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ANALYZING VULNERABILITY BY INTEGRATING A LANDSLIDE IMPACT ASSESSMENT AND SOCIAL VULNERABILITY INDEX ANALYSIS: A CASE STUDY OF THE RÍO GRANDE DE AÑASCO WATERSHED POST HURRICANE MARIA

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ABSTRACT

Hurricane Maria triggered more than 16,000 landslides across the Río Grande de Añasco Watershed, contributing to system-wide failures of critical road infrastructure, stormwater drainage, and damage to homes and farms (Figure 1). Assessing the spatial relationship between the distribution and density of the landslides relative to transportation networks and primary stream input points identifies critical areas for prioritizing recovery and mitigation efforts across this diverse and complex socio-ecological landscape within the Añasco Watershed. Furthermore, considering social context alongside physical and natural science principles contributes to applied scientific inquiry addressing the complex challenges facing a Small Island Developing State (SIDS) in this climate-vulnerable region. Within the socio-ecological landscape, issues surround extremes of wealth and poverty, disenfranchised populations, and disconnected systems, to name a few. This study examines the intersection of the CDC Socio-economic Vulnerability Index with a landslide impact assessment to better understand how social system exposures and vulnerabilities intersect with landscape vulnerabilities and risk. A geospatial proximity analysis comparing the density and area of slides with river networks and manufactured drainage systems highlights future sources of significant sedimentation affecting issues of water quality, erosion control, and ecosystem response and resilience in the face of extreme storm events and observed changes in regional as well as local climate. For example, while the vast majority of landslides occurred within areas dominated by forest land cover, over 1,000 landslides occurred within areas designated by crops in lowland and mountain farming communities. An assessment of landslide density and incidence relative to a critical proximity to roads (325 ft or ~100m) highlights priority regions for focused examination of sustainable land use management practices and road maintenance/mitigation. Landslide distribution in regions dominated by clay soils contributes to the understanding of landscape vulnerability across the watershed. This may also prove key for national housing authority projects examining investments in reconstruction, repair, and potential relocation of communities out of high-hazard regions. Sustainable land use and effective collaborative watershed scale management will play an ongoing role in mitigating repeat failures of slopes and reducing overall sedimentation throughout the watershed. This socio-ecological system evaluation aids a watershed scale risk assessment by exploring opportunities for a multi-system approach to empowering community involvement in sustainable, long-term governance and improved land use and erosion mitigation practices.

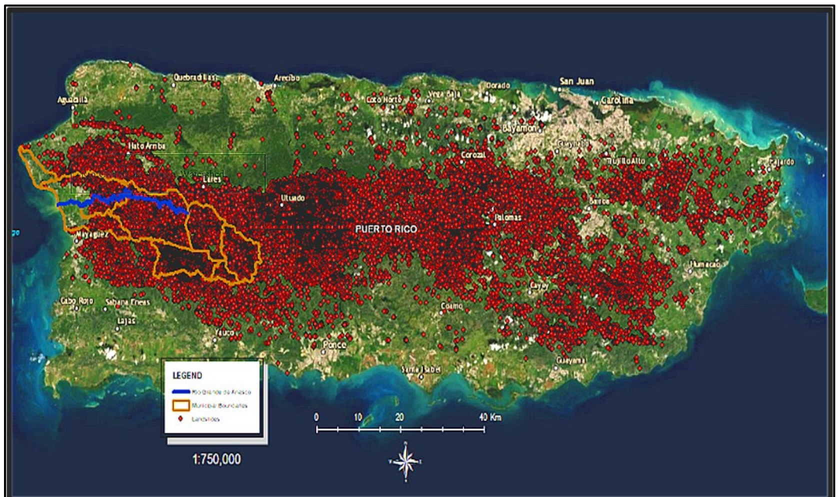

Figure 1. Distribution of landslides post Hurricane Maria with study area and Rio Grande de Añasco Watershed identified.

Keywords. Critical infrastructure, Hurricanes, Landscape vulnerability, Landslides, Puerto Rico, Río Grande de Añasco, Social vulnerability, Soil erosion.

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INTRODUCTION

Landslides, intense rainfall, and dynamic land use change characterize the dramatic and physically limited landscape of Puerto Rico, the smallest and most eastward of the islands in the Greater Antilles chain in the Caribbean, challenging application of sustainable land use and natural resource approaches. The highly varied inter-connected and inter-dependent natural systems across 9,104 km^2 form the backdrop to a dynamic socio-cultural, political, and economic landscape in crisis. Following the impacts of hurricanes Irma and Maria, the latter being the strongest storm to hit Puerto Rico in more than 80 years, socio-ecological systems continue to face challenges from both ongoing earthquake tremors and the 2019-2020 significant increase originating from a fault line along the south of the island, as well as from the spread of COVID-19. Damage to roadways, electrical systems, and widespread geomorphic change to river systems affected short-term and long-term water supplies throughout the island for personal consumption and agricultural production. In addition to the physical impact on ecosystems and critical infrastructure, the storm led to a profound loss of human life (Resilient Puerto Rico Advisory Commission, 2018; Van Beusekom et al., 2018). Flooding and sediment deposition from widespread slope failures decimated valley and mountain crops. Extensive damage to the transportation network isolated communities, cutting them off from access to food and other essential goods and services, particularly for mountain communities (Pasch et al., 2018). In addition to the significant loss resulting from the impact of Hurricane Irma, the economic loss related to agricultural yield as a result of Hurricane Maria measured over $780 million (USDA NRCS, n.d.). Before the storm, a complex land use change history led to a reliance on imports for more than 80% of all food and related products (Gould et al., 2017). Following Hurricane Maria, this dependency increased as farmers struggled to recover from the ~$2 billion in total losses (Rodriguez-Cruz and Niles, 2021). Puerto Rico is now also working on climbing out of the government-debt crisis that began in 2014 with the advent of the 2020 Fiscal Plan. At the heart of the international calls to action (e.g., Sendai Framework, SDGs, MDGs, etc.) is incorporating a social-ecological systems (SES) framework within disaster risk reduction and sustainable watershed management approaches, highlighting the inextricable link between human and natural systems. This is often expressed through identifying points of vulnerability within the systems. Central to evaluating these questions is an assessment of the spatial relationship between the distribution and density of the landslides relative to essential transportation networks to identify critical areas for prioritizing recovery and mitigation efforts. In addition, a geospatial proximity analysis comparing the density and area of slides across river networks and artificial drainage systems highlights future sources of significant sedimentation affecting issues of water quality, erosion control, and ecosystem response and resilience in the face of extreme storm events and observed changes in regional as well as local climate. Comparing the spatial distribution of these results with a social system vulnerability indices informed spatial analysis identifies coupled system feedback loops vital to developing sustainable watershed management and hazard mitigation planning.

METHODS

The Añasco Watershed is currently ranked #5 on the list of impaired watersheds within the United States and Territories and drains one of the largest basins on the island (USDA NRCS, FY 2019 National Water Quality Initiative). The watershed occupies approximately 414 km^2 of highly variable topography, draining nearly 50,000 hectares (ha) of mountain highlands at the western edge of the Cordillera Central to the coastal lowlands ending at Mayagüez Bay (Figure 2). Most of the streams are ephemeral, flowing only when significant rainfall occurs. The Añasco River serves as the main channel of the watershed that encompasses eight municipalities (Añasco, Mayagüez, Las Marías, Maricao, San Sebastián, Lares, Yauco, and Adjuntas). Pollutants resulting from runoff and release of chemicals used in agriculture production (fertilizers, pesticides, and manure) and sedimentation from erosion and mass wasting events affect water quality throughout the watershed, including local ecosystems, fisheries, and coral reef health in Mayagüez Bay (Ramos-Scharrón et al., 2014). Agriculture and forests dominate land use and human activities, in addition to expanding the urban interface and tourism in Mayagüez, home to ~98,000 people (PR.gov, 2023). In the Añasco Watershed, ~50% of the total population (~ 126,000) live in poverty, or >55% of the population in Adjuntas, Lares, Las Marias, San Sebastian, and Yauco (CDC/ATSDR, 2018). While a dominant wet (May - October) and dry season (January – April) persists, recent studies cite increases in the intensity of storms, magnitude, and frequency of large-scale events (hurricanes), alongside periods of increasing drought (IPCC, 2014; Jury, 2020). According to Harmsen et al. (2009), between 1961 and 2000, the average temperature for Mayagüez increased by 1.17ºC. This is particularly relevant given the comparison to the global average increase of 0.6 ± 0.2ºC in the last century (IPCC, 2014). The highly varied land use across significant topographic change from ridge to coast within a single watershed demands a dynamic approach that accounts for discrete differences in local cultural framing, ecosystem resource needs, and use activities and perceptions between mountain and valley farming communities. Landslides occur with high frequency throughout the island annually, particularly in regions dominated by heavy anthropogenic modification, such as agriculture and roads (Larsen and Torres-Sánchez, 1998). Dominant soil textures range from moderately fine to fine, with clay layers near the surface resulting from weathered Volcaniclastic rock in the mountains to coastal plains dominated by depositional sandy soils. Rates of infiltration in mountain regions tend to be slow to very slow (Duque and Melesse, 2016), creating an opportunity for flooding in lower elevations resulting from typically high runoff rates. Agriculture and natural forests constitute the primary forms of land use throughout the Añasco Watershed (Duque and Melesse, 2016). In addition to crops for local consumption, farms in the region support research and several biotech/bio-agricultural companies capitalizing on the extended tropical growing season, fertile soils, and tax incentives (e.g., 2008 Act 73).

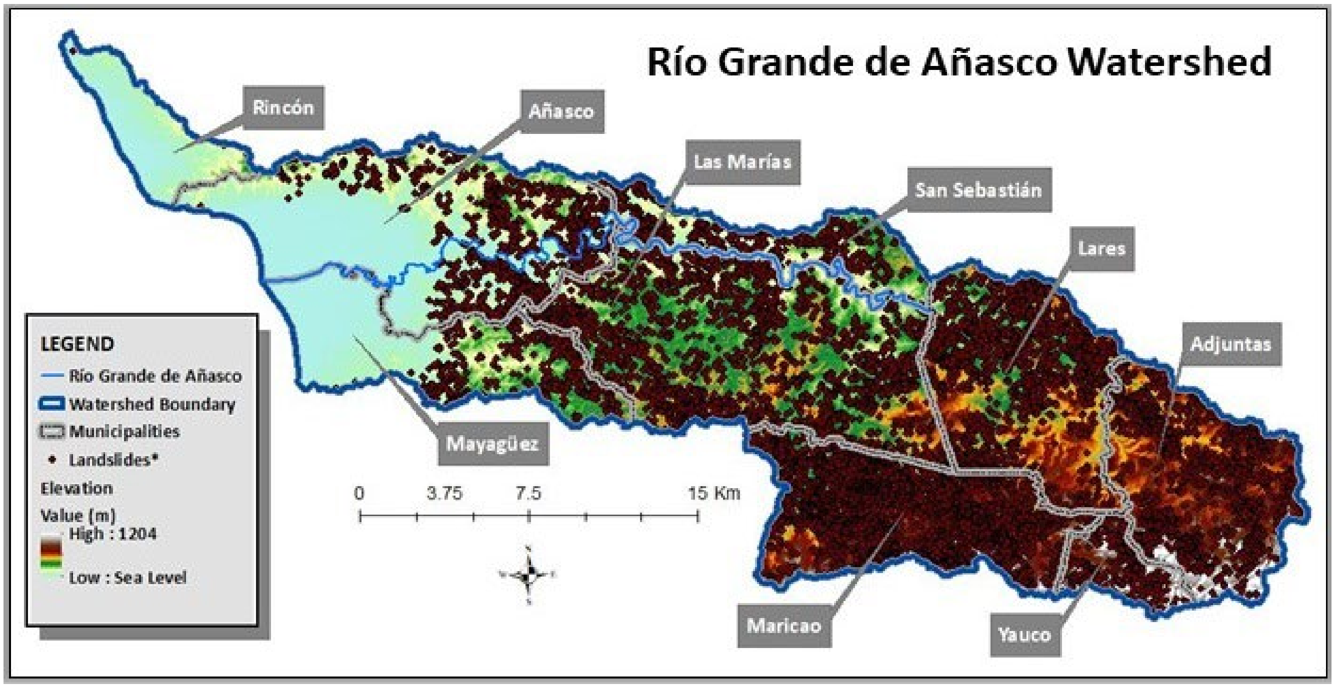

Figure 2. Elevation and distribution of landslides across the Río Grande de Añasco Watershed.

LANDSLIDE IMPACT ANALYSIS

More than 16,000 slides of varying types and sizes were triggered by the torrential rainfall accompanying Hurricane Maria. This analysis sought to explore the dynamics of the impact of the landslides relative to land use practices and physical system characteristics essential to understanding landscape vulnerability and susceptibility (Table 1). Landslide data points were validated against data from FEMA (Federal Emergency Management Agency), IITF (International Institute of Tropical Forestry), and Bessette-Kirton et al. (2019). These data were compared and compiled with GPS point data and photos collected in June 2018 and site visits (March and May 2019). Vegetation and land cover maps were derived from USGS Gap Analysis Project, IITF, and PR DNR datasets. Hydrologic data was derived from the National Hydrography Dataset, NOAA, PR DNR, and Acueducto datasets. Land use/land cover, vegetation, and soil data were derived from USGS, NRCS SSURGO Web Soil Survey, IITF, and PR DNR. The Digital elevation models (DEMs) were created using USGS Landviewer.

The soil type relative to dominant clay soils may influence slope stability when combined with slope distribution, particularly in moist or saturated conditions. Of particular note is that these soils experienced antecedent saturation from Irma before Maria compounding the effect Hurricane Maria had on slope stability (Mecikalski and Harmsen, 2019; Mejia Manrique et al., 2021). The analysis reveals some interesting patterns and correlations consistent with what we have seen concerning landslide density. In Maricao, the potential for sedimentation release due to the density of slides is the highest among all the municipalities (Figure 3). However, notice that the highest density overall with respect to proximity to streams (500 ft = ~152m) can be found in the northern area of the watershed in Lares and with less distance for sediment to travel to the main tributary, potentially overloading smaller streams. These responses and processes increase scouring and erosion, creating a compound effect in upland and lowland regions. Note that in Lares, another hot spot, the dominant soil type does not appear to be the dominating factor in the distribution of slides. Further examination of this relative to soil moisture properties, local land use, and vegetative cover will likely be revealing. Future hazard prevention and land use planning efforts should also account for the proximity of roads and streams to susceptible slopes (primarily slopes 30˚- 60˚) (Ramos-Scharrón et al., 2021; Sassa and Canuti, 2009). Agricultural land use/vegetation cover are key factors in sediment production and landslide incidence across multiple elevations and slope gradients. As shown on the maps below, prioritization of critical regions (municipalities) expands municipal and agency disaster risk reduction plans. The US Geological Survey maintains a stream gauge in the river near San Sebastián. The river direction is highly variable and tortuous at some locations. The water authority (Acueducto) operates several water intake facilities on the river, providing a significant water source for the City of Mayaguez. The meander and sedimentation compromised the intake facilities during Hurricane Maria.

This analysis clarified those road segments not previously identified as located within high-density regions of landslides by analyzing the proximity of slides to roads (325 ft or ~100m). These findings reveal the need for further analysis, particularly concerning land use, road maintenance/mitigation, and transportation corridors for basic livelihood needs (Figure 4). This may be key for national housing authority projects examining investments in reconstruction, repair, and potential relocation of communities out of high-hazard regions as part of recovery efforts across the island. In addition, land use practices such as building roads can segment slopes influencing susceptibility to failure (Ramos-Scharrón et al., 2021). A subsequent phase of the analysis evaluated areas that meet both conditions – density relative to roads and streams and overlain with land use (forest, cropland, and pasture/hay). For example, this highlighted the potential for concern with respect to not only impact on coffee plantations but also coordination with local communities to stabilize slopes in Maricao.

Table 1. Overview of methods used for Landslide Impact Analysis.

Type of Analysis	Method	Data
Slope Map	Slope reclassify and analysis for slides within target moderate to steep slopes.	DEM, Landslide point data
Landslide Density Map	Point kernel density to calculate magnitude-per-unit area (km/km^2)	Landslide Point Data, DEM, Slope Map, Hydrologic boundary layers
Soils and Landslide Density	Derivation of Soils Map; Reclassification of soils data (>40% clay); Intersection of soils polygons with landslide point data and overlay with density.	Soils Data, Landslide Point Data, Landslide Density Map
Surface Water Networks, Roads, and Landcover/Land Use	Intersect functions used for proximity analysis; Overlay with reclassified landcover/land use data.	Hydrologic Data; Roads Data; Hydrologic boundary layers; Landcover/Land Use; Landslide Point Data

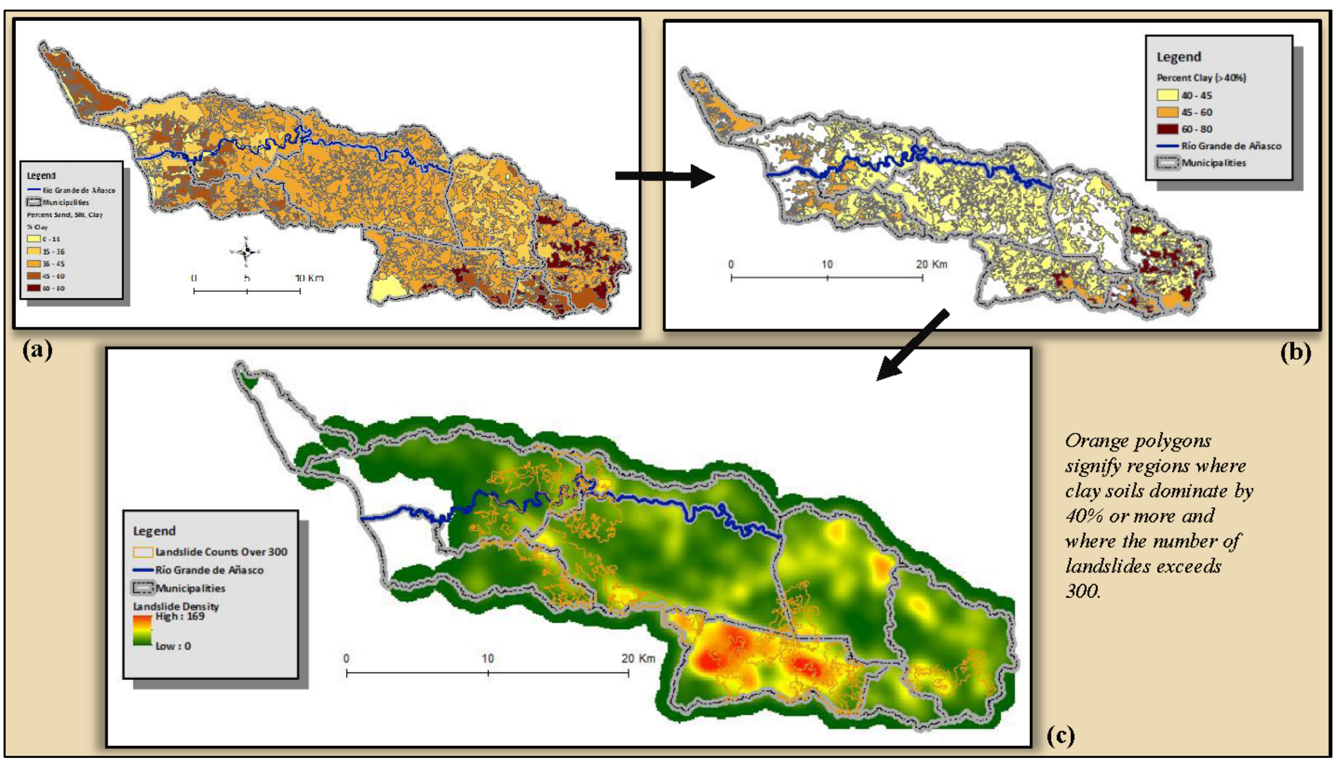

Figure 3. Diagram of analysis used to identify locations where distribution of percent clay >40% (b), derived from a distribution of %clay (a), coincides with high landslide density and frequency to reveal potential priority regions for slope stabilization (c).

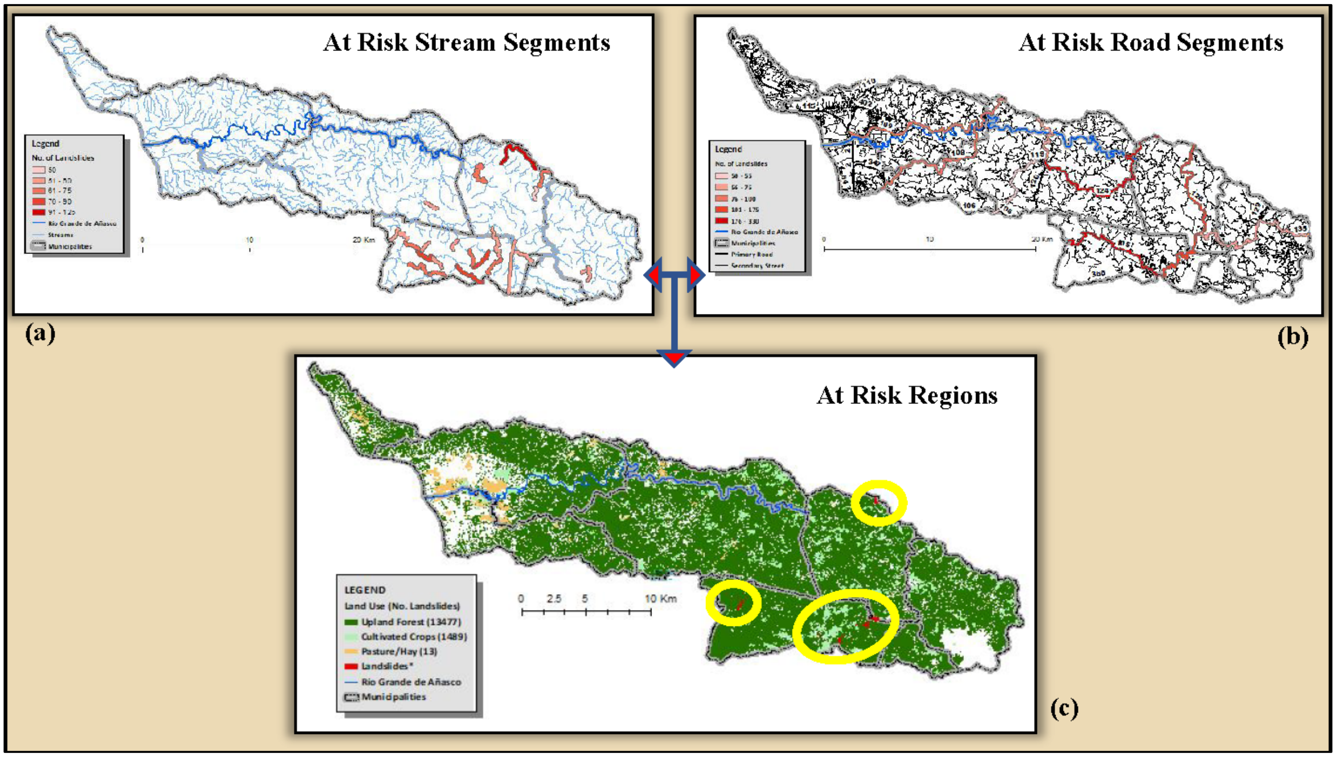

Figure 4. Diagram of risk analysis evaluating proximity of slides (where number of slides >50) to surface water networks (a), roads (b), and resulting composite of highest risk regions relative landcover/land use (c).

SOCIAL SYSTEM VULNERABILITY

Considering social context alongside physical and natural science evaluations contributes to applied scientific inquiry addressing the challenges facing a Small Island Developing State (Puerto Rico) in the Caribbean which is a climate-vulnerable region. Additionally, a social vulnerability assessment moves beyond a simple delineation of the drivers of change and the use of ecosystem services. It illuminates how significant scale disturbances (such as hurricanes and landslides) disrupt the networks, subgroups, and flows essential to social system functioning. When evaluating the feedback loops and interactions between the social and physical systems, it is crucial to identify those social system points of exposure that contribute to vulnerability. We use the Adger (2006) definition of vulnerability in this study and specifically identify the role the "absence of the capacity to adapt" plays in exposure to stressors. This is closely related to the UNISDR definition that references susceptibility to the impact of hazards across the multi-sector dynamic of conditions "determined by physical, social, economic, and environmental factors or processes" (https://www.undrr.org/terminology/vulnerability). To support this analysis, Theme 1 from the CDC Social Vulnerability Index was applied (CDC ATSDR, 2018). Theme 1 evaluates socioeconomic status and incorporates census data for income, poverty, employment, and education variables (Figure 5). While the correlations between education and social vulnerability and disproportionate impact from disasters are pending further study, Tierney (2006) and Morrow (1999) propose there may be a relationship between education, income, access to resources, and increased exposure to institutional and systemic barriers preventing or limiting access to those resources. Additionally, impoverished communities may have fewer financial and physical resources and assets to overcome the loss of property, healthcare, and insurance plans (as a benefit from employment) to recover from injury, and income, according to Morrow (1999) and Cutter et al. (2003). A highly vulnerable community will prioritize needs and likely have reduced resources to respond to a significant disruption event.

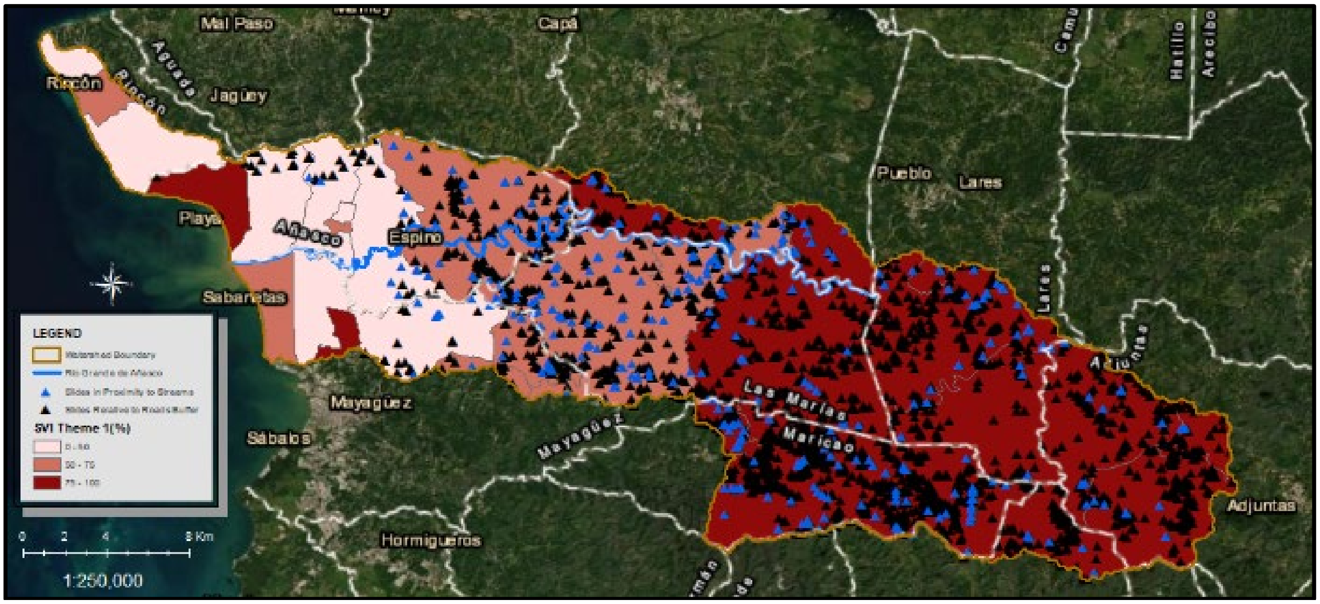

Figure 5. Slide distribution relative to roads and streams displayed over percent SVI distribution.

DISCUSSION AND CONCLUSIONS

The significance of these findings is positioned within the conceptual frameworks of vulnerability and resilience, ongoing hazard mitigation planning throughout the watershed and the island, as well as the projections of the impact of climate change on the magnitude and frequency of storms in the Caribbean. The IPCC (2014) identified a moderate level of disturbances for regions throughout the Caribbean, mainly annually. The 2022 IPCC report evaluating vulnerability throughout the Caribbean underscores these concerns. It reinforces the emphasis on capacity building and adaptive strategies that consider the socio-ecological systems interactions and the resulting impact of ecosystem degradation. Climate predictions cite extreme storms' increased frequency and severity (Jury, 2020; Van Beusekom et al., 2018). This is met with concerns for the region as it relates to drought, sea level rise, and other hazards beyond landslides and flooding. A feedback loop between disturbances and forest health plays out through landslides' contributions to vegetation patchiness within the landscape. Slides also contribute to sedimentation by exposing soils and parent material that may be mobilized downslope into streams or valleys. Soil dynamics in post landslide conditions are a dominant factor contributing to spatial and temporal heterogeneity of ecosystem response (Myster et al., 1997). Additionally, soil catena structure and properties dictate the stability of slopes in addition to the ability of vegetation to establish and/or regrow. Evaluating these variables influencing landscape vulnerability through the lens of SES requires the inclusion of land use practices as well as social system vulnerabilities. Agriculture, for example, contributes to the reduction of stands, patch dynamics, species distribution, and erosion rates, all of which may influence near-surface temperatures and moisture (Foster et al., 1999; Myster and Walker, 1997). Outside the realm of a natural disaster, any significant shift in the capacity of a society to meet basic livelihood needs, the maintenance of the economy, or the instability of a governance system could minimize adaptive capacity. Additionally, inequitable modes of governance, as well as remnants of colonial governance, particularly of Small Island Developing Countries (SIDS), may add a layer of vulnerability to a social system. A multi-scale system assessment of adaptation and resilience also contributes to the growing body of disaster risk reduction studies in the Caribbean. Considering the variability and influence of socio-political and socioeconomic conditions is key to dampening or heightening social resilience (Aitsi-Selmi et al., 2015).

Wisner et al. (2004) carry susceptibility and exposure further by delineating the capacity "to anticipate, cope with, resist, and recover." The function of the character, magnitude, and rate of climate change is also key (IPCC, 2022). So, while vulnerability may have a direct relationship to disturbance frequency, we argue that the diversity and variability of that frequency are difficult to nail down with high levels of certainty, leading instead to a focus on *how* the parameters of a social system proactively accommodate, respond to, or are resistant to impact. This is a bit of a departure from ecological resilience, where the response to disturbance is more cause and effect, with some feedback loops depending on species variation and rate of establishment. Land use change and population shifts also impact socioeconomic resilience and adaptive capacity alongside shifts in the capacity of ecosystems to respond to extreme punctuated events and long-term climatic shifts. According to Gould et al. (2017), urban development in Puerto Rico continues to rise despite a decline in the human population over the last five decades. del Mar López et al. (2001) state that 11.3% of Puerto Rico was classified as urban in 1977. By 1994, urban areas increased by 27.4%, and urban growth on soils suitable for agriculture increased by 41.6%. Urban development leads to shifts in socioeconomic systems' interactions that must be accounted for in sustainable development and resilience planning. Land use conversion influences the dynamics of land-atmosphere interactions, particularly in coastal urban areas, and the available land suitable for agriculture or forest rehabilitation. Agricultural practices affect soil dynamics and hydrologic regimes in response to expanding urban centers or proximate and distal drivers of change. The USDA, in their 2012 Census, found that, in the Añasco Watershed, between 2007 and 2012, the number of farms and total area utilizing irrigation increased. Gould et al. (2017) proposed that multiple factors suggest the need to improve the conservation of forests and reallocate land use for timber harvesting. This land use shift impacts erosion prevention in the face of hurricane-force winds and rainfall. It will also likely impact soil dynamics and stream recharge as well as downstream management of flow and water quality. Increases in crown density in forested areas will also affect surface/canopy temperature exchanges and near surface air temperatures.

Within the socio-ecological landscape of Puerto Rico, there are numerous challenges surrounding extremes of wealth and poverty, disenfranchised populations, and disconnected systems. Outside the realm of a natural disaster, any significant shift in the capacity of a society to meet basic livelihood needs, the maintenance of economy, or in stability of a system of governance could serve to minimize adaptive capacity. However, great ingenuity and resilience, perhaps due to the efforts and movement following Hurricane Maria and, most recently, the impact of earthquakes that began in December 2019. According to Harmsen and Harmsen (2019), ~46% of the island's population lives below the poverty line. This has increased significantly when considering the disproportionate impact of disasters. Climate predictions cite increases in frequency and severity of extreme storms (Harmsen et al., 2009; Larsen and Torres-Sánchez, 1998; Van Beusekom et al., 2018). Disturbance ecology principles cite the magnitude, severity, and frequency of disturbances as primary parameters in understanding the effects on ecosystems, the complexity of natural system responses, and their relationship with disturbances (Rogers, 1996). Compounding the social system impact is the dependency on imports for food and goods and the local economy's subsequent reliance on local agricultural production, primarily for export. This water, energy, and food security nexus provide the backdrop to a complicated and intricate socio-ecological system set of interactions. A multi-scale system assessment of adaptation and resilience also contributes to the growing body of disaster risk reduction studies in the Caribbean which is currently facing a region-wide impact from changing climatic conditions (Harmsen et al., 2009). In summary, the significance of these findings is not only positioned within the conceptual frameworks of vulnerability and resilience and the logistical and immediate implementation of municipal hazard mitigation plans and projects, but also as the critical assessment of the impact of climate change on the magnitude and frequency of storms for the Caribbean.

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