to occur, most mobile, most spatially extensive, most hazardous

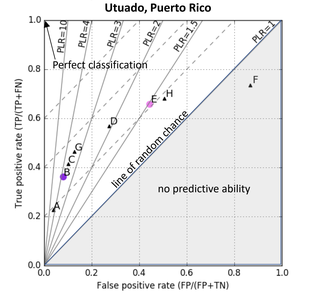
	most restrictive growth zones - smallest c_1/V_{max}	typical growth zones - vary c_1/V_{max}				most generous growth zones -vary c_1/V_{max}	
	less restrictive growth zone -->	increasing volume (c_1/V_{max}) ---->				increasing volume (c_1/V_{max}) ---->	
	A	B	C	D	E	F	G	H
Criteria for debris-flow growth zones								
maximum stream order	2	3	3	3	4	3	4	4
minimum stream slope (degrees)	13	8	5	5	5	5	3	3
minimum curvature (1/m)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
minimum percentage contributing source area	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Parameters for debris-flow volumes								
c_1 (m^3/m^2)	0.01	0.01	0.01	0.05	0.1	0.2	0.01	0.1
V_{max} (m^3)	1000	1000	1000	3000	5000	10000	1000	5000

ROC analysis to evaluate the predictive success of model scenarios provides a method to assess relative success of the eight scenarios and to identify preferred scenarios for regional susceptibility maps

Using the ROC results, we selected two scenarios for regional susceptibility maps

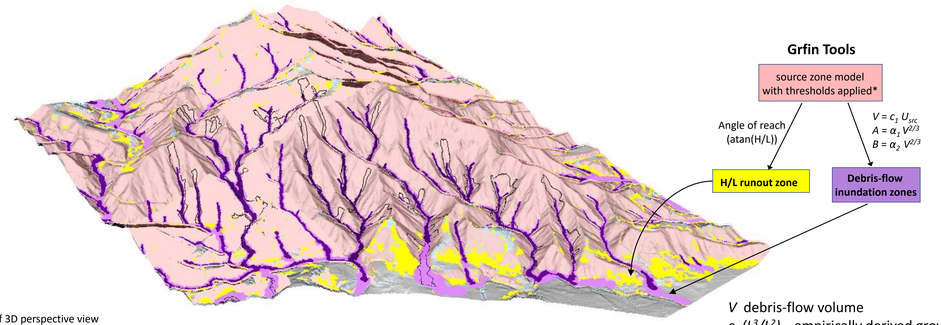
- B - most likely debris-flow scenario minimizes under-prediction
- E provides increased true positive rate (TPR) before the significant decrease in positive likelihood ratio (PLR) seen with scenario H and F

Receiver Operator Characteristic (ROC) plot for eight debris-flow inundation scenarios evaluated for basins affected by Maria's most mobile debris flows - Utuado, Puerto Rico

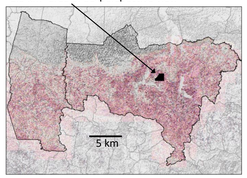


Solid grey lines show positive likelihood ratio (PLR) = true positive rate/false positive rate
Higher PLR indicates higher predictive success
Dashed grey lines show distance from the upper left corner, the location of perfect classification

5) Results in Utuado, Puerto Rico



1.5 km^2 area of 3D perspective view



Landslide susceptibility map of Lares and Utuado.

Black outlines show landslide-affected areas from some of Hurricane Maria's most mobile (MMM) debris flows. Two shades of purple represent relatively more likely and less likely scenarios for debris-flow inundation, based on characteristics of debris-flow inundation zones from MMM.

V debris-flow volume
c_1 (L^3/L^2) empirically derived growth factor
U_{src} upslope contributing area susceptible to shallow landslides
A cross-sectional area
B planimetric inundation area
α_1, α_2 empirically derived coefficients (Griswold and Iverson, 2008)

* We applied factor of safety thresholds for 75% and 90% true positive rates of mapped landslides (Baum et. al., this poster session)

6) Discussion

- Our USGS software package, Grfin (growth+flow+inundation) Tools (under development), integrates methods for portraying runout and inundation for landslides over a range of mobility and enables runout assessment over large regions without the computational effort required by physics-based models.
- We applied these methods in three municipalities that had high landslide density from Hurricane Maria: Utuado, Lares, and Naranjito, covering a total area of 560 km^2.
- The resulting maps provide a preliminary assessment of areas susceptible to landslide runout and inundation from mobile landslides.

7) References

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