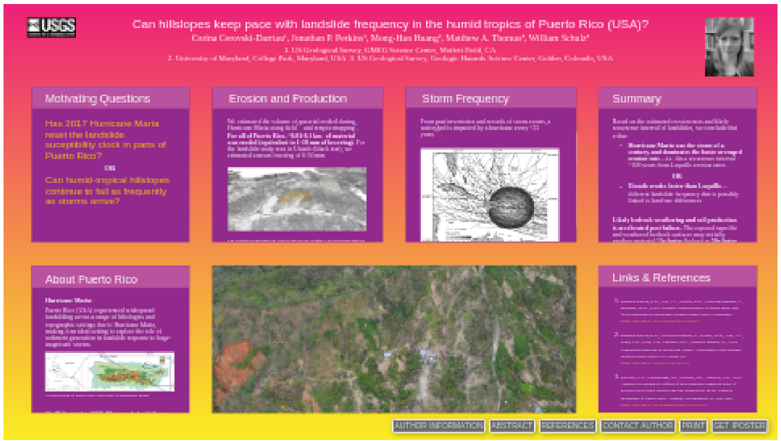
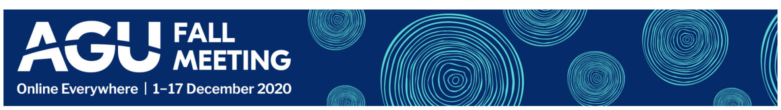
Can hillslopes keep pace with landslide frequency in the humid tropics of Puerto Rico (USA)?



Corina Cerovski-Darriau[1]*, Jonathan P. Perkins[1], Mong-Han Huang[2], Matthew A. Thomas[3], William Schulz[3]

1. US Geological Survey, GMEG Science Center, Moffett Field, California, USA
*corresponding author: ccerovski-darriau@usgs.gov
2. University of Maryland, College Park, Maryland, USA
3. US Geological Survey, Geologic Hazards Science Center, Golden, Colorado, USA

PRESENTED AT:



ABSTRACT

Bedrock weathering and soil production set the rate that hillslope colluvium is produced, while material properties determine whether sediment can fail under a given set of conditions. Together these factors generally control both the frequency and magnitude of landslides. In 2017, Puerto Rico (USA) experienced widespread landsliding across a range of lithologies due to Hurricane Maria, making it an ideal setting to explore the role of sediment generation in landslide response to storms. Based on an inventory of >70,000 landslides island-wide and detailed field mapping from a subset of source areas, we estimate that 0.01-0.1 km^3 of material was evacuated from the hillslopes (approximately 1-10 mm of lowering). Focusing on the high-density landslide area of Utuado, we estimate an average lowering of 5-50 mm. From past inventories and records of storm events, a watershed is impacted by a hurricane every ~25 years with enough rain for widespread landslides every ~5 years. Assuming a similar density, the landslide contribution to hillslope lowering could be on the order of 1-10 mm/yr. In a humid-tropical environment, where weathering rates are likely high, can hillslopes continue to produce material at this pace? Elsewhere on the island, soil production rates are on the order of 0.1 mm/yr leading to soil residence times of approximately 10 ky. However, to keep pace with landslide events like Hurricane Maria, soil production likely needs to be at least an order of magnitude faster to maintain soil-mantled hillslopes in this study area. For our study area, we ask: has the large-magnitude rainfall from Hurricane Maria caused an abnormally high density of landsliding, resetting the clock on the material availability for areas like Utuado? Here we relate measures of material properties, bedrock weathering intensity, denudation, and land-use history to begin answering this question.

MOTIVATING QUESTIONS

Has 2017 Hurricane Maria reset the landslide suceptibility clock in parts of Puerto Rico?

OR

Can humid-tropical hillslopes continue to fail as frequently as storms arrive?

Ariel view of landslides after 2017 Hurricane Maria in Puerto Rico (USA)

ABOUT PUERTO RICO

Hurricane Maria:

Puerto Rico (USA) experienced widespread landsliding across a range of lithologies and topographic settings due to Hurricane Maria, making it an ideal setting to explore the role of sediment generation in landslide response to large-magnitude storms.

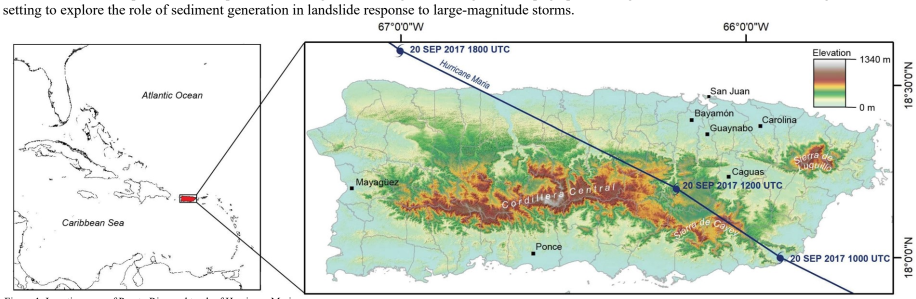


Figure 1. Location map of Puerto Rico and track of Hurricane Maria

On 20 September 2017, Maria made landfall as a category 4 hurricane and triggered over 70,000[5] landslides in most of the 78 municipalities. The municipality of Utuado had the highest density of landslides[1,2,5] (Figure 2), mostly triggered at the soil-saprolite interface[2], which were mapped using a combination of field and remote sensing observations—and will be the focus here.

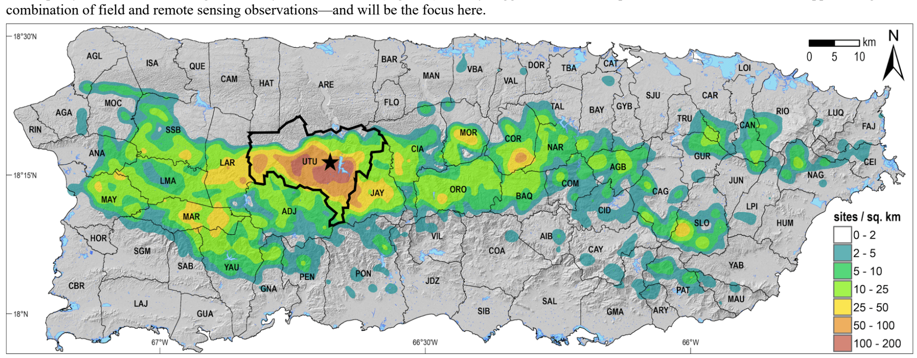


Figure 2. Above figure, adapted from Hughes & Schulz (2020), shows density map of individual landslide source areas mapped from remote imagery. Utuado is outlined and the study area is marked with a star

Geography:

- Island Area: ~8750 km2
- Population: ~3 million people (1 million in mountainous interior)
- Highest rainfall: Sierra de Luquillo (location of Critical Zone Observatory) (>2 m per year, eastern Puerto Rico) (Utuado≈2 m per year)
- Most land has been developed for agriculture or forestry
- 9th densest road network globally[5]

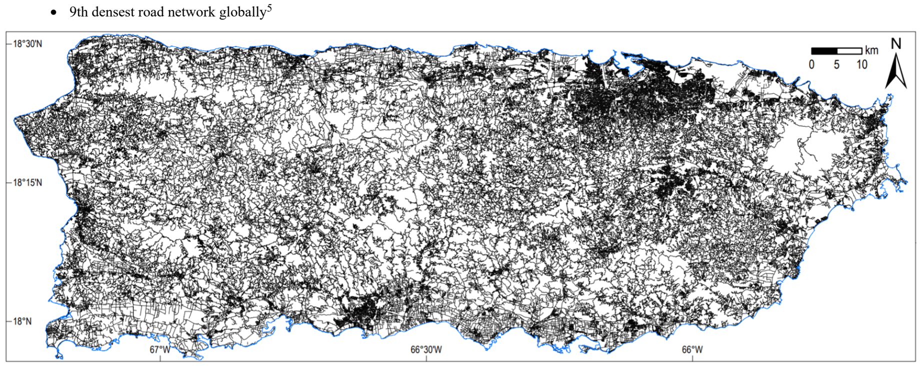


Figure 3. Above figure, from Hughes & Schulz (2020), depicts major roads in Puerto Rico (map does not include the numerous farm or other unofficial roads)

Geology:

- Rapid uplift in the early Pliocene
- Mountainous areas mix of intrusive (light green) and extrusive (browns) rocks
- Carbonates (pink) and alluvium (tan) along northern and southern coasts
- Utuado is mainly granodiorite (light green)

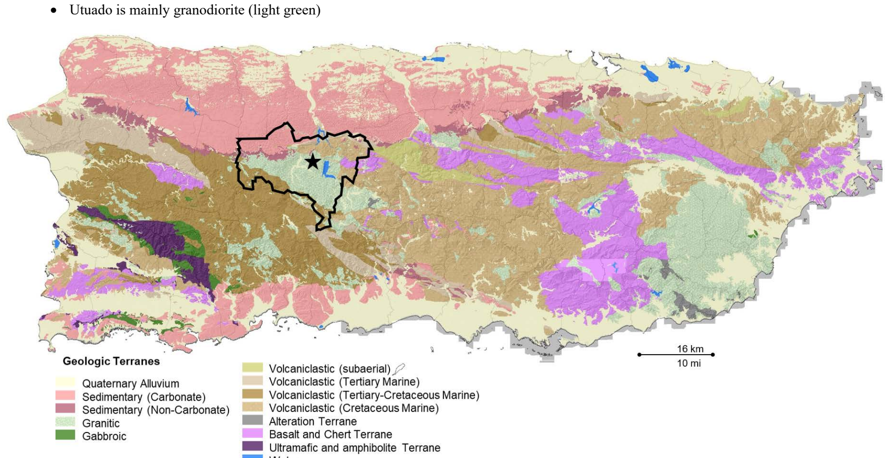


Figure 4. Above figure is a simplified geological terrain map. Utuado is outlined and the study area is marked with a star

EROSION AND PRODUCTION

We estimated the volume of material eroded during Hurricane Maria using field[1,2] and remote mapping[5]. **For all of Puerto Rico, ~0.01-0.1 km^3 of material was eroded (equivalent to 1-10 mm of lowering)**. For the landslide study area in Utuado (black star, Figure 2) (polygons, Figure 5-6), we estimated a mean lowering of ~5-50 mm.

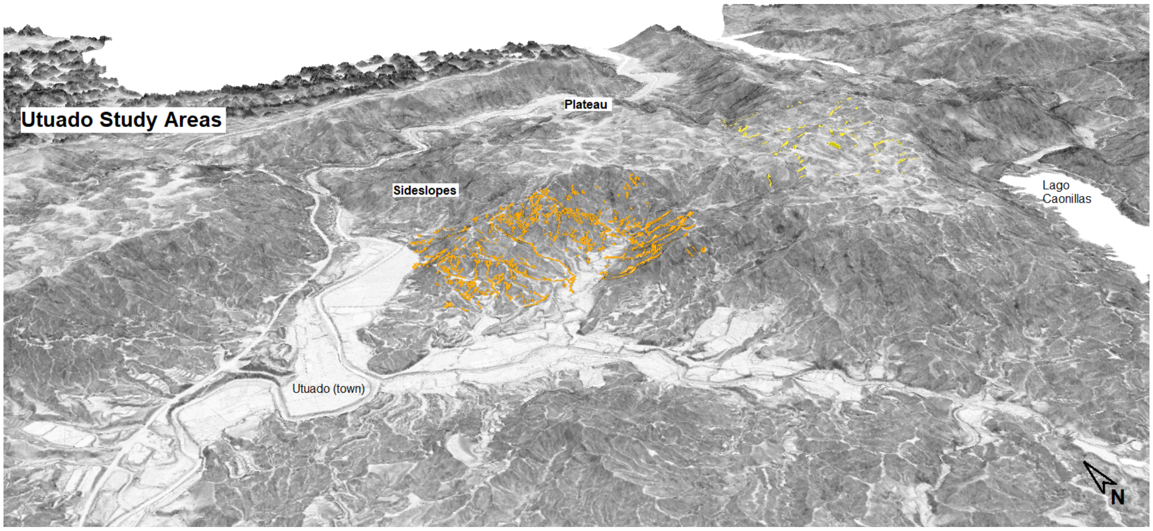


Figure 5. The contrast in morphology can be seen in the oblique 1-m slope map derived from the 2016 lidar (above)—with landslides from Hurricane Maria mapped in orange (sideslopes) and yellow (plateau).

Utuado is a low-relief plateau with steep, dissected sideslopes in a granodiorite batholith (Figure 4-5)—similar to Luquillo (location of the Critical Zone Observatory in eastern Puerto Rico). These landslides, particularly those on the sideslopes, failed predominately in soil[2]. This is a humid landscape where bedrock can weather quickly to soil, especially when newly exposed.

Using detailed mapping from the Utuado study sites (Figure 5-6), and volume estimates from either pre- and post-event lidar differencing or field measurements, **total lowering in Utuado** was:

- Plateau (yellow polygons): **5 mm**
- Sideslope (orange/red polygons): **13 mm** (lidar) **to 50 mm** (field)

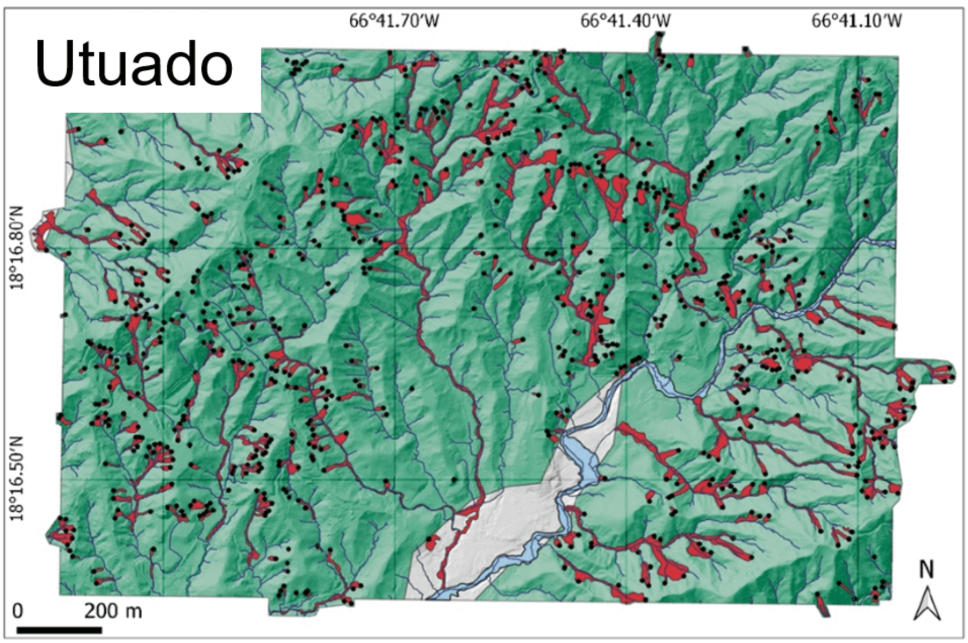


Figure 6. Above figure, from Bessette-Kirton et al. (2019), showing the ~750 remotely mapped source areas (black dots) and landslide polygons (including runout) (red). This is the same area as the orange polygons in Figure 5. A subset (n=17) was measured in the field, and used to estimate mean source area and depth.

Rates:

Catchment-averaged erosion rates from the plateau and sideslopes, using in-situ ^{10}Be, are coming soon. However, assuming the rates are similar to Luquillo[3], using those published rates the **erosion rates above and below the knickpoint are**:

- Above (plateau): **0.05 mm/yr**
- Below (sideslopes): **0.15 mm/yr**

Recurrence:

If we assume a steady-state landscape—where soil production rates are roughly equivalent to erosion rates—and use the **mean landslide depth of 0.5 m** from field-mapping in Utuado, **landslide scars would need ~3000 years to reset**.

This estimate is similar to the modeled infilling time, ~2000 years (Figure 7).

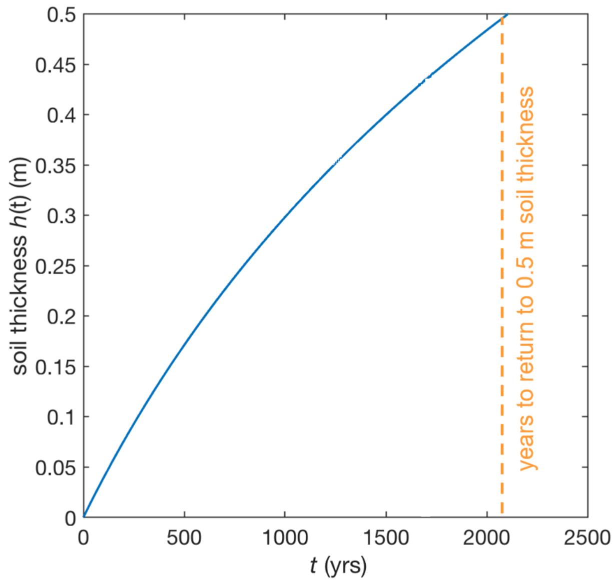


Figure 7. Above graph predicts the time needed to produce 0.5 m of soil using a calibrated soil production function

However, if we assume Maria-style events (5-50 mm of lowering per storm) dominate the erosion rates, **recurrence interval is ~100-300 years**.

Using field monitoring (i.e. erosion pins, Figure 8) of landslides in Utuado, we find the sideslope scars are infilling at a mean rate of **7.5 mm/yr** (Figure 9). If sustained, the **recurrence interval could be as short as ~60 years.**

Figure 8. Examples of erosion pins installed in two landslides scars in Utuado (left is UTU-MS, right is UTU-DG). Pins, installed along a cross-section, are measured periodically to track aggradation and erosion through time.

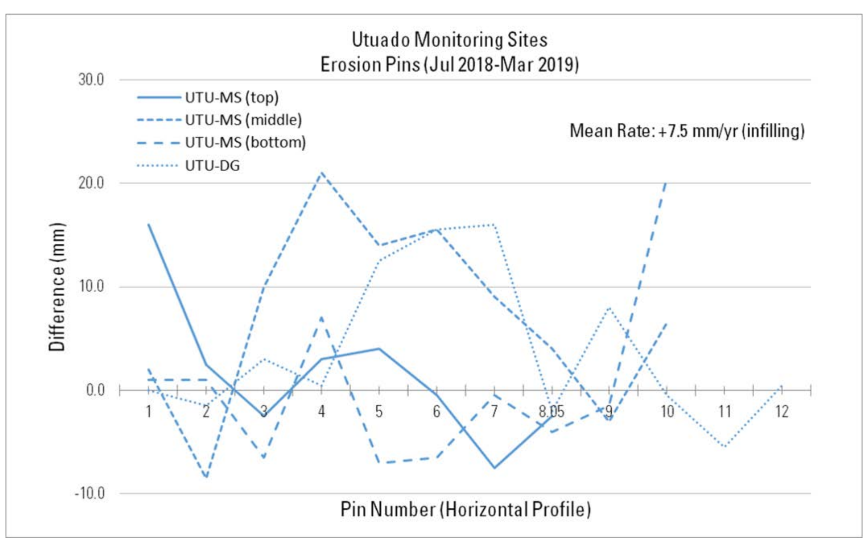


Figure 9. Above graph shows change in surface elevation (erosion and aggradation) at each erosion pin (see example photos in Figure 8), installed across two landslide scars. Each cross-section is represented by a line, with 3 erosion pin lines on UTU-MS and 1 on UTU-DG. The mean net rate since July 2018, calculated from these 4 lines, is 7.5 mm/yr.

STORM FREQUENCY

From past inventories and records of storm events, a watershed is impacted by a hurricane every ~25 years[2,4].

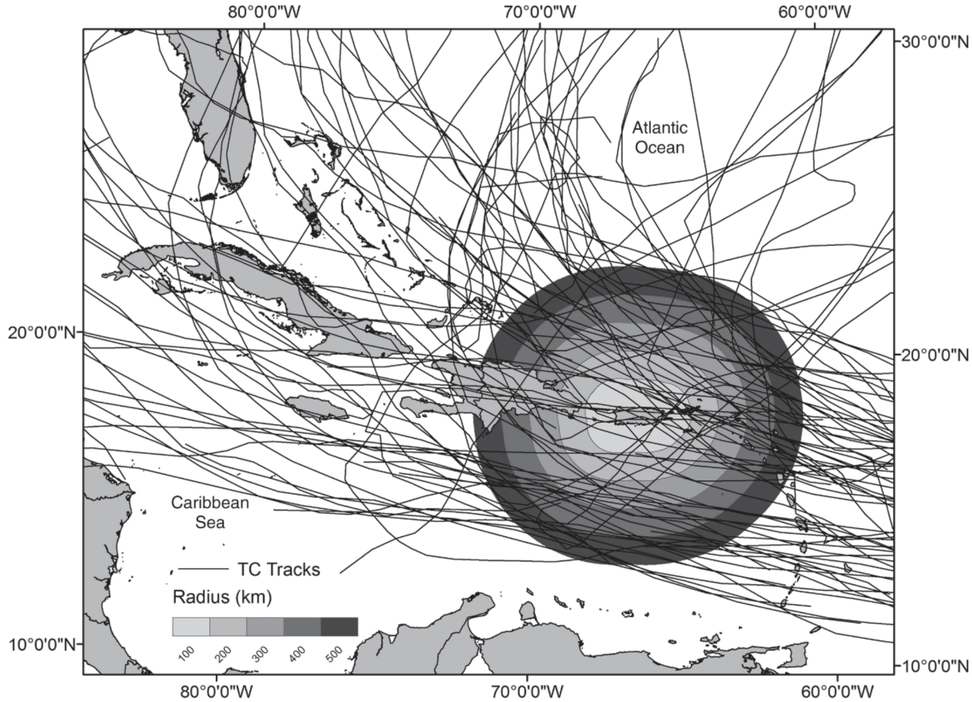


Figure 10. Above figure, from Hernández Ayala & Matyas (2016), shows tracks of all tropical hurricanes/cyclones (TC) within a 500 km radius of Puerto Rico from 1970-2010

The recurrence interval further breaks down by size of event. Landslides are common (~2 landslide-triggering storms per year). But storms causing widespread landslides (many municipalities—100s or more landslides) only occur every ~5 years[2].

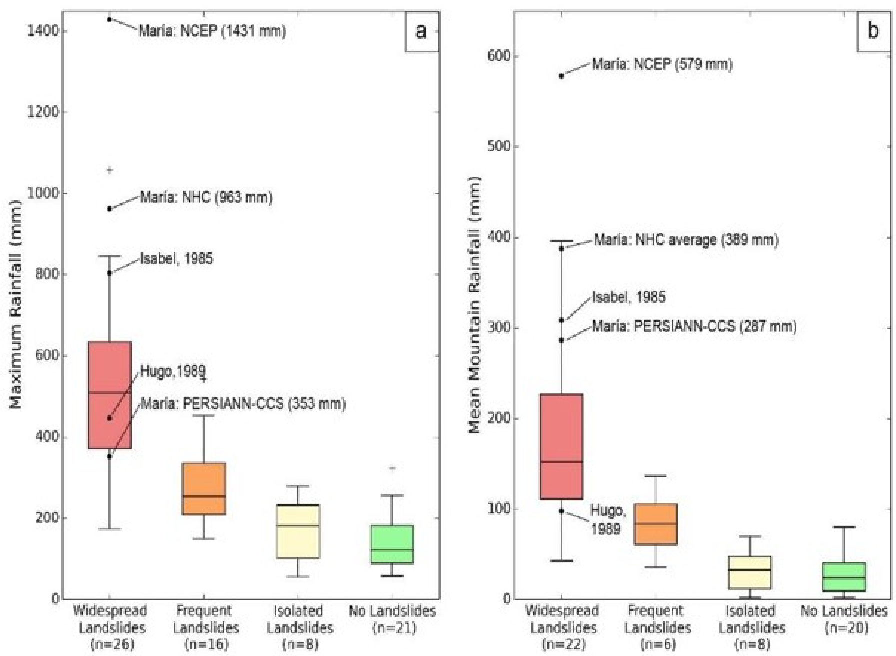


Figure 11. Above graphs, from Bessette-Kirton et al. (2019), show estimated rainfall totals needed to trigger landslides in Puerto Rico. Hurricane Maria rainfall was estimated from various models (NCEP, NHC, and PERSIANN-CCS—see paper for more information)

Hurricane Maria was anomalously large in both the amount of rainfall (Figure 11) **and number of municipalities affected** (97% of the municipalities had at least 1 landslide[5]). The last hurricane of similar magnitude was in 1956[1].

SUMMARY

Based on the estimated erosion rates and likely recurrence interval of landslides, we hypothesize that:

- **Hurricane Maria was the storm of a century, and dominates the basin-averaged erosion rate**—i.e. fits a recurrence interval ~100-300 years from Luquillo erosion rates

OR

- **Utuado erodes faster than Luquillo**—different landslide frequency that is possibly linked to land-use differences

Likely bedrock weathering and soil production is accelerated post-failure. The exposed saprolite and weathered bedrock surfaces may initially produce material **~3x faster** (modeled, Figure 12) or **50x faster** (erosion pins, Figure 9), which could help hillslopes to keep pace with landslide-causing storms.

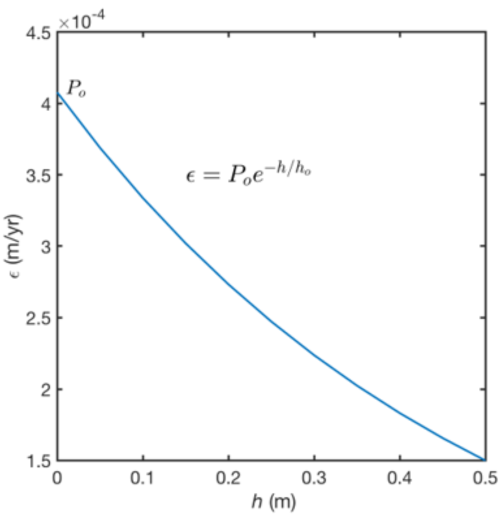


Figure 12. Above graph uses exponential soil production function to estimate initial soil production rates of ~4 mm/yr

Using results from our on-going erosion monitoring and weathering studies, we will test whether this landscape is supply-limited (pausing the landslide susceptibility) **or transport-limited** (and material is ready for the next storm).

LINKS & REFERENCES

1. Bessette-Kirton, E.K., Coe, J.A., Schulz, W.H., Cerovski-Darriau, C., Einbund, M.M., 2020. Mobility characteristics of debris slides and flows triggered by Hurricane Maria in Puerto Rico. Landslides. https://doi.org/10.1007/s10346-020-01445-z

2. Bessette-Kirton, E.K., Cerovski-Darriau, C., Schulz, W.H., Coe, J.A., Kean, J.W., Godt, J.W., Thomas, M.A., Stephen Hughes, K., 2019. Landslides triggered by Hurricane Maria: Assessment of an extreme event in Puerto Rico. GSA Today 29. https://doi.org/10.1130/GSATG383A.1

3. Brocard, G.Y., Willenbring, J.K., Scatena, F.N., Johnson, A.H., 2015. Applied Geochemistry Effects of a tectonically-triggered wave of incision on riverine exports and soil mineralogy in the Luquillo Mountains of Puerto Rico. Applied Geochemistry 63, 586–598. https://doi.org/10.1016/j.apgeochem.2015.04.001

4. Hernández Ayala, J.J., Matyas, C.J., 2016. Tropical cyclone rainfall over Puerto Rico and its relations to environmental and storm-specific factors. International Journal of Climatology 36, 2223–2237. https://doi.org/10.1002/joc.4490

5. Hughes, K.S., Schulz, W.H., 2020. Map Depicting Susceptibility to Landslides Triggered by Intense Rainfall. USGS Open-File Report 2020-1022 https://pubs.er.usgs.gov/publication/ofr20201022
