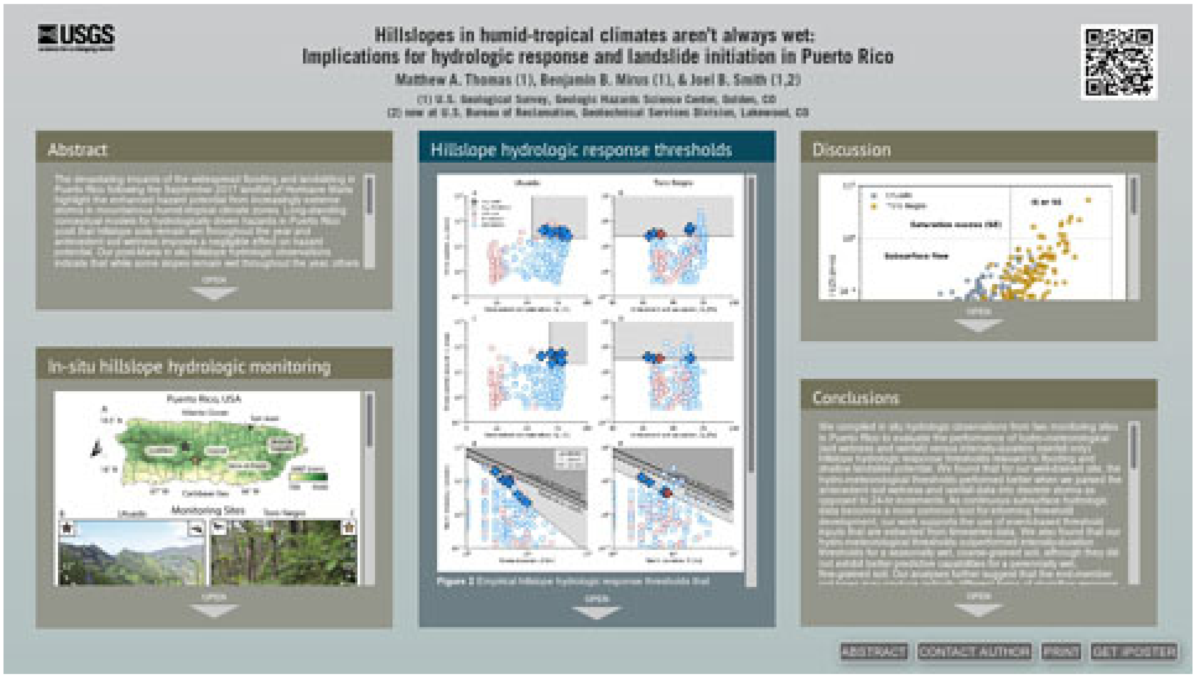
Hillslopes in humid-tropical climates aren't always wet: Implications for hydrologic response and landslide initiation in Puerto Rico



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PRESENTED AT:

ABSTRACT

The devastating impacts of the widespread flooding and landsliding in Puerto Rico following the September 2017 landfall of Hurricane Maria highlight the enhanced hazard potential from increasingly extreme storms in mountainous humid-tropical climate zones. Long-standing conceptual models for hydrologically driven hazards in Puerto Rico posit that hillslope soils remain wet throughout the year and antecedent soil wetness imposes a negligible effect on hazard potential. Our post-Maria in situ hillslope hydrologic observations indicate that while some slopes remain wet throughout the year, others exhibit appreciable seasonal and intra-storm subsurface drainage. Therefore, we used receiver-operating characteristic analysis and the Threat Score (TS) skill statistic to evaluate the performance of hydro-meteorological (soil wetness and rainfall) versus intensity-duration (rainfall only) hillslope hydrologic response thresholds that identify the onset of positive pore-water pressure, a predisposing factor for widespread slope instability in this region. We found that the hydro-meteorological thresholds outperformed intensity-duration thresholds for a seasonally wet, coarse-grained soil (TS = 0.8 vs. 0.6, respectively), although they did not outperform intensity-duration thresholds for a perennially wet, fine-grained soil (TS = 0.2 vs. 0.2, respectively). These soils types may also produce radically different stormflow responses, with subsurface flow being more common for the coarse-grained soils underlain by intrusive rocks versus infiltration excess and/or saturation excess for the fine-grained soils underlain by volcaniclastic rocks. We conclude that variability in soil-hydraulic properties, as opposed to the humid-tropical climate zone, is the dominant factor that controls runoff generation and modulates the importance of antecedent soil wetness for our hillslope hydrologic response thresholds. Our findings encourage further deployment of continuous in situ hydrologic monitoring to facilitate the development of empirical hillslope hydrologic response and landslide thresholds for regional-scale hazard warning systems that must account for spatially variable soil types.

IN-SITU HILLSLOPE HYDROLOGIC MONITORING

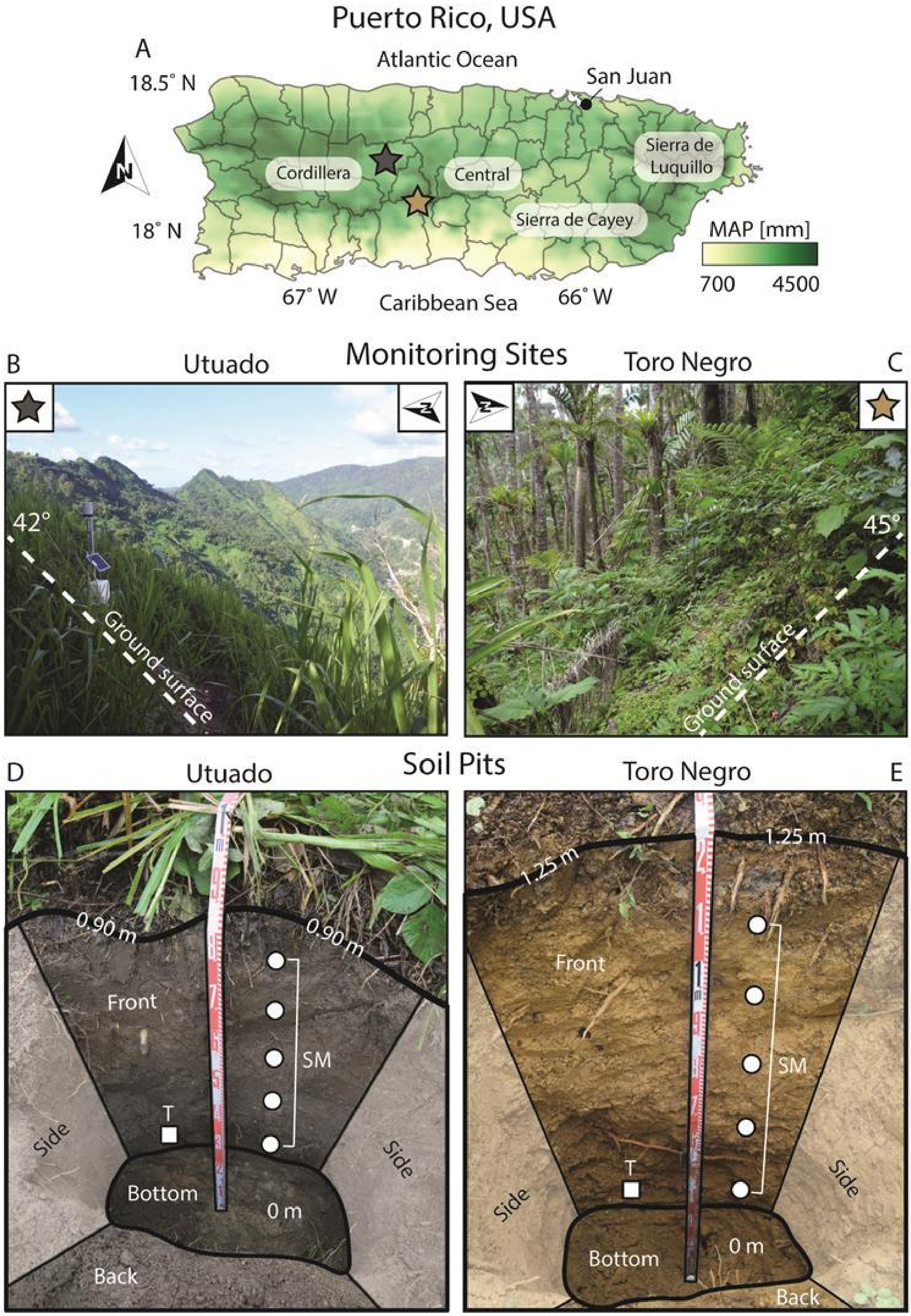

Figure 1 (A) Map of mean annual precipitation (MAP) for Puerto Rico overlain with municipality borders (black polygons) and the location of the two hillslope hydrologic monitoring sites (stars). Slate gray and light brown stars correspond to the Utuado and Toro Negro site, respectively. Photographs of the (B) Utuado and (C) Toro Negro monitoring sites illustrating typical slope

steepness. Hand-dug excavations at the (D) Utuado and (E) Toro Negro sites. Each pit extends through the soil profile to the top of weathered bedrock, indicated by the “bottom” label. Location of the tensiometer (T) and vertical array of soil moisture (SM) sensors that we used in this study are shown with white square and circle, respectively.

HILLSLOPE HYDROLOGIC RESPONSE THRESHOLDS

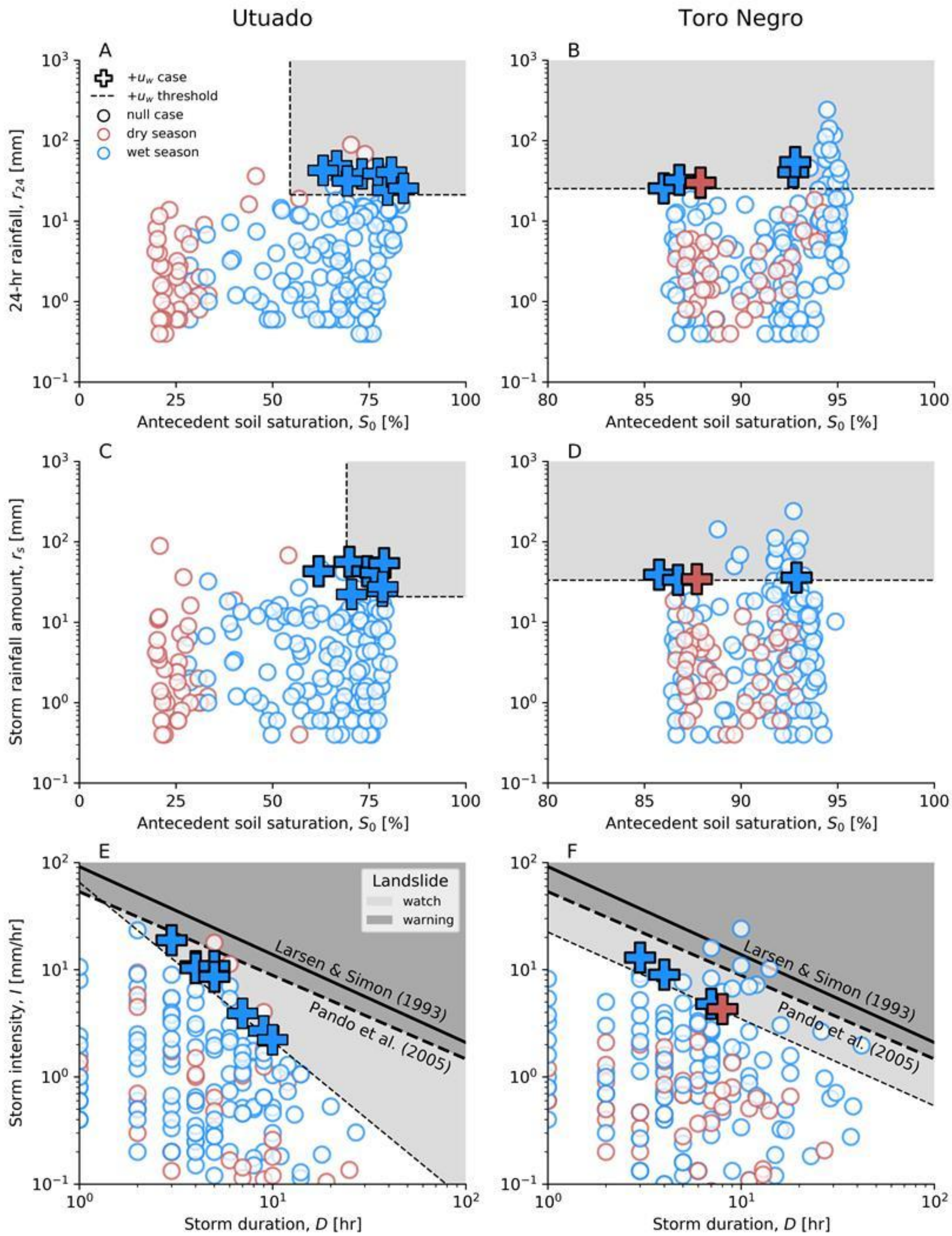

Figure 2 Empirical hillslope hydrologic response thresholds that delineate the onset of positive pore-water pressure (+u_w) at the soil-weathered bedrock interface for three different models at the Utuado and Toro Negro monitoring sites: (A-B) 24-hr rainfall (r_{24}) versus antecedent soil saturation (S_0), (C-D) storm rainfall amount (r_s) versus antecedent soil saturation (S_0), and (E-F) storm intensity (I) versus storm duration (D). Thresholds in the first and second column belong to Utuado and Toro Negro, respectively. The “+” and “o” symbols identify positive pore-water pressure (+u_w) cases and null cases. Light gray regions indicate conditions likely to generate +uw. On the intensity-duration plots (E-F), we juxtapose our +uw thresholds with the Larsen & Simon (1993) and Pando et al. (2005) empirical landslide initiation thresholds for Puerto Rico to identify hypothetical landslide “watch” versus “warning” levels.

DISCUSSION

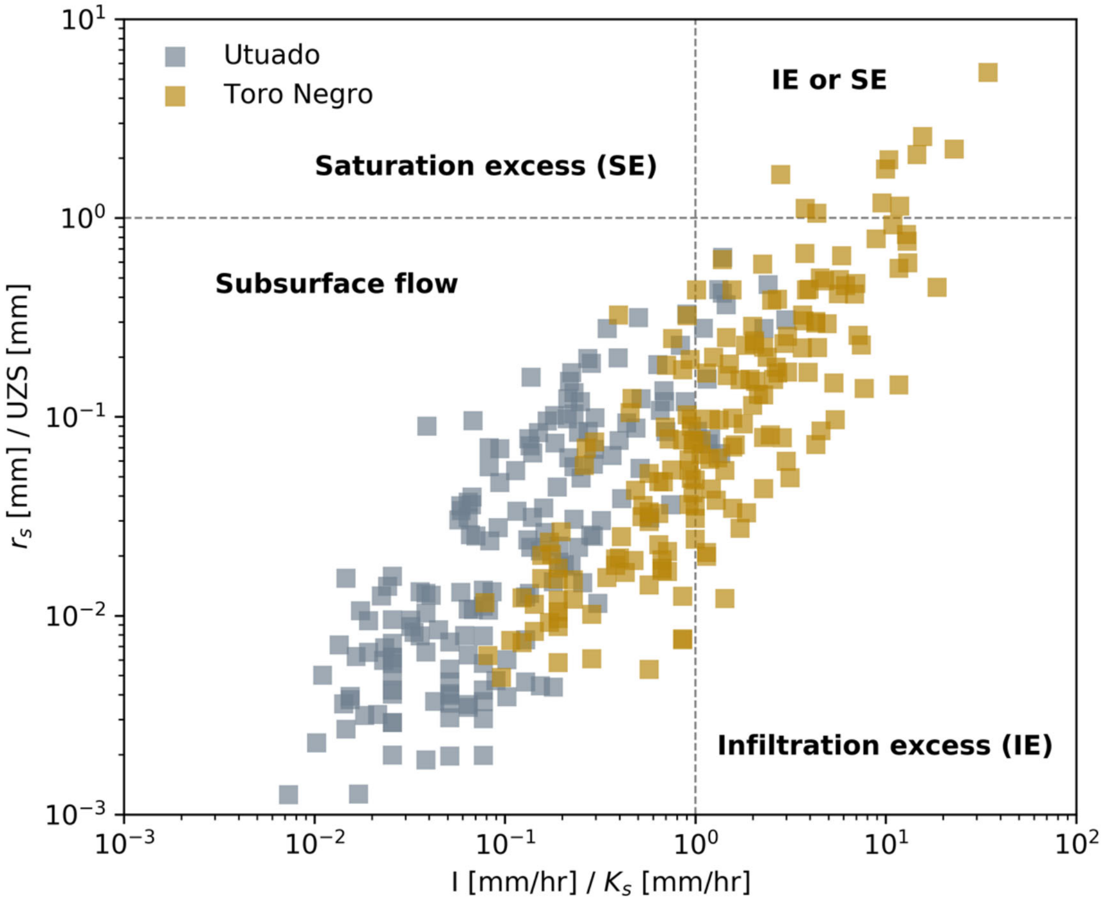

Figure 3 Scatterplot of dimensionless storage- and rate-limited variables that indicate the potential for infiltration excess (IE), saturation excess (SE), and subsurface flow at the Utuado and Toro Negro monitoring sites (figure type adapted from Mirus & Loague [2013]). The x-axis is the average intensity (I) of a storm event divided by the saturated hydraulic conductivity (K_s) of the soil and the y-axis is the storm rainfall amount (r_s) divided by the unsaturated zone storage (UZS) above the soil-weathered bedrock interface before the storm. Dashed lines indicate approximate thresholds for stormflow types.

Our work develops two simple conceptual models that provide a parsimonious approach to incorporating the effects of soil type into characterizing runoff generation and landslide potential across Puerto Rico. In Utuado, and other regions with coarser soils underlain by intrusive igneous rocks, runoff is expected to occur via subsurface flow, with some flashiness related to infiltration excess. Landslide forecasting for Utuado-like soils would be well-suited to the hydro-meteorological method. In contrast, finer-textured soils underlain by volcaniclastic rocks like those at Toro Negro would benefit from traditional intensity-duration thresholds for landslide initiation and intensity-based forecasting for the infiltration excess runoff mechanism.

CONCLUSIONS

We compiled in situ hydrologic observations from two monitoring sites in Puerto Rico to evaluate the performance of hydro-meteorological (soil wetness and rainfall) versus intensity-duration (rainfall only) hillslope hydrologic response thresholds relevant to flooding and shallow landslide potential. We found that for our well-drained site, the hydro-meteorological thresholds performed better when we parsed the antecedent soil wetness and rainfall data into discrete storms as opposed to 24-hr increments. As continuous subsurface hydrologic data becomes a more common tool for informing threshold development, our work supports the use of event-based threshold inputs that are extracted from timeseries data. We also found that our hydro-meteorological thresholds outperformed intensity-duration thresholds for a seasonally wet, coarse-grained soil, although they did not exhibit better predictive capabilities for a perennially wet, fine-grained soil. Our analyses further suggest that the end-member soil types may produce radically different forms of stormflow response. Therefore, it appears that variability in soil-hydraulic characteristics may impose more complexity on hydrologically driven hazard potential than was previously recognized for this mountainous humid-tropical climate zone. Our findings, which are limited to observations spanning two wet seasons, encourages further deployment of continuous in situ hydrologic monitoring to facilitate the development of empirical hillslope hydrologic response and landslide thresholds for regional-scale hazard warning systems that must account for spatially variable soil types.

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Mirus, B.B., & Loague, K. (2013). How runoff begins (and ends): Characterizing hydrologic response at the catchment scale. *Water Resources Research*, 45(5), 2987-3006. https://doi.org/10.1002/wrcr.20218

Pando, M.A., Ruiz, M.E., & Larsen, M.C. (2005). Rainfall-induced landslides in Puerto Rico: An overview. In Gabr M.A., Bowders J.J., Elton D., & Zornberg J.G. (Eds.), Geotechnical Special Publication No. 140, Slopes and Retaining Structures under Seismic and Static Conditions (pp. 2911-2925). Austin, TX: American Society of Civil Engineers.

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ABSTRACT

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