DISSERTATION

ADVANCING CLIMATE-ADAPTIVE WATERSHED HEALTH BY INTEGRATING SOCIO-ECOLOGICAL SYSTEMS AND TEAM SCIENCE

Submitted by

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ABSTRACT

ADVANCING CLIMATE-ADAPTIVE WATERSHED HEALTH BY INTEGRATING SOCIO-ECOLOGICAL SYSTEMS AND TEAM SCIENCE

Strengthening effective watershed health and adaptive capacity amid accelerating climate change and compounding socio-ecological stressors demands integrative approaches that link systems analysis, risk and vulnerability assessments, and justice-centered collaboration. The Río Grande de Añasco (RGA) watershed in Puerto Rico, a landscape still grappling with cascading post-disaster impacts from recent hurricanes and compounding hazards, illustrates the dynamics of a socio-ecological system (SES) under climate stress. This research advances a SES framework for evaluating watershed health, identifies the coupled natural and social drivers of landslide susceptibility, and synthesizes best practices for equitable, transdisciplinary collaboration in a climate-vulnerable setting.

A core contribution of the research is the Socio-Ecological Systems Watershed Health Assessment (SES WHA) Framework, which extends conventional assessment models by embedding climate change impacts, disaster risk reduction, and international guidance within a structure that explicitly integrates justice and equity metrics. Applied to the RGA, the framework evaluates watershed health through interrelated categories (e.g., climate change and disaster resilience, institutional and governance challenges, ecosystem services and ecological needs, infrastructure and resource constraints, long-term monitoring). Each category links indicators to specific challenges and intervention strategies, providing a dynamic approach to diagnosing watershed vulnerabilities and identifying adaptive responses. This approach reveals how ecological degradation, infrastructure fragility, and social vulnerability interact to shape adaptive capacity and inform equitable, climate-adaptive governance.

In 2017, Hurricane María triggered more than 16,000 landslides across the RGA, contributing to system-wide failures of critical road infrastructure, stormwater drainage, and damage to homes and farms. The landslide impact analysis presented in this research demonstrates how natural and social factors jointly influence hazard susceptibility in an active post-disaster landscape. Integrating the CDC Social Vulnerability Index within a spatial proximity model of landslides enabled the identification of vulnerable hotspots, particularly in the municipalities of Maricao, Las Marías, and Lares, where socio-economic disparities, infrastructure fragility, and slope instability converge.

This dissertation synthesizes best practices for team science, bridging disciplinary approaches to collaborative research in a post-disaster context. The analysis identified critical gaps, including power imbalances and challenges in integrating community priorities into scientific processes. Insights from the CRISP project demonstrate how justice-centered, participatory methods enhance stakeholder trust and data relevance, while also revealing unique obstacles faced in post-disaster environments. This synthesis offers a new framework for guiding team science practices where justice and equity are vital considerations. Collectively, the findings presented in this research advance sustainable, risk-informed watershed management by demonstrating how integrating technical assessments, social vulnerability data, and equitable, collaborative research practices can strengthen climate adaptation and socio-ecological resilience. Philosophically, the research reframes watershed, disaster, climate adaptation, and team science as interdependent fields of study and practice, advancing a justice-centered paradigm for knowledge production, collaboration, and adaptive governance.

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DEDICATION

This dissertation is dedicated to my bisabuela, Oliva Venegas von Schmeling, and through her, my Indigenous heritage traced to Chiapas, Mexico — land of farmers, fighters, and survivors, where socio-economic and political complexities played out in the shadows of the Sierra Madres. It is also dedicated to my maternal grandparents, María Oliva Venegas von Schmeling Cook and Thomas H. Cook. She braved the 1950s Deep South systemic racial and social barriers when she immigrated to the United States to build a full and generous life with my grandfather. He instilled in me - perseverance, compassion, and strength. As the eldest of their twenty-five grandchildren, I am part of a lineage shaped by resilience, courage, and love of the land. Through this heritage, I have come to recognize the value of all forms of knowledge, the power of story, the necessity of global perspective, and the essential oneness of humankind.

This work is also dedicated to the resilient, diverse, and generous people of Puerto Rico, whose strength, love of place and heritage, and enduring hope in the face of extreme hardship continue to inspire me. It is my deepest wish that this research may serve, in some small way, to honor their perseverance and contribute to a more just and sustainable future for all life on the island.

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CHAPTER 1 – INTRODUCTION

Hurricanes represent the most recurrent and severe disturbance shaping Puerto Rico's watersheds, yet their impacts rarely occur in isolation. These storms initiate cascading hazards (e.g., flooding, landslides, infrastructure failures) that expose systemic vulnerabilities within both ecological and social systems. The compounding nature of these events underscores the need for integrative, justice-centered approaches that connect socio-ecological dynamics, governance, and collaboration across research and practice to strengthen resilience and adaptive capacity. Additionally, disaster risk, climate change impacts, and socio-ecological system degradation increasingly threaten both natural and human communities around the world (Folke et al., 2021; IPCC, 2023; Steffen et al., 2015; UNDRR, 2019). Nowhere are these challenges more pronounced than in small island contexts like Puerto Rico, where extreme, and often compounding, weather events and hazards (e.g., hurricanes, tropical storms, flooding, landslides), infrastructure vulnerabilities, and historical inequities converge to create complex, socio-ecological systems (SES) stressors, risks and vulnerabilities (Figure 1-1) (Bonilla & LeBrón, 2019; FEMA, 2018; Mimura et al., 2007; Rodríguez-Díaz, 2018; Santos-Burgoa et al., 2018).

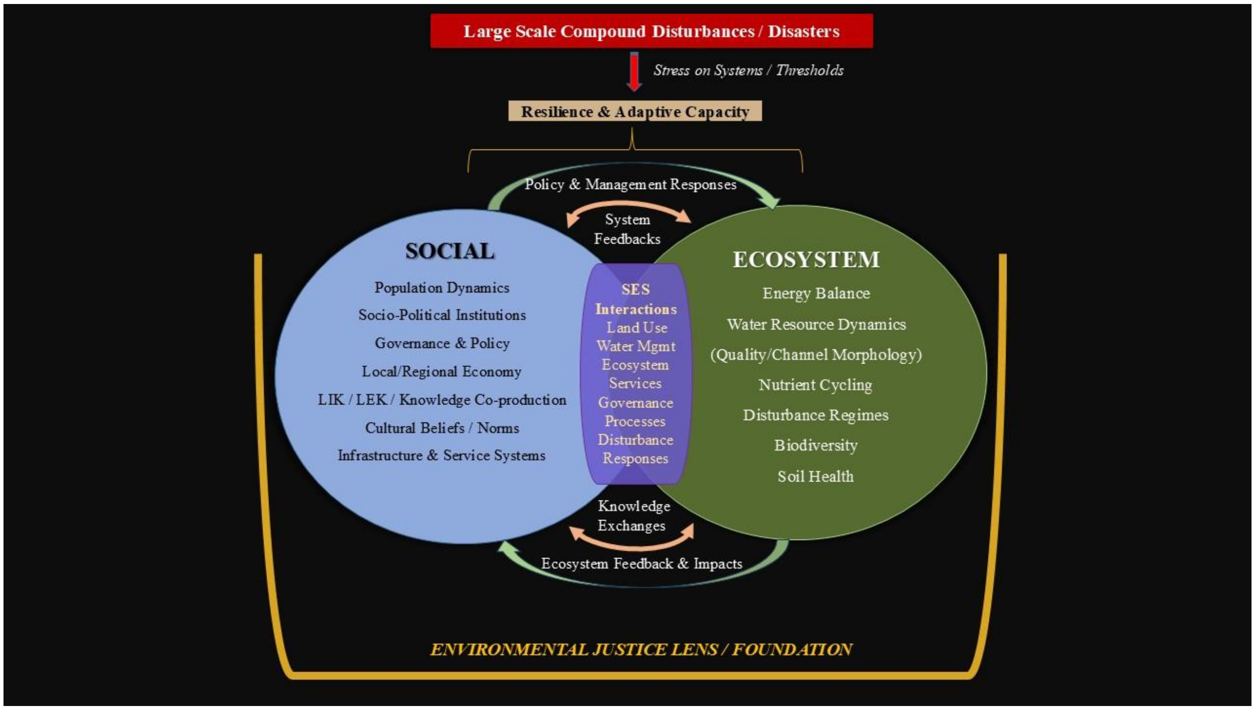


FIGURE 1-1. Conceptual model illustrating the SES interactions and feedback loops relevant to watershed health, resilience, and justice-centered governance. The diagram depicts how compound hazards, system feedback loops, and equity-informed processes interact across social and ecological domains, forming the conceptual foundation that informs analyses throughout the dissertation.

Large-scale compound disturbances introduce stressors that push social and ecological systems toward critical thresholds (Figure 1-1). Through co-produced system feedback and knowledge exchanges, SES interactions emerge at the intersection of population dynamics, governance, local knowledge systems, and ecological processes. Adaptive capacity and resilience are shaped by these dynamic interactions and are interpreted through a justice-centered lens. The environmental justice framing underscores the need for equity-informed integration of local and/or Indigenous knowledge (LIK/LEK), social vulnerability, and ecological function in advancing just, risk-informed watershed governance.

The overarching purpose of this dissertation is to explore how socio-ecological and justice-centered approaches can be integrated to strengthen watershed health assessment, SES resilience, and governance in regions facing extreme, compounding disasters. These foundational concepts inform the development of the SES Watershed Health Assessment (WHA) framework (Chapter 3), the geospatial socio-ecological vulnerability analysis (Chapter 4), and the team science best practices synthesis (Chapter 5). Addressing these complex problems requires not only robust watershed management strategies, but also innovative, interdisciplinary, if not transdisciplinary, approaches for assessing socio-ecological vulnerability that integrates justice and equity throughout design, process, and implementation. To fulfill this purpose, the dissertation pursues three interconnected goals that together address what defines watershed health, what undermines it under compounding disasters, and how socio-ecological and collaborative approaches can improve assessment and governance:

1. To develop and apply a socio-ecological framework for watershed health assessment that prioritizes risk-informed, equitable watershed governance.
2. To assess socio-ecological vulnerability to landslides and extreme erosion within the Río Grande de Añasco (RGA) watershed.
3. To synthesize and critically assess team science best practices across disciplines, using a post-disaster case study to examine unique implementation barriers and highlight justice and equity as vital considerations.

Drawing on the author's post-hurricane fieldwork in Puerto Rico, including focus on the RGA watershed, following hurricanes Irma and María in 2017, this research applies a systems-based, mixed-methods approach that integrates a geospatial analysis, socio-ecological theory, and critical reflections on the challenges of conducting collaborative research in disaster-affected settings. The findings underscore the need for risk-informed watershed management approaches, socio-ecological vulnerability assessments, and strengthening equitable, and justice-centered approaches to team science in post-disaster contexts.

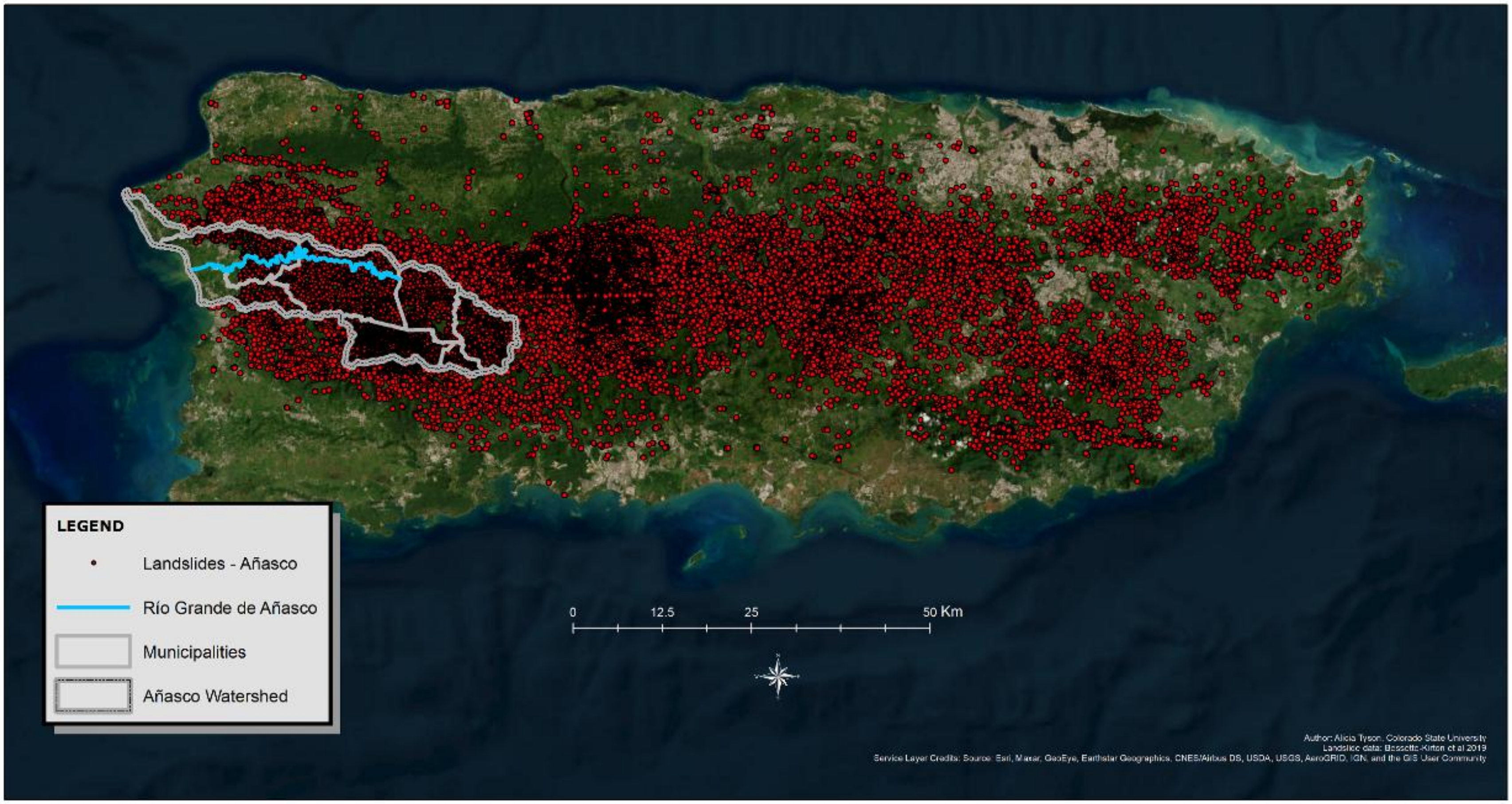
1.1 Overview

Across the island of Puerto Rico, landslides, intense rainfall, and dynamic land-use change characterize a dramatic and limited landscape, challenging sustainable land-use and resource management strategies (Elias & Rios, 2015; EPA, n.d.; University of Colorado-Boulder, Natural Hazards Center, 2025; USGS, 2021). The island, the smallest and easternmost in the Greater Antilles, spans 9,104 sq km (3,508 sq mi). Historically, the economy has shifted from agriculture-dominant to urban-centered manufacturing, resulting in increased population density in cities (Thomlinson et al., 1996). The island's hydrologic network includes both perennial rivers that reach coastal lowlands and intermittent rivers that drain southward. The northern karst region houses the Río Camuy, the world's third-largest subterranean river (Giusti, 1978). The Caribbean National Forest, the only tropical forest within the US system, covers 11,300 hectares (28,000 acres) and receives about 35.4 mm of rainfall annually, much of it during tropical storms or hurricanes, which exacerbate flooding and landslides (Daly et al., 2003). Puerto Rico's rivers play an essential role in irrigation, hydroelectric power, and the marine ecosystem, vital to the territory's economy and culture.

Throughout the Caribbean, climate change exacerbates water management challenges, with projections indicating increased drought frequency, sea level rise, and more frequent and intense hurricanes (Cashman & Nagdee, 2017; IPCC, 2022; Taylor et al., 2018). These changes threaten both water availability and quality, especially for coastal and inland wetlands, and add to compound SES stressors. Managing these impacts requires governance structures that can adapt to long-term climate changes and their impacts, a complexity that static policies, like the Q99 minimum flow standards, fail to adequately address (Lopez et al., 2001; Pahl-Wostl, 2007). The Q99 standard provides a quantifiable benchmark for low-flow conditions but has limitations in the context of integrated water resource management and ecological sustainability (Richter et al., 2006; Murry et al., 2019. Additionally, for regions like Puerto Rico where compounding and increasingly extreme climate challenges, particularly drought, are becoming more frequent, this standard is not sufficiently responsive (Cashman & Nagdee, 2017; PRCCC, 2013; Taylor et al., 2018). Today, Puerto Rico's natural and social systems interact within a disturbance regime marked by frequent heavy rainfall, often triggering landslides and floods (Gould et al., 2017; Larsen & Torres-Sánchez, 1998).

Understanding the impact of natural and human disturbances on Puerto Rico's socio-ecological systems is complicated by the increasing influence of climate change. Projections indicate more frequent and severe storms (Comarazamy & González, 2011; Harmsen et al., 2009), challenging resilience efforts. Principles of disturbance ecology, such as the magnitude, severity, and frequency of events, are key to understanding ecosystem impacts (Rogers, 1996). However, Puerto Rico's reliance on imported food and goods places additional strain on its economic and agricultural systems, further complicating the water-energy-food security nexus.

The island encompasses varied, interconnected natural systems that are currently in crisis following Hurricane Maria, the strongest storm to hit Puerto Rico in over 80 years. With sustained winds of 249 km/h (155 mph) and 130 - 940 mm (5–37 in) of rainfall, Hurricane María triggered widespread flooding and ~71,000 landslides as it traversed the island (Bessette-Kirton et al., 2019; USGS, n.d.) (Figure 1-2).



Author: Alicia Tyson, Colorado State University
Landslide data: Bessette-Kirton et al 2019
Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

FIGURE 1-2. Distribution of landslides across Puerto Rico, post Hurricane María, with RGA Watershed identified.

The economic toll on the island's infrastructure and essential services (e.g., water, food, shelter, energy, communication, and transportation) was estimated at over $90 billion. Agricultural losses exceeded $780 million. These impacts were compounded by Hurricane Irma, which struck just weeks earlier and added approximately $45 million in agricultural losses (USDA, ERS, 2023; USDA NRCS, n.d.). Puerto Rico faces unprecedented challenges to its energy, water, and infrastructure systems in the wake of Hurricane María, a Category 4 storm in September 2017. Landslides affect Puerto Rico annually, particularly in heavily modified regions such as agricultural lands and road networks (Larsen & Simon, 1993). Following Maria, approximately 71,000 landslides occurred across the island, with around 16,000 within the RGA watershed alone, leading to widespread infrastructure failures, including road and drainage systems, and severe impacts on homes and farms (Bessette-Kirton et al., 2019).

Assessing impact, socio-ecological vulnerability, and the implications for adaptive capacity at multiple scales is essential as the Caribbean faces region-wide impacts from climate change (Comarazamy & González, 2011; Nurse et al., 2014). In recent decades, the importance of social resilience has grown, reflecting the need to address climate change and disaster risk in policy and practice. Studies of social resilience, inspired by ecological resilience frameworks, parallel the urgency of addressing climate change and disaster preparedness, despite the challenges of evaluating these concepts amid uncertainty (Munang et al., 2013; O'Brien et al., 2008). With the Sendai Framework (UNISDR, 2015), the UN's Millennium Development Goals, and the Sustainable Development Goals (SDGs), international development efforts emphasize resilience and empowerment of marginalized communities, targeting poverty and inequality as barriers to resilience (Barrett & Constas, 2014; UNISDR, 2015; United Nations, 2000; United Nations, 2015). By applying socio-ecological system frameworks and principles from disturbance ecology, we can enhance our understanding of how to integrate sustainable watershed management with ecosystem function and disaster risk reduction (Renaud et al., 2013).

1.1.1 Key Concepts Underpinning Socio-Ecological and Justice-Centered Analysis

Several foundational concepts inform the approach and analysis presented throughout this dissertation. Clarifying these terms is essential to understanding the research design, case study application, and critical synthesis of best practices for interdisciplinary collaboration in post-disaster settings. **SES** frameworks conceptualize the dynamic, interconnected relationships between human societies and ecological systems. These frameworks emphasize that social and environmental processes are deeply intertwined, and that sustainable management requires an integrated understanding of these interactions (Figure 1-1) (Berkes et al., 2003; Ostrom, 2009).

Local Indigenous Knowledge (LIK) and **Local Ecological Knowledge (LEK)** refer to the place-based knowledge systems developed by communities through generations of interaction with their environment. LIK encompasses culturally embedded understandings and practices rooted in Indigenous worldviews, while LEK focuses more broadly on localized ecological observations and stewardship practices (Berkes, 2018; Huntingdon, 2000; Kimmerer, 2013). Both forms of knowledge are essential for designing adaptive, contextually relevant watershed management strategies. **Explicit Knowledge** refers to knowledge that can be easily articulated, codified, and transmitted through formal communication channels, such as reports, guidelines, and databases. In contrast, **Tacit Knowledge** is rooted in personal experience, intuition, and context-specific understanding, often difficult to fully document or transfer (Nonaka & Takeuchi, 1995; Polanyi, 1966). In inter or transdisciplinary team science, especially in emergent post-disaster contexts, the ability to integrate both explicit and tacit knowledge is critical for effective collaboration, decision-making, and knowledge co-production.

Environmental Justice (EJ) is the principle that all people, regardless of race, ethnicity, income, or national origin, have the right to equal protection and meaningful involvement in the development, implementation, and enforcement of environmental laws, regulations, and policies (Bullard, 2000; Schlosberg, 2007; US EPA, 1998). In this research, EJ considerations frame the analysis of watershed governance and research practices as well as considerations for the implementation of team science in post-disaster settings where considerations for EJ may be more acute due to complex institutional inequities (Fothergill et al., 1999; Peek & Sutton, 2004; Tierney, 2006). **Social Vulnerability** refers to the degree to which individuals and communities are susceptible to harm from hazard events, shaped by factors such as income, education, age, disability, housing conditions, and access to services (Cutter et al., 2003; Flanagan et al., 2011; U.S. Census Bureau, 2023). High levels of social vulnerability can magnify the impacts of natural disasters and hinder recovery processes. **Socio-Ecological Vulnerability (SEV)** refers to the susceptibility of socio-ecological systems to harm from external disturbances, including natural disasters, climate change, and human activities (Adger, 2006; Turner et al., 2003). SEV considers not only the exposure and sensitivity of ecological and human components but also their adaptive capacity, making it a crucial lens for assessing risk and resilience across interconnected systems.

The concepts explored in this section provide the foundation for how justice is embedded throughout the design and analyses of this dissertation. Environmental justice functions both as a normative lens, guiding ethical engagement, indicator selection, and interpretation of SES vulnerability, and as a diagnostic component within the SES WHA framework used in this research to evaluate watershed health and the social, ecological, and institutional factors that shape it. Consistent with international guidance (e.g., IPCC, UNDRR, SDGs), justice considerations are explicitly linked and integrated across the purpose of each of the primary research chapters. Chapter 3 assesses governance legitimacy and equity and also calls attention to the essential value of LIK and LEK in watershed health assessments. Chapter 4 incorporates socially vulnerable indicators in evaluating landslide risk and impact. Chapter 5 examines participatory knowledge and power dynamics within team science practice in a post-disaster setting. Together these applications underscore the rationale for integrating justice and equity as central analytical threads, rather than peripheral themes, linking the conceptual, empirical, and reflective dimensions of this research.

1.1.2 Defining Team Science Through Levels of Disciplinarity

Understanding the distinction between multidisciplinary, interdisciplinary, and transdisciplinary approaches is essential for assessing whether these frameworks accurately set the stage for team science, and, if so, at what corresponding level of integration, given research aims and context. These seemingly interchangeable terms are often defined differently across disciplines, reflecting varying levels of collaboration and integration. Mauser et al (2013) presents the comparison between academic only teams and academic/nonacademic teams. Whereas a blended industry team might conduct “participatory” research or work with multiple partners, it is, in essence, conducted in parallel with low integration across institutions/disciplines (Table 1-1).

TABLE 1-1. Comparative review of definitions for multidisciplinary, interdisciplinary, and transdisciplinary team science approaches, illustrating key distinctions in integration, collaboration, and stakeholder involvement across sources.

Source(s)	Multidisciplinarity	Interdisciplinarity	Transdisciplinarity
Bui et al., 2022	Way of "being together",	Way of "thinking together".	Way of "doing together"
DeHart, 2017; Borrego & Newsander, 2010; Hall et al., 2008; Nash, 2008; Stokels et al., 2008; Cummings et al., 2013	Contributions from researchers from multiple fields; Researchers remain within their fields to complete project tasks.	Research is integrated from multiple disciplines; Encourages the synthesis of methods/approaches.	Moves beyond traditional disciplines with the goal of developing novel conceptual frameworks, methods, languages; Includes stakeholder involvement at all stages of research.
Lotrecchiano & Misra, 2018	Multiple closed systems; Overlapping interests, but little to no integration.	Differing disciplines interact and integrate perspectives, theories or methods.	Integration across teams; Transform and transcend traditional disciplines
Natural Research Council, 2015	Researchers make separate contributions in an additive way.	Researchers integrate from across disciplines in order to advance fundamental understanding or solve a problem.	Researchers integrate and transcend to generate fundamentally new conceptual frameworks, theories, models and applications.
Allegretti et al., 2015; Rosenfield, 1992	Sequential process: Researchers from multiple disciplines work independently and may eventually combine data to solve a problem.	Interactive process where researchers work together to address a research problem/question held in common.	Integrative research where teams develop novel conceptual frameworks, methods, languages beyond a single discipline.; Stakeholder involvement at all stages of research.
Baker, 2015	Team members, separate disciplines, make separate contributions.	Researchers from different disciplines integrate information, data, techniques, tools and understanding.	Team integrates and transcends disciplinary approaches and develops new understandings.

Matsuura & Razak, 2019; Ismail-Zadeh et al., 2017	Each researcher produces knowledge in parallel though contributing to addressing the same problem.	Increased integration found in conceptual framework and findings with the goal of creating new knowledge for common goal.	Working beyond a single discipline to create new solutions for joint implementation.

Conversely, transdisciplinary approaches implemented by a blended industry team tend to be integrative in their application of conceptual models and methodologies. In intra-academic team science environments, Mauser et al (2013) argue that multidisciplinary teams work in parallel with low integration whereas interdisciplinary teams, often comprising members from differing departments and institutions, engage in more integrative collaboration. Beyond defining these terms within the Science of Team Science (SciTS) context, it is equally important for team members, whether leadership, scientists, or external partners, to develop a shared understanding of their collaborative approach. To achieve optimal team functioning and intended scientific outcomes, it is crucial to clearly define the team science orientation at the outset. Whether the approach is multi/inter/transdisciplinary, this articulation informs the team's collaborative strategy, guiding how integration is managed, and expectations are aligned throughout the life of the project and beyond. Chapter 5 explores these concepts and relationships to team science conducted in a post-disaster setting.

1.2 Research Objectives

The overall goal of this research is to demonstrate the value of incorporating a mixed-method, systems-based framework, interdisciplinary team science approach to an analysis of landslide impact, socio-ecological vulnerability, challenges to effective, just watershed governance and management within a hazard prone landscape. In this context, team science refers to collaborative research that integrates theory, methods, and application from multiple disciplines to address complex scientific challenges. Depending on the level of integration (e.g., multi/inter/transdisciplinary), team science can range from loosely coordinated efforts to deeply collaborative, co-produced knowledge practices with partners and communities (Bennett & Gadlin, 2012; Hall et al., 2012; Love et al., 2022; Stokols et al., 2008a).

The case studies presented in chapters 3 and 5 explore and address conceptual and methodological obstacles to scientifically address the socio-ecological challenges exacerbated by the compounding impact of hurricanes Irma and María, as well as pre-existing and ongoing systemic vulnerabilities. Additionally, exploring the characteristics, challenges, and role of team science conducted in a post disaster setting identifies opportunities to redress a research gap within the SciTS literature. Chapter 5 presents a literature review synthesis, exploration of best practices in a post-disaster setting through the lens of a case study of the RGA watershed in western PR (e.g., applicable aspects of the author's research experience) intended to highlight the value and difficulty of implementing team science in such a setting thereby contributing to emergent disaster science research. The analysis in Chapter 4 fills a data and analysis gap by providing a multi-scale (e.g., watershed, municipality (county scale), barrio (neighborhood scale)) landslide impact and vulnerability assessment in the RGA watershed. Additionally, the mixed methods geospatial analysis incorporates social vulnerability as well as the relationship with the built environment, moving beyond a quantitative assessment limited to the evaluation of the physical landscape.

1.3 Dissertation Organization

This dissertation is organized into six chapters, each building upon the preceding sections to advance an integrated analysis of watershed management, socio-ecological vulnerability, and post-disaster team science best practices.

- **Chapter 1** introduces the research problem, objectives, and key concepts that frame the study. It outlines the interconnected challenges of climate change, disaster risk, and socio-ecological degradation in Puerto Rico, emphasizing the need for interdisciplinary, justice-centered approaches to watershed governance and disaster resilience.

- **Chapter 2** provides an overview of the Río Grande de Añasco watershed, the study site for this research. It describes the watershed's climate, topography, geology, hydrology, ecological landscape, social dynamics, and land use and land cover characteristics, establishing the environmental and social context for the analyses that follow.
- **Chapter 3** presents the development and application of a socio-ecological systems watershed health assessment framework to support risk-informed, community-centered watershed management. This chapter explores how integrating socio-ecological principles can strengthen strategies for addressing water management and disaster risks in hazard-prone landscapes.
- **Chapter 4** applies a mixed-methods geospatial analysis to assess landslide impacts and socio-ecological vulnerabilities within the Río Grande de Añasco watershed. It evaluates how physical exposure, social vulnerability, and infrastructure conditions interact to shape risk, offering a holistic approach to landscape-scale vulnerability assessment.
- **Chapter 5** synthesizes best practices for team science across disciplines, evolves these practices to incorporate justice and equity considerations, and critically assesses their application in post-disaster research contexts. This chapter draws lessons from a transdisciplinary case study conducted in Puerto Rico following Hurricanes Irma and Maria.
- **Chapter 6** discusses the broader implications of the findings across the three research threads, highlighting contributions to watershed governance, vulnerability assessment, and the evolving Science of Team Science. It identifies areas for future research and application, particularly at the intersection of socio-ecological systems analysis and justice-centered disaster research.

- **Appendices** provide supplementary materials, including additional data tables, methodological details, and supporting documentation relevant to dissertation analyses and case study reflections.

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CHAPTER 2 - STUDY SITE

2.1 Overview

The Río Grande de Añasco (RGA) Watershed is ranked fifth on the list of impaired watersheds within the United States and Territories (USDA NRCS, n.d.b). This 414 km² watershed, characterized by highly variable terrain, is located on the western side of the island of Puerto Rico and is one of the five largest hydrologically defined basins on the island. It encompasses portions of the municipalities (e.g., equivalent to counties) of Rincón, Añasco, Mayagüez, Las Marías, San Sebastián, Lares, Adjuntas, Yauco, and Maricao (Figure 2-1).

The watershed boundary used in this study provides a standardized topographic definition commonly applied in watershed-scale assessments across the United States. However, other hydrologic studies and planning efforts define a broader drainage area for the RGA, ranging from 469 to over 500 km², to account for additional headwater tributaries (e.g., Río Guayo, Río Yahuecas, Río Prieto) and engineered diversions originating in the Cordillera Central uplands, primarily to the south and east of the HUC-12 boundary (AFI & Instituto de Recursos de Agua del RUM, n.d.; Picón-Ruíz et al., 2018). These broader definitions, while not reflected in national geospatial datasets, have been applied in sediment transport studies, runoff modeling, and infrastructure planning.

The RGA watershed drains a diverse mosaic of upland terrain from the western edge of the Cordillera Central (e.g., Monte Guilarte) through foothills and agricultural valleys to the coastal lowlands at Mayagüez Bay (Figure 2-2). Land use and land cover patterns across the watershed include a mix of agricultural activity, extensive forest cover, and growing urban areas, particularly in and around Mayagüez, the largest city within the watershed, with a population of approximately 70,000 people (US Census Bureau, 2023).

The Coastal Zone, which stretches from Mayagüez Bay up through a portion of the Mayagüez and Añasco municipalities, is dominated by agricultural production (e.g. crops/pasture/hay), urban, and wetland (Palustrine and Estuarian) land use/land cover (Figure 2-3; Figure 2-5). Flooding drives change on varying temporal and spatial scales to wetland dynamics including facilitation of deposition of sediment from upland regions and inundation of wetlands influencing biochemical processes. Deposition in this coastal region can lead to changes in coastline shape and interact with coastal erosion processes. It also impacts coastal ecosystems such as coral reefs. Anthropogenic change influences feedback loops between flooding (coastal, urban, and river), sedimentation from upland sources, and landscape change (e.g. farming activities, informal road construction, unplanned conversion from forest to housing).

The Transition Zone (e.g., Coastal to Valley to Mountain) extends into the municipalities of Las Marías and the lower elevations of San Sebastián along the Río Añasco (Figure 2-3). Land use/land cover is dominated by agricultural production and forested land. Flooding along the main channel can lead to deposition on croplands. It contributes to channel morphology. Valley channel beds are dominated by sandy soils over underlying limestone beds and are prone to shifting. In stream and edge of channel vegetation acts to stabilize. Alluvium deposited by floods contributes to sandy stream beds, high suspended clay sediments in stream, and high frequency of deposition on banks, in stream island development, and on cropland.

The Mountain Zone drains the Central Mountains and is dominated by forests, rural development, and coffee and banana/plantain plantations (Figure 2-3). Examining dynamics in the upper reaches of the watershed reveals locations of localized flooding and a higher density of slope failures, particularly in Maricao, as well as increases in sedimentation into tributaries leading to a compounding effect on lower reaches of the Río Añasco (See Chapter 4). This zone is also characterized by narrow, steep valleys, throughout the regions of Adjuntas, Maricao, and Lares. These serve to increase rates of flow of both excess runoff, formation of rills and gullies and, in extreme cases, significant detachment of slopes (landslides). During the rainy season, subsurface flow, saturated soils, and excess overland flow exacerbates the impact of flooding in mountain communities and in the valley as the upland drains to the bay. Flash flooding and landslides (primarily along roads and on/near cropland) are common to this zone.

2.2 Climate

Historically, the island experiences a dominant wet (May–October) and dry season (January–April), along with moderately high temperatures and humidity (Gould et al., 2017). The majority of the watershed experiences a subtropical climate with increasingly humid higher elevations. Annual precipitation varies widely across Puerto Rico from approximately 5,000 mm/year in El Yunque (northeast) to around 1,000 mm/year in Ponce (southwest) (Runkle et al., 2022). In comparison, the RGA watershed receives roughly 1,750 mm/year in the lowlands and up to 2,500 mm in the mountains (Ramos-Scharrón et al., 2014). About 70% of annual rainfall occurs during the May–October wet season (USGS, 1985), roughly 1,225–1,750 mm across the basin's elevations.

Hurricane María produced intense rainfall in Puerto Rico's mountainous areas, with at least 250 mm falling within 48 hours. Hurricane Irma, occurring just weeks prior, dropped an additional 250–380 mm (10–15 in) in parts of Puerto Rico (Hernández Ayala & Méndez Tejeda, 2023). Localized accumulations surpassed 1,029 mm in the southeast (Bessette-Kirton et al., 2019; Keellings & Hernández Ayala, 2019). The storm is recognized as the highest-rainfall tropical event since 1956, with return periods rising nearly 50%, a trend Keellings & Hernández Ayala (2019) link to climate change. Although precipitation gauges within the RGA watershed do not have complete records for 2017, regional observations from NOAA and USGS reports indicate that Hurricane María delivered between 600 and 965 mm (24–38 in) of rainfall over 48 hours across the island, with the heaviest totals concentrated in mountainous interior and western regions (USGS, 2018; Ramos-Scharrón et al., 2021). Simulated rainfall during Hurricane María peaked at 762 mm across the island, with observed maxima exceeding 965 mm. Modeled results show enhanced rainfall intensity of over 640 mm across the central and northwestern interior during multiple 6-hour windows (Pokhrel et al., 2021). These figures, which align with rainfall-enhancing orographic uplift in Puerto Rico's mountainous interior, suggest that watersheds such as the RGA likely received over 700 mm of rainfall during the event.

According to regional climate models, island-wide climatic shifts are predicted to affect the seasonality of precipitation and temperature, increase the magnitude, frequency, and unpredictability of slow-moving, larger storms alongside extended droughts, resulting in an increase of the probability of greater incidences of slope failure (Hayhoe 2013; Hughes & Schulz, 2020; Harmsen et al., 2009; Jennings et al., 2014; Keelings & Hernández Ayala José, 2019; Knutson et al., 2010; NOAA, 2024; Ramos-Scharrón et al., 2021). Recent trend analyses using station and gridded datasets reveal that summer precipitation across Puerto Rico, particularly in northwestern and western regions, has decreased by more than 20% since the mid-20th century (e.g., 1955–2021) (Hernández Ayala & Méndez Tejeda, 2023). This drying trend is especially pronounced during early wet season and dry season months, although late wet season precipitation has shown relative stability or slight increases in some regions, underscoring evolving seasonal dynamics. Within the lower valley, at Mayagüez Airport, NOAA 1991–2020 climate normals report an annual precipitation of 1,742 mm/year (68.6 in), with approximately 70% (~1,220 mm) falling during the May–October wet season (NOAA NCEI, 2021).

2.3 Ecological Landscape

2.3.1 Hydrology

The Añasco River, with headwaters in Lares, meanders through the Añasco valley and empties into the Bahai de Añasco, serves as the main channel of the watershed that includes nine municipalities, in total or in part (Rincón, Añasco, Mayagüez, Las Marías, San Sebastián, Maricao, Lares, Yauco, Adjuntas). The perennial Añasco River is fed by 13 main tributaries, identified through a systematic streamflow analysis of the watershed (Raul Diaz & Jordan, 1987). These tributaries range from primarily intermittent in the mountains to perennial in the lowlands (Picón Ruíz et al., 2018; Raul Diaz & Jordan, 1987) (Figure 2-4).

Pollutants resulting from runoff and release of chemicals used in agriculture production (fertilizers, pesticides, and manure) and sedimentation (e.g., suspended sediments, nitrogen, phosphorous) from erosion and mass wasting events in addition to saltwater encroachment affect water quality throughout the watershed, including local ecosystems, fisheries, and coral reef health in Mayagüez Bay (Corvera-Gomringer, 2005; Duque & Melesse, 2016; Gilbes et al., 1996; Ramos-Scharrón et al., 2014; Rodríguez-Guzmán & Gilbes-Santaella, 2009; Sotomayor-Ramirez et al., 2004). This impact is punctuated during extreme events (Gilbes et al., 2001).

Excessive streamflow influences longitudinal changes to upstream and downstream channel width, depth, and carrying capacity (flow, sedimentation, debris/wood in streams). For example, floodwaters triggered by rainfall brought with Hurricane María led to significant shifts in channel width, depth, and course of river. Excess overland flow in this region drains quickly, due in part to active landslides, resulting in exposed soils, and slope gradient changes.

The Río Grande de Añasco experiences frequent flooding and excess runoff, often resulting in sediment deposition on croplands and significant alterations to channel morphology, including scouring, bank erosion, changes in bed composition, and shifts in channel gradient (Díaz & Jordan, 1987; Duque & Melesse, 2016; Gould et al., 2017). Excessive streamflow influences longitudinal changes to channel width, depth, and hydraulic capacity. For example, rainfall from Hurricane María in 2017 generated peak streamflows across western Puerto Rico well above typical flood stages. Based on USGS estimates, peak flows in the RGA watershed during María likely exceeded 5,900–6,300 m^3/s, surpassing bankfull discharge by an order of magnitude. Such extreme events significantly alter channel width, depth, and alignment, compounded by overland flow contributions from active landslides, exposed soils, and slope instability in the uplands (USGS, 2022)."

Prior to Hurricanes Irma and María, average annual runoff rates for the Río Grande de Añasco watershed were approximately 1,100 mm, which is comparable to runoff contributions from the neighboring Río Culebrinas and Río Guajataca watersheds (Larsen & Webb, 2009; Ramos-Scharrón et al., 2014). Excess runoff contributing to collection system failure, insufficient municipal infrastructure (e.g., stormwater sewers, wastewater systems, damaged roadways etc.), along with point and nonpoint sources of pollution (e.g., agriculture, clear cut clearing, informal road development, destabilized slopes, mass wasting, industrial production, animal feeding operations, landfills) remain significant problems across the watershed (Puerto Rico Department of Natural and Environmental Resources, 2023).

2.3.2 Geology & Soils Formation

The watershed spans a highly diverse set of lithologies, from volcanic and intrusive igneous rocks (e.g., Andesites, Diorites, Basalts) dating back to the early Tertiary and Cretaceous Age to sedimentary formations (e.g., Aguada Limestone, Alluvium, Beach Deposits) (Díaz & Jordan, 1987). This variation underpins the spatial variability in soil texture, mineral content, permeability, and erodibility observed across the basin. Additionally, the presence of hydrothermally altered rock, quartz-diorite, and rhyodacitic units indicates tectonic complexity and zones of potential weakness. These formations can be highly fractured and weather rapidly, increasing the likelihood of slope failure under intense rainfall. Geologic units like the Maricao, Yauco, and Andón Formations, often interbedded, dominate in the mountainous eastern and central zones. These rocks weather into clay-rich, fine-grained soils that are highly prone to landslides and surface erosion, especially when vegetation is removed or slopes are disturbed (Chapter 4).

Alluvium and beach deposits in the western lowlands contribute to more fertile but flood-prone soils, often found in agricultural areas. These unconsolidated materials are easily mobilized during flood events, contributing to downstream sedimentation. For example, the Añasco valley is comprised of limestone, clay and Quaternary alluvium that stretches to the coastal depositional sandy soils (Díaz & Jordan, 1987; Rodríguez González, 2004). Within the Coastal zone, the primary geologic material is alluvium. On larger temporal scales deposition and inundation from flooding along with coastal erosion processes has led to formation of wetlands. Land use practices have acted on these natural processes and landscape changes as well. In upland regions, slow-weathering igneous rocks may generate thinner, poorly developed soils. In contrast, limestones and volcaniclastic rocks weather more quickly, forming deeper soils, but often clay-rich and prone to shrink-swell behavior or saturation. An analysis of soils using the NRCS Web Soils Survey database and supported by Ramos-Scharrón et al. (2014) revealed that clayey and clayey-loam textures dominate across 80 soil types found within the RGA (Figure 2-6).

Understanding soils distribution and formation in the RGA is essential for assessing their role in slope stability, sedimentation rates, runoff processes, ecosystem formation and response to disturbances, and hazard mitigation. According to Ramos-Scharrón et al. (2014), the majority (85%) are classified as high runoff potential clayey soils, contributing 88% of the sediment to the system. Moderately high runoff potential soils cover 13% of the area and contribute 12% of sediment yields.

The overall pattern reveals a distinct soil zonation that corresponds closely with elevation zones and geologic formations, from steep uplands in the southeast to flatter coastal plains in the northwest. Soil units like MfF2 (Mayagüez clay), MuF2 (Mucarabones series), and MkF (Maricao clay) dominate the upland and mountainous soils in the east and central regions of the watershed. These soils tend to form on volcaniclastic or igneous bedrock, often steeply sloped, shallow, and moderately to severely eroded. Their clayey texture and slope position make them highly prone to landslides, especially where vegetation is disturbed or roads are cut into slopes.

A mosaic of soil units, including LoF (Los Guineos clay loam), EdJ (Edison clay), and combinations of Guayabo and Humatas series dominate the majority of the Transition Zone. This area reflects variable topography with interbedded geologic formations, leading to soils that vary in depth, texture, and drainage. Many of these soils are moderately well-drained but are still vulnerable to saturation and overland flow under heavy rainfall. Units like AnF2 (Añasco series), AoF2, and CfF2 are more common, with some areas showing alluvial soils and flatter topography across the Coastal and lower reaches of the watershed, particularly in the West. These soils tend to be deeper, with higher fertility, but may have variable drainage due to fine texture and low slope. Coastal floodplain soils often support agriculture, but are susceptible to flooding, compaction, and sedimentation.

2.3.3 Land Use / Land Cover

Since the 1970s, the watershed experienced significant land cover/use conversation, primarily agriculture to urban (Gould et al., 2017). The largest percentage of land committed to agriculture is found in small scale lower valley farms supported root vegetable crops. Many farmers altered crops following María due to the impact of meters of sediment deposition from midland and upland landslides as well as loss of land due to floodwaters and slope failure. Agriculture and forests dominate land use and human activities (Picón-Ruíz et al., 2018) (Figure 2-7). Mountain agriculture primarily supports plantain and coffee crops. Larger scale mechanized lowland agriculture supports root and plantain crops (Figure 2-7).

The vast majority of the watershed, particularly in the central and eastern mountain zones, is classified as forest (dark green). These forested areas are critical for slope stability, infiltration, and erosion control, buffering the watershed against flash floods and landslides. Cultivated crops and pasture/grasslands (yellow and light green) are heavily concentrated in valley bottoms and transitional slopes, particularly in the mid-to-lower watershed. These areas coincide with moderate to high landslide risk zones and likely contribute to sediment loading due to limited ground cover and root structure (Chapter 4). Around Añasco and Mayagüez, there is a mosaic of developed land, impervious surfaces, and wetlands, indicating the urban footprint is expanding near the floodplain and estuarine zones. This development raises concerns about stormwater runoff, pollution loading, and loss of flood-buffering ecosystems like wetlands (US

EPA, 1993; US EPA, 1997; Wengrove & Ballestero, 2012;). The riparian buffer along the Río Añasco appears discontinuous in some agricultural and urbanized areas. Fragmentation of riparian zones limits their ability to filter runoff, retain sediments, and moderate streambank erosion (Dosskey et al., 2010; Wenger, 1999). The distribution of land use reflects historical settlement and economic patterns but also points to opportunities for strategic intervention including riparian restoration, agroforestry adoption in slope-sensitive areas, and urban green infrastructure in flood-prone zones (Khodadad et al., 2023; Puerto Rico Department of Natural and Environmental Resources & U.S. Forest Service, 2016).

2.4 Social Landscape

The Taíno, Puerto Rico's Indigenous people, historically inhabited regions overlapping the present-day RGA watershed, leaving enduring cultural and ecological imprints (Díaz Bassat, 2010; Tió & Nazario de Figueroa, 1968). The river now known as the Río Grande de Añasco was referred to as *Guaorabo* by the Taíno, underscoring its significance as both a cultural corridor and a geographic landmark central to pre-Columbian settlement patterns (Díaz Bassat, 2010; Tió & Nazario de Figueroa, 1968). Archaeological surveys of the lower RGA valley and adjacent western regions document long-standing human-environment interactions, including the development of complex agricultural systems and ceremonial landscapes shaped by the river and its floodplains (Díaz Bassat, 2010).

Though major Taíno ceremonial centers like the Caguana Ball Courts Site lie outside the watershed, they contextualize the broader sociocultural networks into which the Río Guaorabo was integrated (Barnes, 1993; ORIAS, n.d.). Notably, historical records indicate that in 1511, Cacique Urayoán, whose chiefdom encompassed the Guaorabo River valley, orchestrated the drowning of Spanish conquistador Diego Salcedo in the river, an act that catalyzed the island-wide Taíno rebellion against colonization (Tió & Nazario de Figueroa, 1968). Today, many Taíno descendants and cultural advocacy groups in western Puerto Rico actively engage in cultural revitalization, focusing on language preservation, agricultural traditions, and oral histories that maintain living ties to ancestral landscapes like the RGA basin (Díaz Bassat, 2010; UC Berkely, 2025). Public-facing initiatives, including cultural tourism efforts, further highlight the watershed's historical significance in promoting broader awareness of Taíno heritage (Discover Puerto Rico, n.d.; Puerto Rico Herald, 2005).

Beyond the Indigenous historical context, the social history of the RGA watershed also reflects layered legacies of forced labor and freedom-seeking movements. As Fernández-Sacco (2018; 2023) documents, enslaved Indigenous and African peoples shaped the agricultural and social landscape of communities, including Barrio Cerro Gordo, Añasco and Mayagüez. For example, under Spanish colonial rule, coartación, the purchase of one's own freedom, emerged as a critical pathway to autonomy in the nineteenth century, granting legal personhood, Spanish colonial citizenship, and other civil rights that redefined their social and political standing (Fernández-Sacco, 2023). 19th Century historical accounts find that while coffee was the dominant crop in the uplands of Western Puerto Rico, communities in and around Añasco also engaged in sugar, tobacco, and subsistence cultivations (e.g., plantains, yuca, beans, corn) (Dietz, 1989; Picó, 2006; Scarano, 1993). These agricultural systems contributed to dispersed rural settlement patterns that, in many cases, continue to characterize the region (Clark, 1930; García-Colón, 2009).

Migration historically shaped Puerto Rico's demographic trajectory, both within the island and to the continental United States. During the mid-twentieth century ~400,000 Puerto Ricans emigrated during the 1950s alone, described as one of the largest population exoduses of the era (Di Núbila, 1997). In the 12 months following hurricanes Irma and María, an estimated 114,000 – 213,000 residents left (Meléndez & Hinojosa, 2017) with more than 135,000 within the first six months (Center for Puerto Rican Studies, 2018) and ~300,000 over 2017 – 2021 (Ruggles et al., 2023; US Census Bureau, 2020). These historical and disaster-driven movements provide essential context for understanding contemporary demographic changes within the RGA.

Contemporary change within the RGA includes significant shifts in population distribution as well as demographics. Between 2014 and 2022, the overall total population of the watershed has decreased by 6% (approximately 15,000) (CDC/ATSDR, 2022$_{a,b}$). Across the watershed the distribution of the estimated total population per census tract has shifted between 2014 and 2022, with noticeable patterns between municipalities primarily located in the upland and lowland regions (Figure 2-8). Namely, the lowland areas of the watershed are consistently more densely populated over time. Within the Transition Zone, barrios (e.g., neighborhood) in eastern Añasco and in the center of Las Marías population density has increased.

Conversely, barrios in Rincón have experienced a decrease in population during the same period. According to the U.S. Census Bureau data (2023), Mayagüez currently hosts an estimated population of 69,798, a 4.5% decrease since April 2020 and a ~29% decrease from 2016. Across the RGA, approximately 50% of the total population (~126,000) live in poverty, and more than 55% live in poverty in Adjuntas, Lares, Las Marías, San Sebastián, and Yauco (CDC/ATSDR, 2018). The lowest estimated percent of the population below poverty level (~15%), based on population estimates from 2014-2018, is found in Mayagüez.

This metric is used to assess the level of economic hardship. As of the 2022 US Census Data, approximately 66% of the population were found to be at/below 150% of the poverty estimate (CDC/ATSDR, 2022$_{b}$) (Figure 2-9). The data presented in Figure 2-9 are derived from a comparison to the federal poverty guideline for a given household size. If it is less than 1.5 times that among, then they are considered below 150% poverty (CDC/ATSDR, 2022$_b$). Additionally, the multiple layered impacts and devastation of hurricanes Irma and María, the earthquakes of 2019-2020, Hurricane Fiona, and the COVID pandemic, contributed to other shifts in demographics across the watershed. For example, by 2022, 20-30% of the population were aged 65 and older across more than 75% of the watershed (US Census Bureau, 2023) (Figure 2-10).

A dramatic increase in the percent aged 65 and older is also visible by a comparison of data from the 2010 - 2014 ACS and the 2018 – 2022 ACS. These dynamic demographics representing social characteristics of the watershed add greatly to the complexity inherent to studying and applying holistic, sustained solutions to effective, just, collaborative management of a socio-ecological landscape frequently experiencing external and internal systemic stressors. Upland, rural municipalities such as Adjuntas, Lares, Maricao, and San Sebastián exhibit consistently high social vulnerability rankings across all census years, reflecting persistent economic hardship, geographic isolation, and infrastructure limitations (CDC/ATSDR, 2018; Tyson, et al., 2023). These vulnerabilities are compounded by reliance on informal transportation networks, aging infrastructure, and steep, landslide-prone terrain, particularly in high-elevation farming communities.

Recent assessments have highlighted the intersection of social vulnerability and landslide susceptibility across rural, mountainous regions of Puerto Rico, including areas within the RGA watershed (Bessette-Kirton et al., 2021; Noble et al., 2022; West et al., 2023). For example, a preliminary public health report identified that approximately one-third of Puerto Rico’s population resides in zones classified as high to extreme landslide susceptibility, with heightened vulnerability among older adults, individuals with disabilities, and residents in geographically isolated communities (West et al., 2023). These findings underscore well-established concerns for socio-ecological health impacted by compounded disaster risks in western Puerto Rico (Bessette-Kirton et al., 2019; Garriga-López, 2020; Hain et al., 2023; Kinol & Kuhl, 2023; Puerto Rico Climate Change Council, 2022; Rivera et al., 2024; Rodríguez-Díaz, 2018; Stablein et al., 2022; West et al, 2023). However, such studies have yet to integrate socio-ecological systems-level assessments specific to the RGA watershed. The research presented here builds upon this foundational work by spatially coupling social vulnerability with ecological risk factors (e.g., slope instability, land use practices, and road network exposure) at a resolution and scale necessary to inform localized hazard mitigation and resilience strategies. These social, cultural, and demographic complexities underscore the critical importance of integrating place-based, interdisciplinary knowledge in addressing watershed governance, disaster resilience, and long-term socio-ecological sustainability in the RGA watershed.

2.5 Tables and Figures

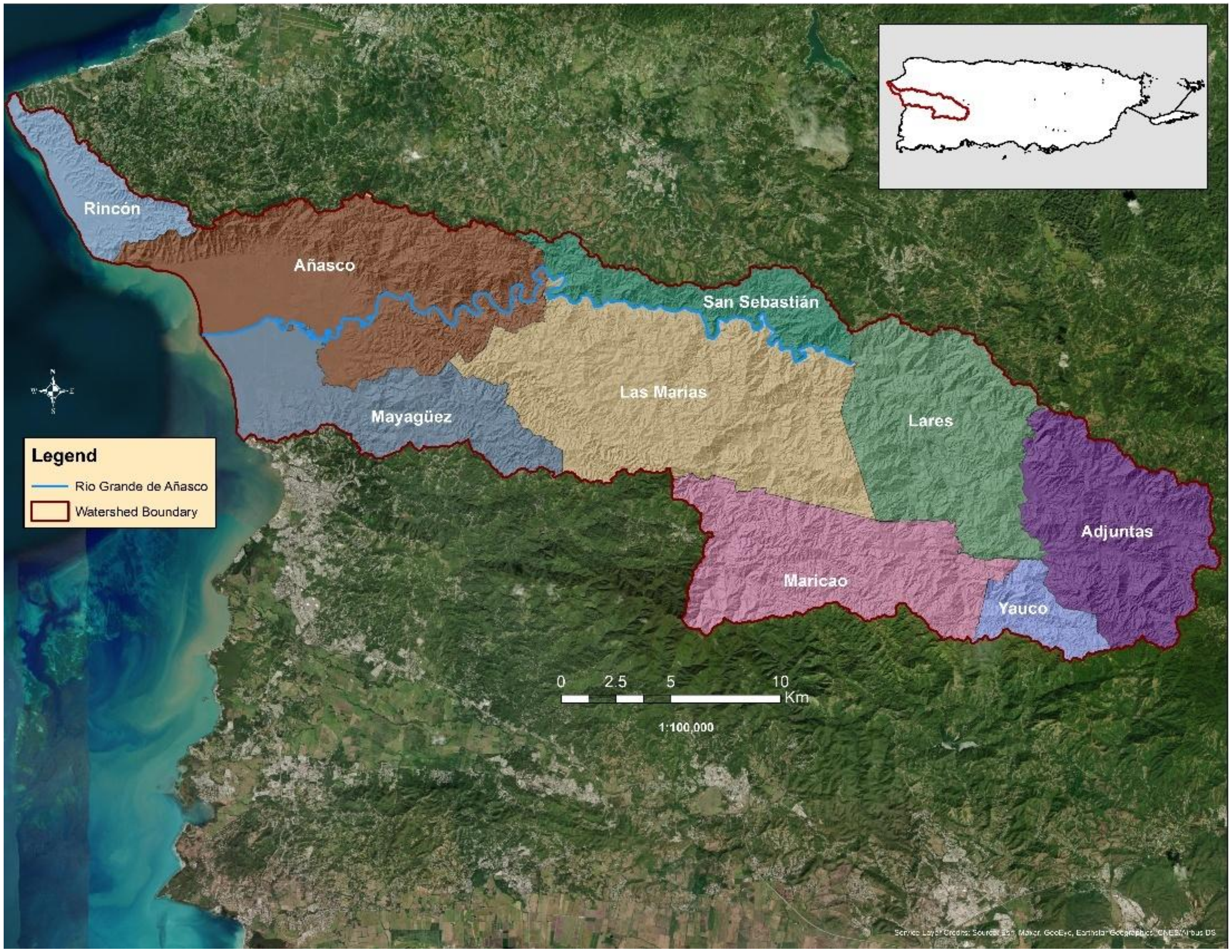


FIGURE 2-1. Reference map showing relative location of the RGA Watershed on the island with municipalities identified. Extent of the RGA watershed delineated using the U.S. Geological Survey (USGS) Hydrologic Unit Code (HUC-12) boundary from the National Hydrography Dataset (NHD).

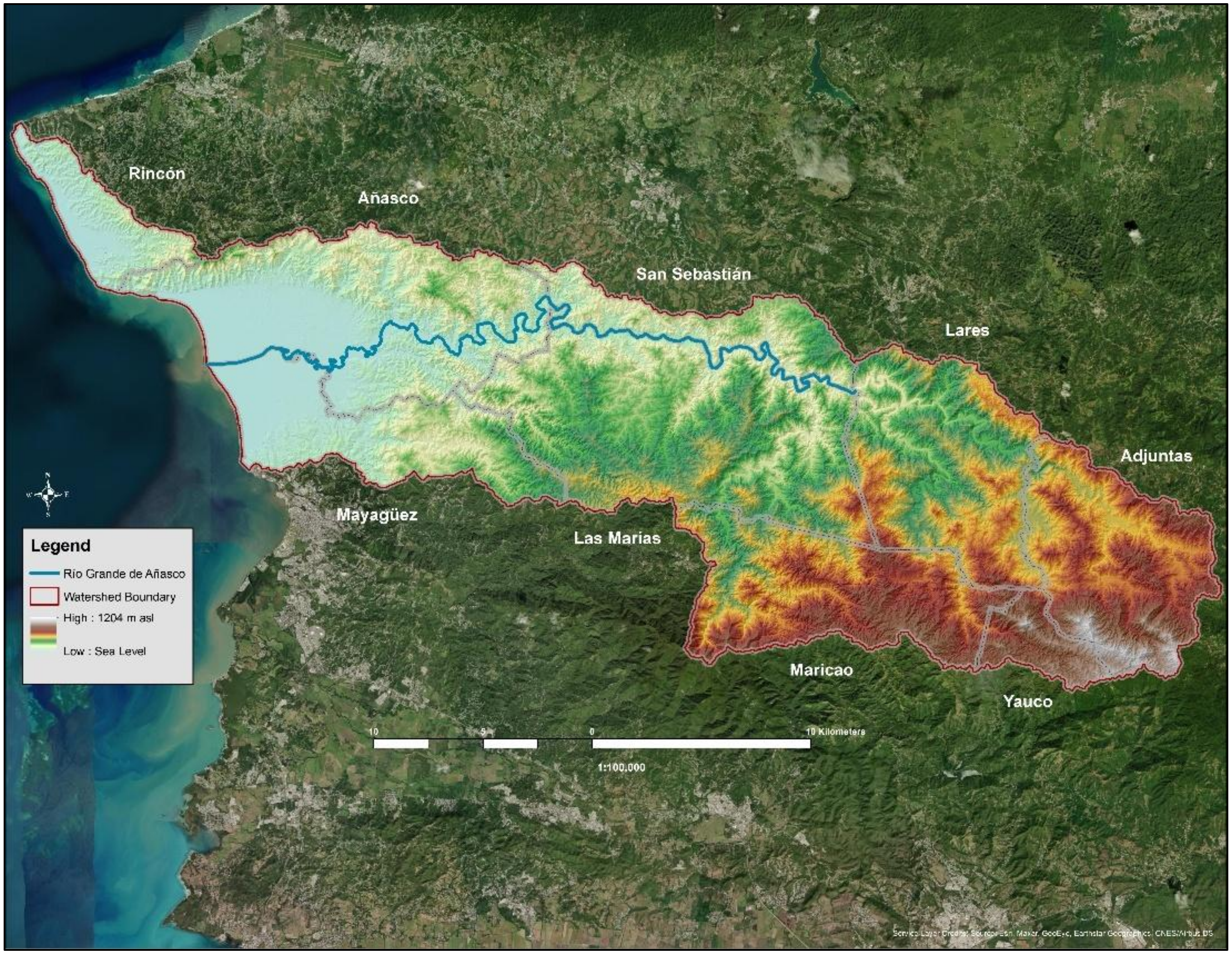


FIGURE 2-2. Elevation map of the RGA Watershed.

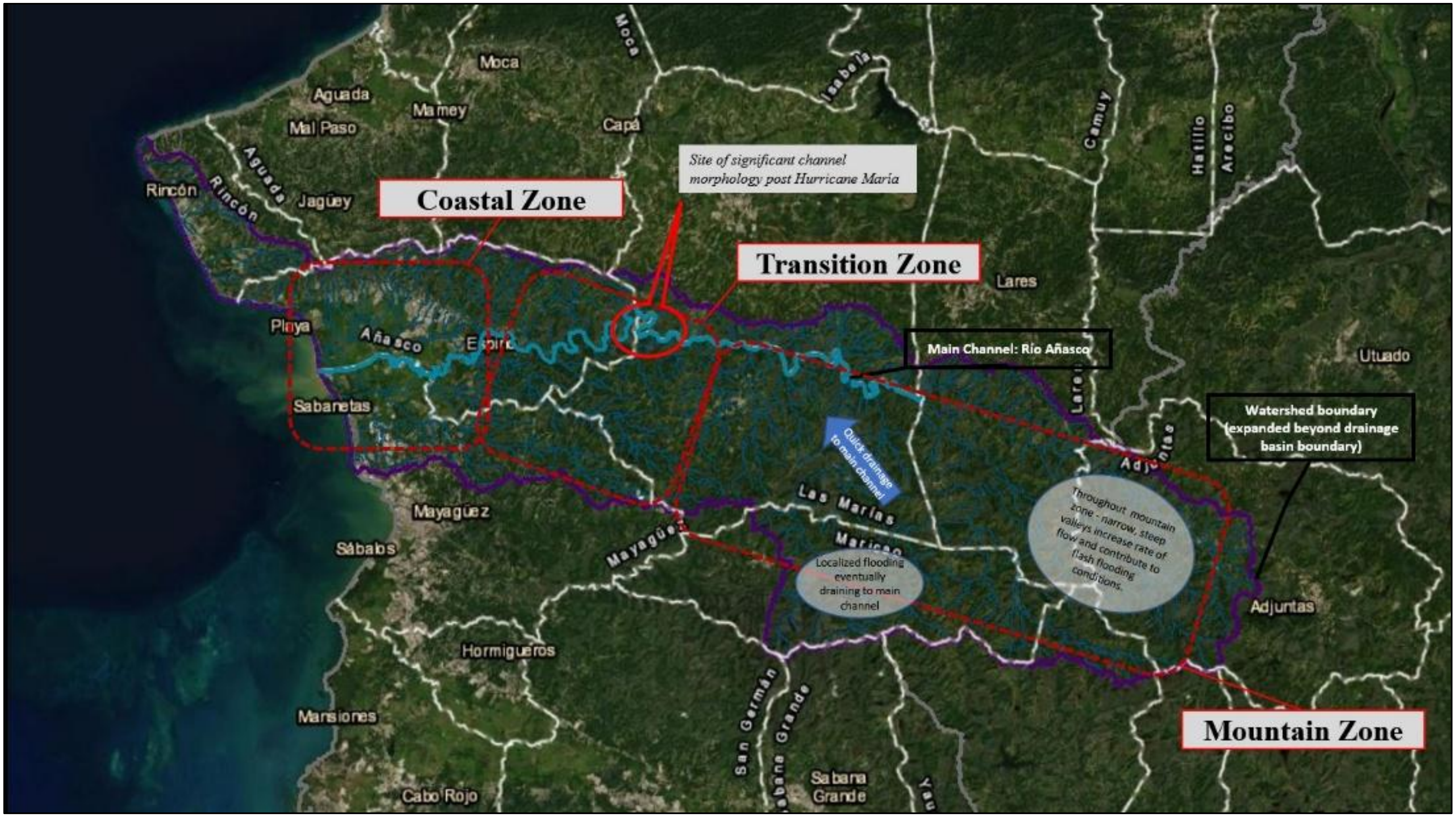


FIGURE 2-3. Diagram of primary ecological zones within the RGA watershed.

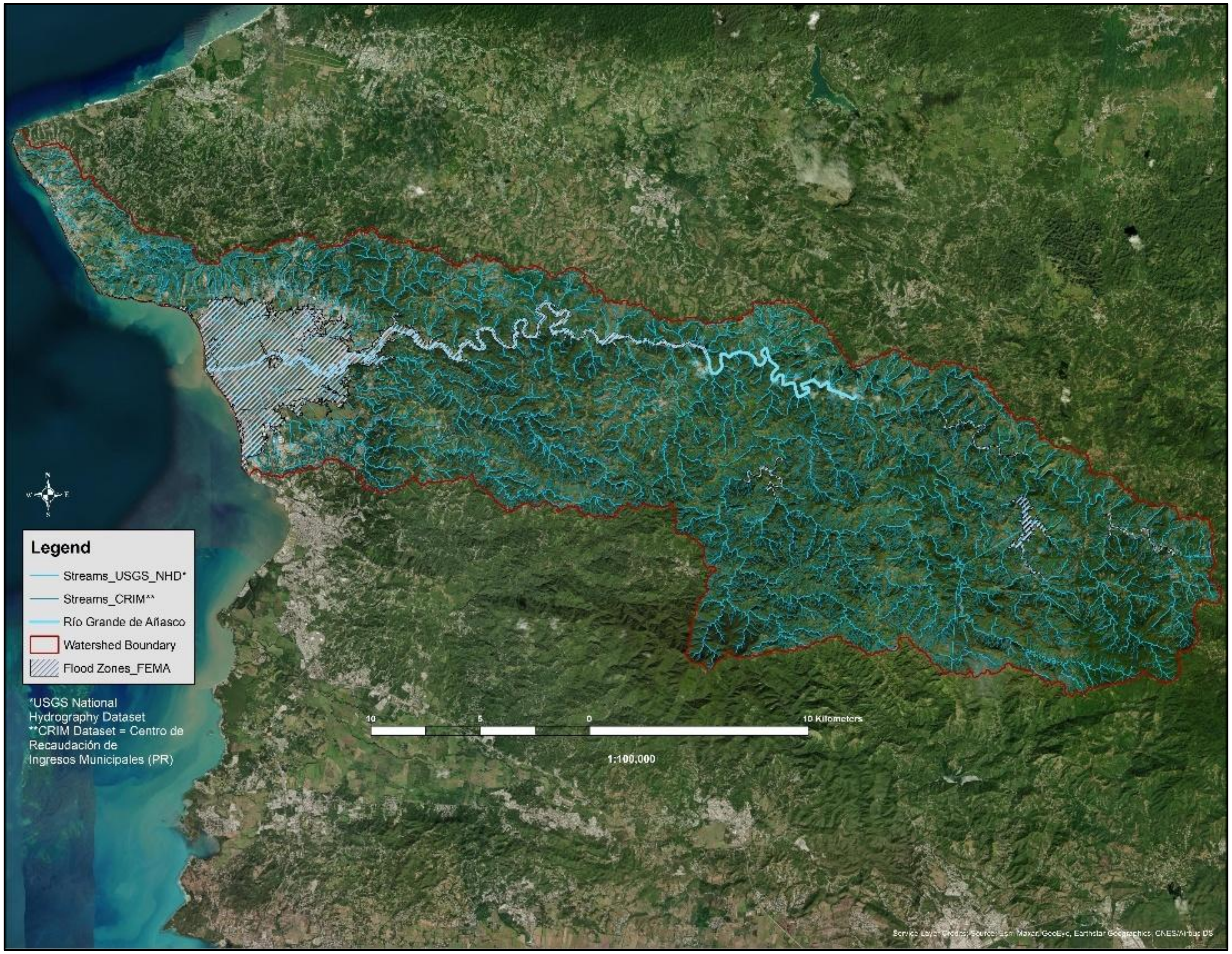


FIGURE 2-4. Hydrography of the RGA Watershed with FEMA defined flood zones identified.

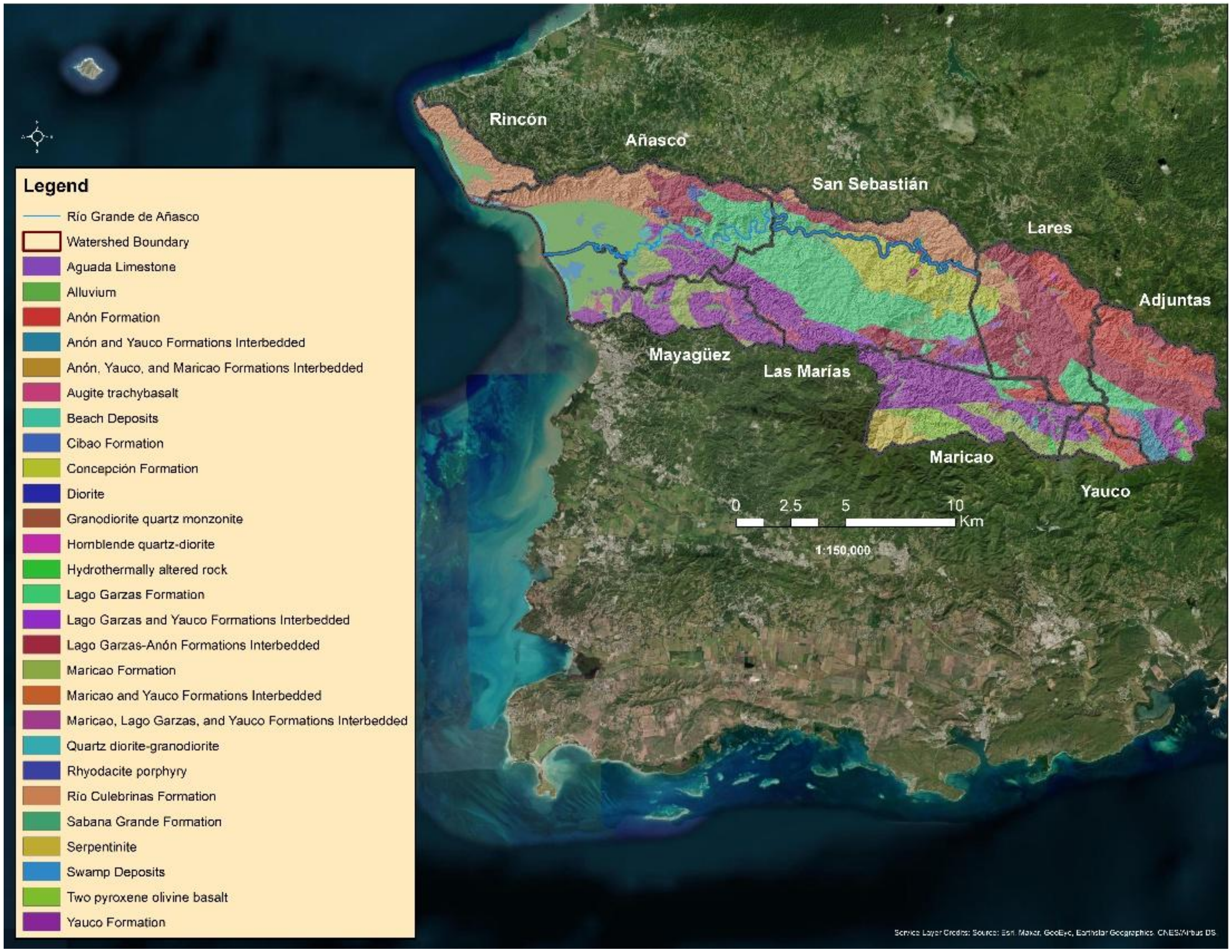
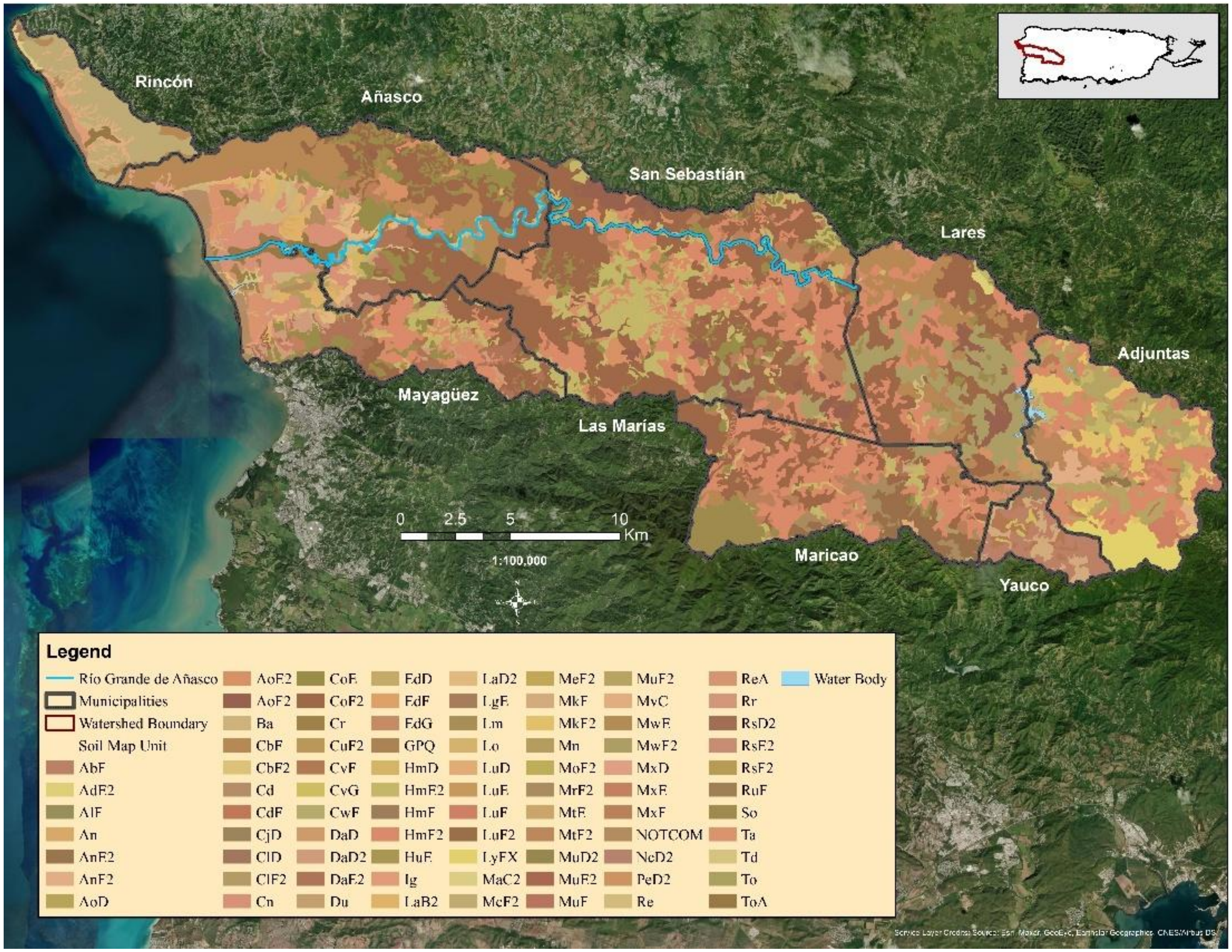


FIGURE 2-5. Geology of the RGA Watershed.



Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS

FIGURE 2-6. Distribution of soil types across the RGA Watershed (as designation by NRCS Web Soil Survey) revealing a high density of unique soil units, reflecting the complex geology and topography of the watershed.

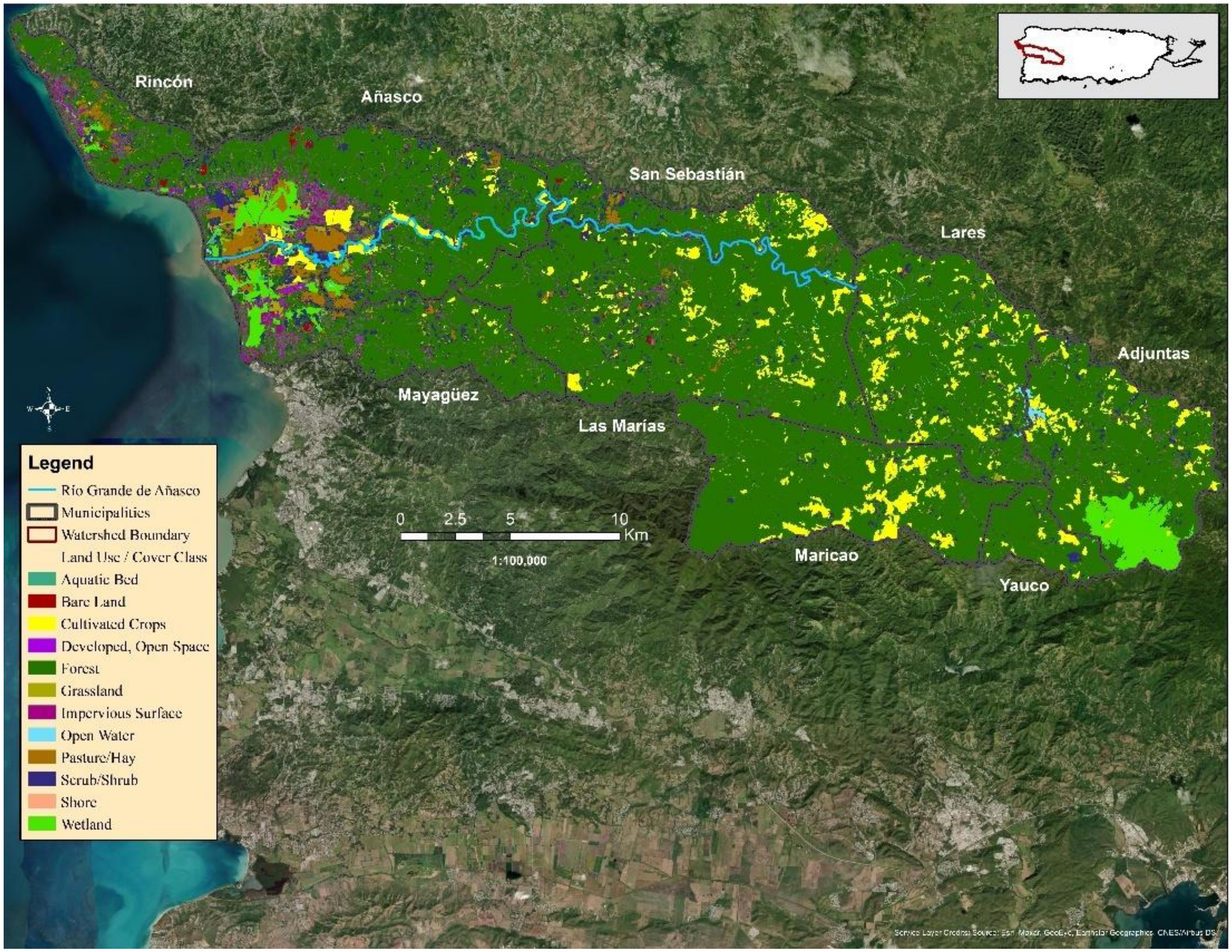


FIGURE 2-7. Distribution of land use/land cover across the RGA Watershed.

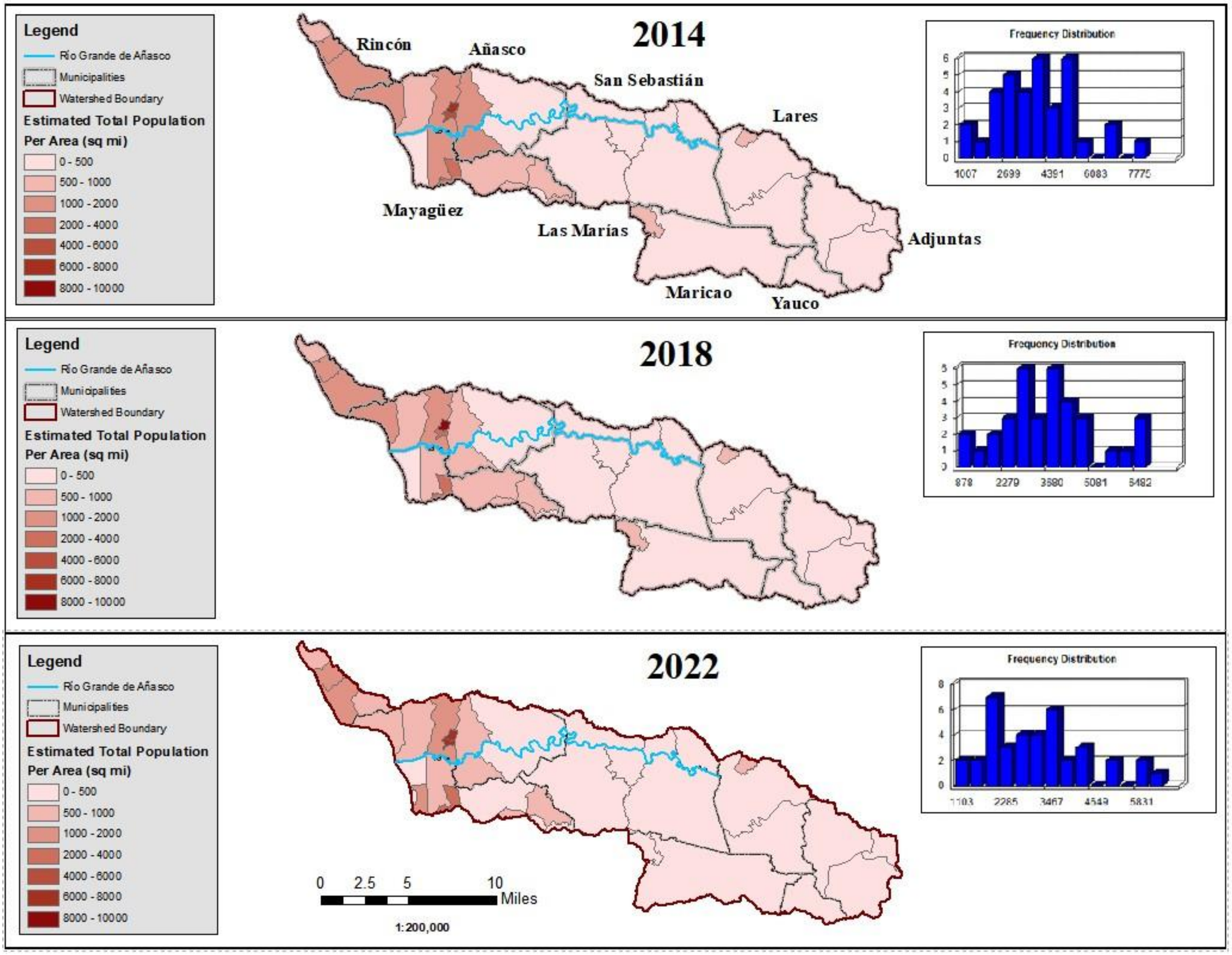


FIGURE 2-8. Distribution of estimated total population (per census tract) across the RGA across three 4-year increments (2014, 2018, 2022).

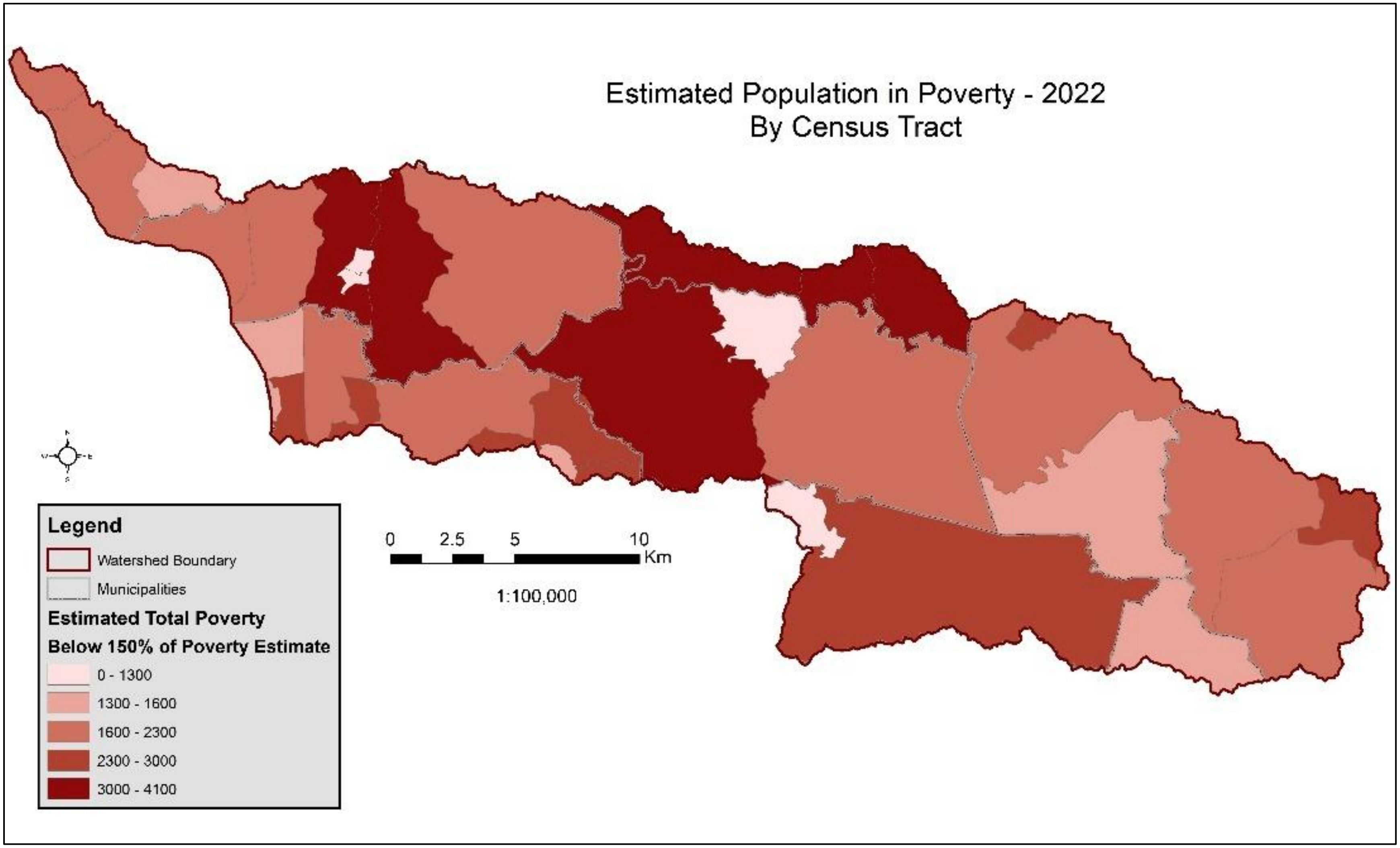


FIGURE 2-9. Distribution of total population in poverty (estimated at below 150% of poverty estimate) for 2022.

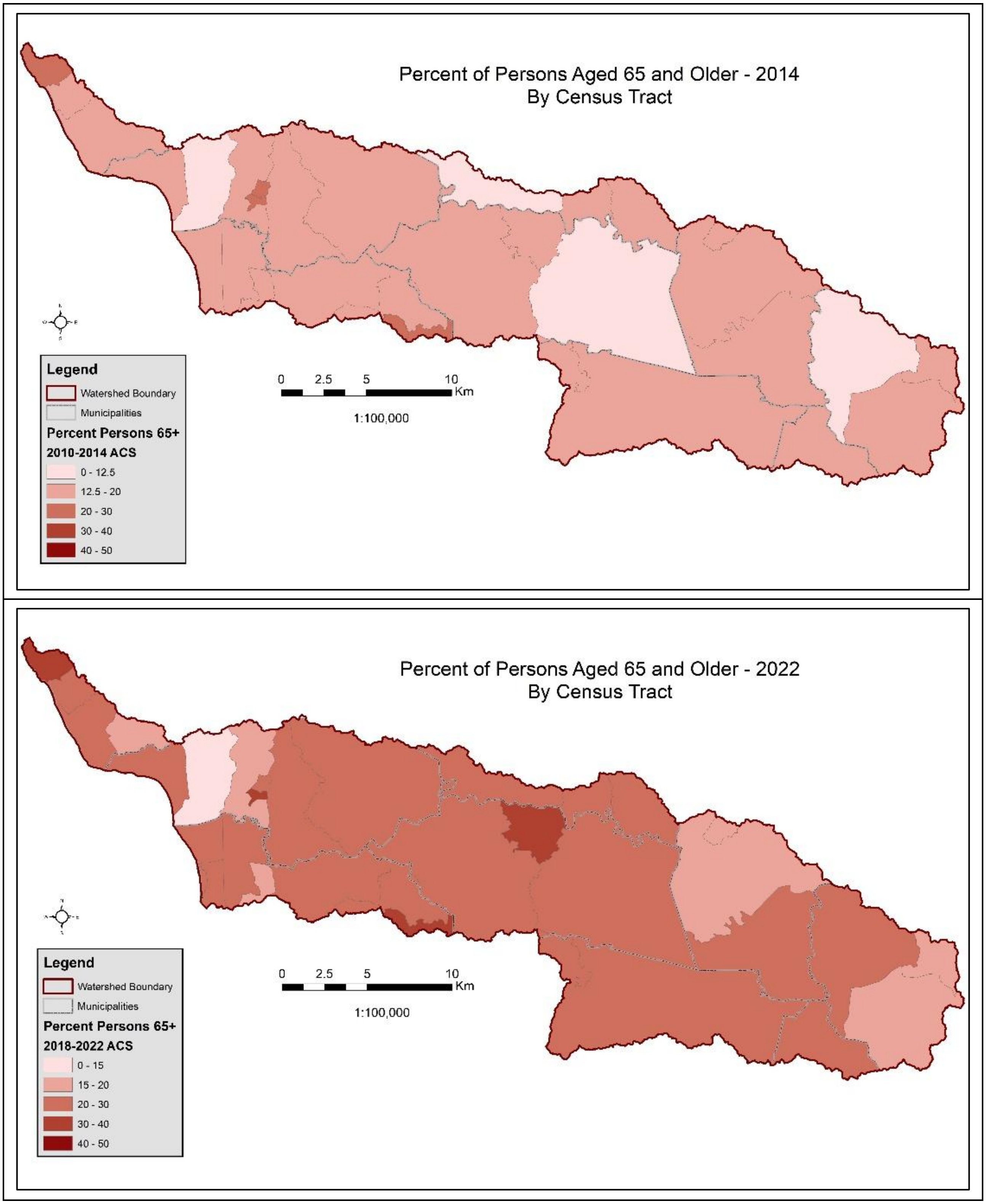


FIGURE 2-10. Comparison of the distribution of percent population aged 65 and older between 2014 and 2022.

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CHAPTER 3 – BRIDGING SCALES AND FRAMEWORKS: INCORPORTATING SOCIO-ECOLOGICAL STRATEGIES INTO WATERSHED MANAGEMENT

3.1 Introduction

The Caribbean has been identified as a region particularly vulnerable to extreme weather events such as hurricanes along with drought, floods, and landslides exacerbated by anthropogenic activities such as deforestation and urbanization (Roopnarine et al. 2021; Others). The region as a whole also faces issues of ecosystem degradation (sedimentation, nutrient runoff, pollution from agriculture and urban development). Urban landscapes, in particular, can be areas of vulnerability. Political and social system instability throughout the region challenges adaptive capacity as well as conflicts over water usage, economic losses in agriculture and tourism, and declining public health due to water quality issues (Roopnarine et al., 2021). Climate adaptation efforts are often hindered by high infrastructure costs and restricted financial resources (World Bank, 2016; World Bank, 2018). Climate projections for the Caribbean anticipate increased frequency and magnitude of hurricanes, increased drought frequency, and coastal impacts, intensifying risks to water availability, wetland integrity, and socio-economic systems (Hill, 2023; US Global Change Research Program, 2018).

Effective watershed management, particularly in post-disaster settings, requires evaluating the interactions between social systems and natural processes under conditions of stress and disturbance (Folke, 2016; Turner et al., 2003; Walker et al., 2006). Understanding the disturbance regime for a watershed contributes to a risk informed approach to watershed management (Bousquet et al., 2016; Biggs et al., 2012). The methods and metrics used to assess watershed health is a critical step essential for socio-ecological, risk-informed watershed management that enables equitable watershed governance. The Caribbean's vulnerability to hurricanes, droughts, and sea-level rise underscores the need for resilient watershed governance.

Climate-resilient watershed governance integrates adaptive, inclusive, proactive strategies to manage resources in the face of increasing climate uncertainty (Pahl-Wostl, 2015; UNEP & GEF, 2020). This approach emphasizes ecosystem-based management (e.g., flood regulation, slope stabilization, sedimentation control) while also prioritizing social equity (Global Commission on Adaptation [GCA], 2019b). Vulnerable and marginalized communities are disproportionately affected by climate change (IPCC, 2020; United Nations Office for Disaster Risk Reduction [UNDRR], Centre for Research on the Epidemiology of Disasters, 2018). Equitable governance ensures vulnerable groups are prioritized as participants in decision-making and benefit-sharing from adaptive strategies. This prioritization is necessary to address historical inequities and disproportionate climate risks faced by marginalized communities (GCA, 2019a; IPCC, 2022; UNDRR, 2015). By combining scientific models with local and/or Indigenous knowledge (LEK/LIK), and by adopting flexible, learning-oriented governance frameworks, watershed managers can build resilience into both ecosystems and human communities (Brand, 2005; Hiwaski et al., 2014; Morss et al., 2011; Pahl-Wostl, 2015; IPCC, 2022). This includes ongoing monitoring, feedback, and evolution of strategies based on new socio-ecological information and understanding. Equity is essential, not just as a moral imperative, but, as a practical necessity for long-term sustainability (GCA, 2019b).

Collaborator/stakeholder decision-making at all levels, particularly with those that are most exposed and vulnerable, plays a pivotal role in evaluating interactions between external systemic shocks and localized disturbances, such as land use conversion (Colding & Barthel, 2019; Eakin et al., 2014; Friis & Nielsen, 2014; Liu et al., 2007; Morss et al., 2011). However, incorporating the lived experiences of the localized, and potentially marginalized communities, as relates to impact to agricultural economy, critical infrastructure, and other disruptions to livelihoods (e.g., food and health access), is noticeably absent from evaluations of watershed health (Arora-Jonsson, 2011; Ghezzehei et al., 2020; Harlan et al., 2019; Lukacs & Ardoin, 2022; Turner et al., 2020; Whyte, 2013).

To address these gaps, this research introduces a Socio-ecological System (SES) Watershed Health Assessment (WHA) Framework for evaluating watershed health through the lens of equitable governance and risk-informed strategies for management. The framework integrates LEK, LIK, environmental justice (EJ), social-ecological vulnerability (SEV), and climate resilience. Its design is informed by two complementary literature reviews that together establish the methodological foundation and socio-ecological context for the framework development. The analytical approach then applies the framework to the Río Grande de Añasco (RGA) watershed as a proof of concept, demonstrating how a SES lens can inform watershed health assessment and management. The research is guided by the following questions:

- To what extent do current WHA methodologies incorporate ecological conditions alongside social system dynamics (e.g., LEK, LIK, EJ, SEV)?
- What priorities for watershed management and governance are emphasized in international guidance, Caribbean/Puerto Rican studies, and related literature on disaster risk reduction, climate adaptation, and governance?
- What SES WHA framework emerges from these gaps and priorities?
- When applied to the RGA, what does the SES-WHA reveal about data gaps and potential pathways for connecting assessment to more inclusive, climate-adaptive management and governance?

3.2 Methods

For both literature reviews detailed below, searches were conducted across multiple academic databases and professional repositories, without restriction to a single platform (Table 3-1). These included Web of Science, Scopus, JSTOR, ScienceDirect, ProQuest Dissertations & Theses, and Google Scholar. Publicly accessible government and institutional repositories and libraries included U.S. Geological Survey (USGS), U.S. Environmental Protection Agency (EPA), Centers for Disease Control/Agency for Toxic Substances and Disease Registry, National Oceanic Atmospheric Administration (NOAA) Digital Coast, IPCC, United Nations Digital Library.

3.2.1 Literature Review I Approach – Watershed Health Assessment Methodologies

This literature review surveyed methodologies commonly used for watershed health assessments, including scoring frameworks, ecological condition indicators, governance performance evaluations, and integrated water resources management (IWRM) approaches. The search terms applied intentionally overlapped to account for results that might appear under multiple searches (Table 3-1). The process used for synthesizing the results of this literature review aimed to reveal the presence, absence, and degree of integration of social system variables within existing WHA methodologies along with a compilation of common and key indicators and metrics. Results are reported collectively rather than tied to a single term (Table 3-5).

3.2.2 Literature Review II Approach – Governance and Socio-ecological Priorities Across Scales

The second literature review targeted peer-reviewed articles, international frameworks and guidance, and grey literature to identify sources on watershed governance, socio-ecological assessment and management, environmental justice, knowledge systems (LIK, LEK), and risk-informed governance. The searches were also intentionally multi-scalar, examining sources at the international (including US domestic), regional (Caribbean), island (Puerto Rico) and watershed scale (Table 3-1). Screening of titles, abstracts, and full texts were used to ensure thematic relevance (Booth et al., 2016; Synder, 2019). Search terms included both general concepts and place-specific phrases (Table 3-1). Key international frameworks reviewed included the Global Commission on Adaptation (GCA) guidance, the UN Sustainable Development Goals (SDGs), the Sendai Framework for Disaster Risk Reduction, the Brisbane Declaration, the Paris Agreement, and the IPBES Global Assessment (Table 3-; Appendix A). A thematic synthesis approach (Booth et al., 2016; Snyder, 2019; Thomas & Harden, 2008) was used to code and organize findings. Sources were grouped by key themes (e.g., Climate Adaptation, Disaster Risk Reduction, Governance, Justice & Equity, Knowledge Systems, SES Integration) and analyzed to identify convergences, divergences and gaps across scales (Table 3-1). This synthesis along with the results of the first literature review informed the development of the SES WHA Framework.

TABLE 3-1. Overview of literature reviews I and II: Search terms and analytical focus.

Literature Review	**Purpose**	**Search Terms**	**Analytical Focus / Key Outputs**
I. Watershed Health Assessment Methodologies	Identify methodological approaches, indicators, and gaps in current watershed health assessment frameworks.	watershed health assessment, watershed health index, watershed report card, integrated watershed assessment, water quality index, watershed indicators	Synthesizes methodological foundations and limitations that inform framework design; Clarifies data needs and analytical dimensions of WHA.
II. Governance and Socio-Ecological Priorities Across Scales	Synthesize governance, justice, and climate adaptive priorities in watershed management from international to local scales.	**Climate and risk**: climate change adaptation, disaster risk reduction, risk-informed governance **Governance and management**: watershed governance, watershed management, integrated watershed management, governance challenges **Knowledge systems**: local ecological knowledge, indigenous knowledge **SES Integration**: socio-ecological systems, socio-ecological resilience **Justice & Equity**: environmental justice, equity **Geographic context**: Puerto Rico, Caribbean watershed management, climate Caribbean, climate Puerto Rico	Identifies SES and governance considerations included in framework design; Underscores equity, resilience, and cross-scale integration as essential dimensions of watershed health.

3.2.3 Development of SES WHA Framework

Utilizing the gaps and limitations that emerged from Literature Review I and the synthesis of literature from Literature II, I developed a novel framework for assessing socio-ecological watershed health, incorporating metrics for climate adaptation and disaster risk reduction. The SES WHA Framework organizes indicators into five key assessment categories to capture the complex interactions between ecological, social, and governance factors that influence watershed health (Table 3-2). To map the results of Literature Review I across indicator categories, I included sources that (a) operationalize a category (indicators, protocols, applications) and (b) explicitly frame that category as a determinant of watershed health, including proxy measures when stated by the source; I do not infer indicators where none are provided.

TABLE 3-2. Watershed health assessment categories with corresponding descriptions.

Assessment Category	Description of Category
Climate Change & Disaster Resilience	Examines the watershed's capacity to absorb, adapt to, and recover from disturbances such as floods, hurricanes, and droughts.
Institutional & Governance Challenges	Evaluates decision-making processes, multi-sector coordination, and the inclusion of marginalized communities in governance.
Ecosystem Services & Needs	Focuses on ecological functions (e.g., biodiversity, carbon storage) and stressors (e.g., habitat loss, pollution).
Infrastructure & Resource Constraints	Assesses the adequacy and condition of built infrastructure related to water supply, sanitation, and social services.
Long-term Monitoring (Qualitative/Quantitative Indicators)	Provides measurable metrics (e.g., water quality indices, erosion rates, per capita water availability) that enable tracking of temporal and spatial changes to watershed conditions and trends in support of evidence-based decision-making.

The SES WHA Framework explicitly integrates LEK, LIK, EJ, and SEV as foundational elements. By centering the framework on these foundational elements, the tool supports equitable, climate-adaptive, and inclusive watershed governance, especially in regions prone to heightened socio-ecological risks (Armitage et al., 2012; Berkes, 2018; Folke et al., 2021; Whyte, 2013). To ensure integration of knowledge justice and avoid abstraction of Indigenous epistemologies, the framework distinguishes between Traditional Ecological Knowledge (TEK), LEK, and LIK. While TEK has historically provided a bridge for recognizing Indigenous relationships with the environment, its institutional use reinforces colonial conceptual framings by translating relational worldviews into categories legible to Western science (Nadasdy, 1999; Todd, 2016; Whyte, 2013). As Tuhiwai Smith (2012) argues, the effort to decolonize research requires resisting frameworks that reify Indigenous knowledge as an object of study rather than as a living, sovereign practice. Accordingly, the SES WHA Framework does not operationalize TEK as doing so could perpetuate epistemic extraction and diminish Indigenous governance authority. Instead, the framework centers LIK, along with LIK, as participatory, context-specific knowledge systems that can be ethically integrated through co-production, data sovereignty, and reciprocal collaboration, particularly in implementation of strategies resulting from the assessment. Table 3-3 summarizes the distinctions among TEK, LEK, and LIK as synthesized from the literature, highlighting their implications for equitable watershed governance and the rationale for prioritizing LEK and LIK within the SES WHA Framework.

TABLE 3-3. Distinctions among TEK, LEK, and LIK and the rationale for prioritizing LEK and LIK in this SES WHA Framework.

Concept	Knowledge Holder	Epistemology & Scope	Governance & Ethics	Implications for Watershed Governance
TEK	Indigenous peoples and Nations	Cumulative ecological knowledge grounded in long-term environmental observation; Often framed through Western ecological lens	Frequently abstracted or decontextualized; Vulnerable to extractive use when disconnected from Indigenous governance	May obscure Indigenous relationality, sovereignty; Not used in SES WHA Framework due to ethical concerns over generalization, colonial conceptualization
LEK	Local communities and practitioners	Place-based, experiential, often multi-generational knowledge rooted in local practice, environmental interaction.	Informally transmitted; May blend with scientific knowledge; Less protected legally	Valued in SES WHA Framework for its adaptability, relevance to hazard response, place-based land management practices
LIK	Indigenous communities and knowledge holders	Holistic, relational, intergenerational knowledge embedded in language, ethics, and governance systems	Governed by protocols of consent, responsibility, reciprocity; Non-extractive engagement required	Centered in the SES WHA Framework to support Indigenous sovereignty, knowledge justice, and ethical climate adaptation practices

Sources: Berkes, 2012; Berkes & Ross, 2016; Brook & McLachlan, 2005; Gadgil et al., 1993; Hill et al., 2020; McGregor, 2018; Nadasdy, 1999; Raymond et al., 2010; Reid et al., 2021; Smith, 2012; Tengö et al., 2017; Todd, 2016; Whyte, 2013; Wilson, 2008.

3.2.4 Application of SES WHA Framework to RGA

Rather than conducting a comprehensive watershed health assessment of the RGA, I applied the SES WHA Framework to illustrate its practical utility, highlight data gaps, and connect assessment to governance and management strategies. Data inputs included peer-reviewed and gray literature, selected GIS datasets, agency and policy documents (e.g., federal hazard mitigation and funding programs), and RGA municipal hazard mitigation plans. I also incorporated participant-observation fieldnotes (auto-ethnographic) recorded during field work and professional activities on the island (2018 – 2024), inclusive of lived experiences from Dec 2018 – Jan 2020. Documentation of federal policy shifts (e.g., the cancellation of BRIC funding in 2025) and RGA watershed council materials (e.g., agendas, presentation materials, meeting notes, and shared planning documents) from the Iniciativa de Cuencas del Oeste Working Group (Table 3-4), on which I participated for >12 months also informed the assessment.

I did not conduct formal interviews or collect identifiable human-subjects data for this research. Therefore, no IRB-approved direct interviews (LEK/LIK) are reported. Fieldnotes are treated as contextual observations from my professional practice (e.g., site conditions, publicly shared concerns in open meetings, professional conferences, workshops, and presentations). Access to, and protocols for, Indigenous knowledge (LIK) were outside the scope of this research. LEK is acknowledged as a critical component of the framework, but in this application is represented only through published sources and publicly available materials.

TABLE 3-4. Key challenges identified by the Iniciativa de Cuencas del Oeste Working Group.

Challenge	Description
Need for Watershed Perspective in Hazard Mitigation Planning	A critical need exists to incorporate a watershed perspective within municipal hazard mitigation planning efforts.
Insufficient Support for Hazard Mitigation Planning	Limited data, resources, and coordination hinder effective hazard mitigation planning at the watershed level.
Varying Municipal Priorities	Differences in municipal priorities and the varying stages of related activities create challenges for watershed-scale coordination.
Missed Opportunities for Integrated Watershed Management	There are missed opportunities to leverage studies, deliverables, and resources across institutions for watershed management.
Lack of Awareness of Available Resources and Technical Expertise	Many municipalities and institutions are unaware of existing resources and technical experts who can support their efforts.
Gaps in Funding and Staffing	Limited funding and insufficient staffing levels impede consistent municipal engagement in watershed governance.
Incomplete or Outdated Data	Physical and ecological data are often incomplete, outdated, or missing, reducing the capacity for informed decision-making.

3.3 Results

3.3.1 Literature Review I Findings – Watershed Health Assessment Methodologies

Sources reviewed reveal a consistent emphasis on ecological, hydrologic, sediment/erosion, social, and water quality dimensions as the core domains for watershed health assessment (Table 3-5). Most methodologies rely on well-established field, laboratory, and GIS-based methods to generate operational indicators such as biodiversity metrics, streamflow rates, erosion loads, and water quality indices. Integrated approaches to water systems are increasingly emphasized for WHA design (e.g., Fassnacht & Ma, 2020), yet most draw on methodological source that remain rooted in biophysical indicators (e.g., Ahn & Kim, 2017; Mallya et al., 2018; Minnesota DNR WHAF, 2010; CCME WQI manual, 2017; Wait & Pak, 2022). Widely adopted approaches include water quality indices (e.g., CCME, 2017; Lumb et al., 2011) and composite ecological assessments (e.g., Karr & Dudley, 1981, Minnesota DNR WHAF, 2010), which have been replicated across diverse contexts. While several methodologies attempt to account for socio-ecological interactions (e.g., Ahn & Kim, 2017; Mallya et al., Wait & Pak, 2022), integration of social system indicators remains limited and often secondary to biophysical metrics.

Social vulnerability, governance effectiveness, and equity considerations are rarely operationalized beyond descriptive analysis or conceptual framing, with only a few exceptions drawing on census data or participatory surveys (Table 3-5). U.S. Climate Smart Framework and Clean Water Act compliance measures provide additional operational examples for integrating resilience and compliance in watershed management systems (USDA, 2016; US EPA, 1972). The latter illustrating how these approaches integrate with adaptive management principles and disturbance ecology principles to promote resilient and sustainable watershed management

(Copeland, 2016; Stein et al., 2014; US EPA 2023; U.S. Forest Service, 2016). In summary, Literature Review I highlights both the strength of operational ecological and hydrologic indicators and the shortfall in systematically incorporating social, governance, and equity factors. This gap underscores the need for approaches that bridge ecological and social domains to reflect the dynamics of SES in watershed health assessments.

TABLE 3-5. Conceptual and operational domains of current WHA methodologies: Indicators, methods, sources.

Indicator Category	Examples of Indicators	Common Methods Used	Supporting Citations
Ecological Health	Wetland extent/condition; Coral reef conditions; Biodiversity metrics; Habitat health/connectivity; Landcover	Field surveys; GIS/remote sensing analysis; Modelling; Assessment protocols (biology, habitat)	Aredo et al., 2024; California Water Boards, 2024; Dallmeier et al., 2013; Hawaii State Department of Health, 2024; Hazbavi et al., 2018; Karr & Dudley, 1981; Minnesota Department of Natural Resources, 2010; Perdinan et al., 2024; The Resource Innovation Group, 2012; USDA, 2011; US EPA 1997a; US EPA, 2002; Wait & Pak, 2022
Hydrology	Streamflow rates; Runoff patterns; Peak discharge during flood events; Water availability/use; Storage; Groundwater dynamics	Stream gauges; Precipitation-runoff modeling (e.g., SWAT, HEC-HMS); Groundwater monitoring/modelling; Streamflow assessments	Ahn & Kim, 2017; Aredo et al., 2024; California Water Boards, 2024; Duan et al., 2022; Hazbavi et al., 2018; Minnesota Department of Natural Resources, 2010; Perdinan et al., 2024; The Resource Innovation Group, 2012; USDA 2011; US EPA, 2002; Wait & Pak, 2022
Sediment & Erosion	Soil erosion rates; Sediment yield/load; Sediment accumulation in streams and reservoirs; Mass wasting susceptibility	Erosion plots; Sediment cores; Sediment transport modeling (SWAT)	Duan et al., 2022; Hawaii State Department of Health, 2024; Hazbavi et al., 2018; Karr & Dudley, 1981; Minnesota Department of Natural Resources, 2010; Perdinan et al., 2024; The Resource Innovation Group, 2012; Tsai et al., 2021; USDA, 2011; US EPA, 1997a; US EPA, 2002; Wait & Pak, 2022; Zerga, 2025
Social System	Access to clean water; Socio-economic vulnerability/EJ exposure; Land use/Built environment;	Household surveys; Participatory mapping; Census/ACS data; GIS spatial	Aredo et al., 2024; California State Water Board, 2024; Duan et al., 2022; Hawaii State Department of Health, 2024; Hazbavi et al., 2018; Minnesota Department of

	Governance/Institutional status/effectiveness; Stakeholder involvement	overlays/analysis; GDP; Policy/governance analysis	Natural Resources, 2010; Perdinan et al., 2024; The Resource Innovation Group, 2012; US EPA, 1997a; US EPA, 2002; Wait & Pak, 2022
Water Quality	Nutrient concentrations (N, P); Biochemical oxygen demand (BOD); Chemical oxygen demand (COD); Dissolved Oxygen; Total suspended solids; Chlorophyll-a; Turbidity; Fecal indicator bacteria (FIB); Toxic contaminants/Pollutants (point, non-point); Heavy metals	Water sampling; In situ continuous sampling; Laboratory analysis; Remote sensing; Composite Indices	Ahn & Kim, 2017; Aredo et al., 2024; California State Water Board, 2024; Canadian Council of Ministers of the Environment, 2012, 2017; Dallmeier et al, 2013; Duan et al., 2022; Hawaii State Department of Health, 2024; Hazbavi et al., 2018; Karr & Dudley, 1981; Lumb et al., 2011; Mallya et al., 2018; Matthews et al., 2015; Minnesota Department of Natural Resources, 2010; National Research Council, 2001; Perdinan et al., 2024; The Resource Innovation Group, 2012; Tsai et al., 2021; USDA, 2011; US EPA, 1997a, 1997b, 1997c, 2002; Vollenweider & Kerekes, 1982; Wait & Pak, 2022

3.3.2 Lit Review II Findings – Governance and Socio-ecological Priorities Across Scales

The second literature review synthesized evidence on what constitutes effective watershed management and healthy SES systems, alongside criteria for equitable and risk-informed governance (Table 3-6). Several themes emerged:

1. Climate adaptation & DRR: International and regional frameworks emphasize mainstreaming climate adaptation and disaster risk reduction into watershed and land-use planning. NbS and EbA are highlighted as cost-effective strategies, though gaps remain in implementation capacity and long-term monitoring.
2. Governance: Fragmented, sectoral governance structures and limited institutional capacity were identified at all scales. Sources highlight the need for multi-level, cross-sector coordination, decentralization, and mechanisms that build trust with communities. In Puerto Rico and the RGA specifically, weak institutional linkages and reliance on informal measures exacerbate governance gaps.
3. Justice & Equity: A persistent finding is the disproportionate impact of disaster and environmental degradation on vulnerable and marginalized communities. International frameworks stress equity and inclusivity, but operationalization is inconsistent. Island and watershed scale sources underscore inequities in disaster recovery, land tenure, and access to infrastructure, reinforcing the importance of embedding justice and equity in governance mechanisms.
4. Knowledge Systems: Across scales, the literature emphasizes integrating LEK and LIK with scientific data. Calls for co-production, participatory governance, and data sovereignty are strong, particularly in the Caribbean and Puerto Rico, though formalized mechanisms remain limited.

5. SES Integration: While SES thinking is increasingly recognized in frameworks and scholarship, operational tools to integrate ecological and social indicators remain underdeveloped. Most sources identify ecosystem services and risk metrics but fall short of embedding social vulnerability, equity, and governance into assessment frameworks.

In summary, Literature Review II underscores that while international and regional frameworks provide conceptual guidance, island and watershed scale sources reveal persistent implementation gaps, governance fragmentation, and inequities. Effective watershed management and functioning require more than ecological health and monitoring. It depends on risk-informed governance, equity-centered approaches, and open, inclusive knowledge systems. These findings reinforce the need for the SES WHA Framework to explicitly bridge ecological social, technological, governance dimensions, with particular attention to justice, equity, and knowledge pluralism.

TABLE 3-6. Literature Review II findings across scales and categorized by themes.

	Findings by Theme					
Scale / Context	**Climate Adaptation**	**Disaster Risk Reduction (DRR)**	**Governance**	**Justice & Equity**	**Knowledge Systems**	**SES Integration**
International & US Based* *ADPC, 2013; Aguilar et al., 2015; Begum et al., 2014; Brand, 2005; Bridges et al., 2014; Cohen & Davidson, 2011; Colls et al., 2009; Glantz et al., 2014; Golladay et al., 2021; Gregg et al., 2018; Grover, 2006; Gupta & Nair, 2012; Hirokawa, 2012; Hiwasaki et al., 2014; Horne et al., 2017; London School of Economics and Political Science, 2017; Morss et al., 2011; O'Brien et al., 2012; Perera et al., 2014; Porio et al., 2010;UNICEF, 2014; UNISDR, 2007; UNISDR, 2012; UNISDR & CRED, 2018; Webb et al., 2017; Yoder & Ward, 2019*	▪ Emphasize resistance, resilience, and adaptive strategies to manage non-stationary water flows and shifting baselines. ▪ Promote NbS / EbA and Eco-DRR integration in long-term planning and development. ▪ Systemic, climate-adaptive approaches linked to DRR and public engagement enhance resilience and well-being.	▪ Advocate for adaptive, multi-hazard, risk-informed investment w/ stronger institutions. ▪ Thresholds of Potential Concern are flexible benchmarks & apply vulnerability / performance metrics. ▪ Gaps in early-warning systems. ▪ Ecosystem service valuation = cost-effective DRR. ▪ Donor-driven project cycles hinder sustained adaptation, resilience. ▪ Integration into all scales of planning = poverty-sensitive strategies, reduce intergenerational vulnerability. ▪ Cultural heritage risk, multi-stakeholder models essential (e.g., LIVE)	▪ Boundary and accountability challenges with watershed approach (problem-sheds vs policy-sheds). ▪ Institutional fragmentation, bureaucratic rigidity, financing gaps are key barriers. ▪ Call for enabling leadership, decentralization, Eco-DRR planning, and empowerment of local governments. ▪ Emphasize coordination across sectors and scales through climate-informed, child-centered, collaborative governance structures supporting collective, equitable water management.	▪ Promote procedural, distributive, recognition equity thru transparent, participatory, inclusive, accountable, governance. ▪ Disproportionate impacts on low-income, urban, marginalized groups. ▪ Call for gender and child-sensitive DRR/climate policies. ▪ Importance of incorporating Indigenous and sacred knowledge addresses biases of economically valued ecosystem services over equity. ▪ Water access is a human right. ▪ Linkage between poverty reduction / social development and equitable watershed governance.	▪ Emphasis on collaborative learning, co-production across all sectors to reduce uncertainty, strengthen adaptive management. ▪ Scenario planning, vulnerability assessments, decision-support systems, and iterative knowledge exchange enable collective risk management. ▪ Integrating Indigenous & Western knowledge enhances relevance, legitimacy and is supported by interdisciplinary networks, outreach, and technical committees, sustaining continuous learning. ▪ Global under-implementation of adaptive management.	▪ Promotes Eco-DRR, EbA as integrated SES approach + mitigation + adaptation = enhanced resilience. ▪ Emphasis on hybrid ecosystem management balancing natural & built systems, linking governance, communities, and ecosystem services. ▪ Call for embedding SES principles in law, policy and fostering cross-jurisdictional collaboration = resilience at multiple scales. ▪ Promote alignment with SDGs. ▪ Increases adaptability to shocks to the system.
	▪	▪	▪	▪	▪	▪

	Climate Adaptation	**Disaster Risk Reduction**	**Governance**	**Justice & Equity**	**Knowledge Systems**	**SES Integration**
Regional (Caribbean) *IBRD/The World Bank, 2018; IPCC, 2014; Roopnarine et al., 2021; The Water Institute of the Gulf, 2015*	▪ Caribbean nations face growing urban water demand, drought, and water excess (floods, storms). ▪ Adaptation priorities include runoff and stormwater management, solid waste, competing water uses, water harvesting, reforestation, drought-tolerant crops. ▪ DVRPs** and national investment plans must integrate adaptation with infrastructure and policy for long-term resilience.	▪ Promotes proactive, participatory DRR for both social and economic benefit. ▪ Strengthening institutional capacity requires multi-sectorial training and improved risk communication. ▪ Community-based measures such as rainwater harvesting enhance resilience but face class-based barrier to adoption. ▪ Call for investment in resilient housing, transportation, energy, building codes to align DRR and climate adaptation objectives.	▪ Limited resources, weak coordination hinder local governments' ability to manage water and drainage infrastructure. ▪ Strengthening governance requires coherent national legislation, financing mechanisms, participatory approaches that complement top-down policies. ▪ Greater integration of hazard mitigation into planning and cross-scale partnerships essential for effective risk governance.	▪ Unequal access to rainwater harvesting, basic infrastructure underscores persistent social disparities. ▪ Adaptive policies must address needs of poor and vulnerable households and incorporate community groups, NGOs, marginalized voices, Indigenous practices. ▪ Disasters deepen poverty and inequality, reinforcing need for transparency and equity in regional governance.	▪ Increasingly important to link watershed management, urban planning, water resources planning to address water shortages and stormwater management. ▪ Examples of decision-support tools include CHARIM*** and CDRPs for hazard data integration and planning. ▪ Knowledge sharing, training, and data access are critical for region. ▪ Research and knowledge gaps remain across LAC.	▪ Promotes systems-based management linking ecological, social, and technological dimensions of water security. ▪ Urbanization, infrastructure stress, and climate variability intensify competition for shared resources across region. ▪ Holistic, cross-sector approach guided by "build back better" principle is essential to strengthen socio-ecological resilience.
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	Climate Adaptation	**Disaster Risk Reduction**	**Governance**	**Justice & Equity**	**Knowledge Systems**	**SES Integration**
Island (Puerto Rico) AECOM, 2017; Burgos-Rodríguez_2020; Díaz, 2005; GMA Engineering, 2009; Larsen, 2017; López et al., 2001; Lugo, 2020; PRWRERI, 201-2019; PRWRERI, 2020-2021; RTI International & Paradigm Environmental, 2017; Stablein et al., 2022; The Nature Conservancy, 2019; USDA, NRCS, 2017, *2018, 2020, 2021; Valdés-Pizzini & Schärer-Umpierre, 2014*	▪ Hurricane María exposed need to adapt ecological and technological systems as infrastructure failures amplified socio-ecological impacts. ▪ Adaptive capacity depends on communication, trust, and management of hydrologic and land-use vulnerabilities (i.e., urbanization of ag lands, threats to food security). ▪ Climate-smart watershed and reef management approaches support long-term resilience, but fiscal austerity measures undermine Puerto Rico's adaptive capacity.	▪ Disaster vulnerability stems from interaction between natural hazards, urbanization, and deteriorating infrastructure, with steep-slope development, sediment discharges amplifying risks. ▪ Community-led initiatives often compensate for state neglect. ▪ Improved rainfall mapping, green infrastructure strengthen local resilience. ▪ Persistent data (i.e., lack of historical data) and engineering gaps (i.e., dam stabilization needs) constrain effective hazard mitigation, long-term planning. ▪ High geomorphic change following Hurricane María.	▪ Institutional collapse → community networks, NGOs essential governance intermediaries. ▪ Persistent regulatory, capacity gaps (i.e., compliance, enforcement, training) undermine erosion and sediment control. ▪ Fragmented responsibilities, fiscal austerity (i.e., debt crisis), colonial governance structures constrain local authority and environmental law enforcement. ▪ Strengthening multi-level coordination, institutional capacity (i.e., Clean Water Act) remains critical for watershed > reef management.	▪ Hurricane María exposed deep inequities in disaster impacts and recovery. ▪ Cascading system failures disproportionally affected vulnerable populations. ▪ Urbanization pressures, tourism-driven development undermine food sovereignty, intensify spatial inequity between transient, long-term residents. ▪ Persistent governance instability, weakened rule of law continue to perpetuate systemic inequities.	▪ Transdisciplinary approaches needed to understand and manage SE-technological (SET) systems. ▪ Need for training, interagency coordination, technical tools, GIS-based land use change analysis and outreach. ▪ Focus needed on co-production and participatory mapping/modeling workshops. ▪ Knowledge integration between local communities and researchers lacking. ▪ Valuation and payments for ecosystem services can incentivize sustainable management, knowledge integration.	▪ SET systems perspective essential for assessing climate risk and resilience. ▪ Adaptive, risk-informed development must account for interdependencies among power, transportation, water, food systems while maintaining watershed-reef connectivity. ▪ Cross-sector, interdisciplinary integration within environmental governance underpins resilient SET system. ▪ SET destabilized by cascading hazards.
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	Climate Adaptation	Disaster Risk Reduction	Governance	Justice & Equity	Knowledge Systems	SES Integration
Watershed *Adrianzen et al., 2013; Colón López & Restrepo, 2019; Conallin et al., 2017; CWP, 2008; Delphi Group, 2023; Fenta et al., 2023; Fernández-Giménez et al., 2012; García et al., 2019; Guzmán-Morales et al., 2024; Kingsford et al., 2017; Luhring-González et al., 2023; Murphy & Stallard, 2012; Murry et al., 2019; Ortiz-Zayas & Scatena, 2004; Santiago & Hong, 2020; Smith et al., 2017; Viqueira Ríos, 2018; Wagner et al., 2002*	▪ Strategic Adaptive Management (SAM) essential for tropical watershed that respond rapidly, nonlinearly to climate extremes (e.g., projected rainfall reductions 5-30% intensifying drought, evapotranspiration, flow intermittence). ▪ Adaptive objectives for flow management, water supply, and land use critical to sustaining ecological and agricultural functions. ▪ IWRM and risk-sharing approaches strengthen adaptive capacity and balance trade-offs between terrestrial, marine ecosystem services. ▪ Climate variability in tropical mountains influences nutrient and sediment loads. ▪ Climate extremes/storms overshadow watershed mgmt efforts.	▪ Emphasize long-term resilience over short-term hazard control. ▪ Use Thresholds of Potential Concern as early-warning indicators to prevent ecological collapse. ▪ Erosion, sedimentation, nutrient loading major concerns, particularly in steep, urbanizing watersheds with limited municipal capacity. ▪ Integrated use of structural measures, NbS strengthen flood, drought mitigation but depend on stakeholder negotiation, adaptive reframing under extreme events. ▪ Municipalities have frontline role but limited by authority/resources. ▪ Natural disasters outweighed interventions by watershed management.	▪ Effective watershed governance requires adaptive, multi-stakeholder cycles grounded in SAM****, IWM, CBNRM. ▪ Fragmented agencies, weak enforcement, limited municipal authority hinder implementation of erosion, sediment control measures. ▪ Bridging institutions (e.g., NGOs, UPRM Extension Service, RWAs) aid integration of community, agency perspectives. ▪ Participatory decision-making, evidence-based planning, flexible / hybrid governance structures essential to reduce inequities, strengthen long-term coordination. ▪ Lack of long-term monitoring, limited resources and authority at municipal level.	▪ Equitable watershed management depends on inclusive, transparent engagement that builds trust, acknowledges power asymmetries among stakeholders. ▪ Semi-private land tenure, urban-biased water provision marginalizes rural, farming communities & reinforces uneven socio-economic conditions. ▪ Persistent distrust in government -led processes, tokenistic participation undermines justice. ▪ Targeted outreach, incentive programs, farmer stewardship initiatives strengthen equity, local ownership. ▪ Farmers sidelined in watershed councils.	▪ SAM fosters co-learning, co-production by integrating scientific data, real-time monitoring, local knowledge. ▪ Participatory modeling, collaborative tools help bridge mismatched timelines between research and management, incorporates farmer, Indigenous, community priorities. ▪ Focus groups and other stakeholder-driven processes strengthen conservation, agricultural alignment within adaptive management. ▪ Values-based visioning and incorporation of local and Indigenous perspectives key. ▪	▪ Balances ecological integrity with human water demand requires integrated SES planning, supported by SAM, ecosystem service frameworks. ▪ Land cover change and socio-economic disparities jointly influence hydrologic sustainability, water quality, underscoring value of SES monitoring and participatory ecosystem service approaches. ▪ Puerto Rico serves as model site for advancing SES-based water research where flow policies must recognize trade-offs between human and ecosystem needs.

**Not including Puerto Rico; **Disaster Vulnerability Reduction Project; ***Caribbean Handbook on Risk Information Management; ****Strategic Adaptive Management*

In addition to the literature presented in summary above, international frameworks and guidance were integrated into the synthesis. These frameworks establish shared priorities for resilience and equity and set the stage for regional and local action. Table 3-7 synthesizes six of the most widely recognized frameworks, highlights their main components and points of emphasis

TABLE 3-7. International frameworks and guidance.

Framework / Guidance	Summary of Main Components
Global Commission on Adaptation	Water & Infrastructure Resilience/Action Plans/Financing; Inclusive adaptation/governance; Knowledge sharing is key; EbA Strategies & NbS emphasized
SDGs (UN 2015)	SDG 6 (Clean Water; Ecosystem Protection); SDG 11 (Sustainable Cities/Infrastructure); SDG 13 (Climate Action; Disaster resilience planning); SDG 16 (Inclusive, Accountable Governance)
UNDRR (Sendai Framework)	Priority 1: Understanding Disaster Risk; Priority 2: Strengthening Disaster Risk Governance; Infrastructure; Role of risk monitoring assessments
Brisbane Declaration	Commitment to ecological water governance; Ecosystem function preservation; Ecosystem services for advancing conservation and resilient watersheds
Paris Agreement (UNFCCC, 2015)	Global climate agreement; National adaptation planning/governance; Water resource adaptation measures; Equity prioritized across water/climate sectors
IPBES (2019)	Biodiversity-ecosystem services linkages; Assessment of degradation impacts; Emphasizes NbS, integration of Indigenous/Local knowledge in governance

3.3.3 SES WHA Framework

A central limitation across prior frameworks is the absence of clear, reproducible, social indicators (Table 3-8). Governance, equity, and exposure were frequently acknowledged in principle, but rarely defined in operational terms or integrated with ecological metrics. Where considered, they were often reduced to proxies (e.g., land use or built environment variables) or generalized under broad governance language. Few approaches specified monitoring mechanisms or indicators for social dynamics. Literature Review II also highlighted the value of implementing CBNRM, NbS, and EbA, especially through integration of local ecological knowledge and inclusive decision-making processes.

Building on the findings of the Literature Review I and II, the SES WHA Framework organizes socio-ecological watershed health into five interrelated categories: climate change and disaster resilience, institutional and governance challenges, ecosystem services and ecological needs, infrastructure and resource constraints, and long-term monitoring through quantitative indicators (Table 3-9). These categories provide a structured lens for linking ecological and social dimensions of watershed health.

The SES WHA Framework advances watershed health assessment by explicitly defining a core set of social indicators alongside ecological metrics, and by providing a basis for integrating them through SES WHA. In doing so, it moves beyond descriptive inclusion of social dimensions toward operational tools that capture equity, governance capacity, and local knowledge systems as measurable determinants of watershed health. The Framework also moves beyond assessment to identification of challenges and proposed implementation solutions.

TABLE 3-8. Gaps, limitations and challenges identified in the literature review.

Category	**Key Challenges Identified**
Climate Change & Disaster Resilience	• Increasing frequency and severity of storms and droughts (Hill, 2023; USGCRP, 2018) • Weak integration of Disaster Risk Management (DRM) and Climate Change Adaptation (CCA) (Iglesias, 2013; Begum et al., 2014) • Limited fiscal space for resilient infrastructure investments (IBRD, 2018; World Bank, 2016) • Need for NbS and ecosystem-based adaptation (EbA) (Lo, 2016; Bridges et al., 2015)
Institutional & Governance Challenges	• Fragmented and top-down governance structures (Stablein et al., 2022; Smajgl & Ward, 2013) • Lack of multi-scalar coordination (UNDP, 2023) • Inconsistent stakeholder participation and LEK/LIK integration (Baptiste et al., 2019) • Post-disaster erosion of institutional trust (Center for Puerto Rican Studies, 2018)
Ecosystem Services & Ecological Needs	• Urban expansion reducing freshwater and wetland integrity (López et al., 2001; Murry et al., 2019) • Increased sedimentation and nutrient runoff harming coastal ecosystems (Smith et al., 2017; Guzmán-Morales et al., 2024) • Need for balancing ecosystem conservation with development pressures (Viqueira Ríos, 2017)
Infrastructure & Resource Constraints	• Aging and damaged water infrastructure (Stablein et al., 2022) • High water losses and sedimentation challenges (Murry et al., 2019) • Limited adoption of new technologies due to governance gaps (Gallick, 2019; Luhring-González et al., 2023)
Long-term Monitoring (Qualitative / Quantitative Indicators	• Traditional watershed assessments overlook SES linkages (Duan et al., 2022; Hazbavi et al., 2020) • Need for integrated socio-ecological frameworks (Aredo et al., 2024)

- Challenges with spatiotemporal variability in water quality and socio-economic linkages (Colon Lopez & Restrepo, 2019)

TABLE 3-9. SES WHA Framework: Linking assessment categories to indicators, systemic challenges and intervention strategies.

Assessment Category	Description	Indicators / Metrics	Challenges & Intervention Strategies
Climate Change & Disaster Resilience	Assess watershed's/community ability to absorb, adapt to, and recovery from climate-related disturbances (e.g., floods, droughts, hurricanes, extreme events)	o % of watershed area within natural buffers (e.g., wetlands, riparian zones) o Frequency of flood / drought events o Existence of climate adaptation plans (prioritization of needs of vulnerable communities) o Incorporation of NbS	**Challenges**: Insufficient integration of DRM and CCA; Limited climate-resilient infrastructure; Fiscal constraints (Hill, 2023; USGCRP, 2018; Begum et al., 2014). **Strategies**: Scaling up NbS and EbA for adaptive resilience.
Institutional & Governance Challenges	Evaluates decision-making processes, equity, transparency, coordination among sectors, and inclusion of marginalized communities	o Establishment of watershed management authority / council o Stakeholder participation index (qualitative / quantitative) – including incorporation of LIK/LEK & representation o Existence of equitable water allocation mechanisms o Recognition of data sovereignty / co-ownership agreements	**Challenges**: Fragmented governance; Low community engagement (Stablein et al., 2022; Baptiste et al., 2019). **Strategies**: Strengthen co-management and LIK / LEK integration.
Ecosystem Services & Needs	Reviews ecological functions (e.g., filtration, carbon storage, biodiversity) and stressors (e.g., habitat loss, invasive species)	o Biodiversity index o Land cover / use changes o Erosion / sedimentation rates o % Green space / Forests	**Challenges**: Urban sprawl; Nutrient pollution; Ecosystem degradation (Center for Watershed Protection, 2008; Viqueira Ríos, 2017). **Strategies**: Implement NbS for erosion control, hydrological restoration.

Infrastructure & Resources Constraints	Considers the adequacy and condition of built infrastructure (e.g., water supply, stormwater, sanitation, monitoring systems); Includes health of social system infrastructure (e.g., medical facilities, schools / universities, food)	○ % coverage of safe drinking water infrastructure ○ Age and reliability of SES infrastructure ○ Water supply / demand gaps	**Challenges**: Aging water infrastructure; Disaster-related damages; Inequitable access (Murry et al., 2019; Stablein et al., 2022). **Strategies**: Integrate resilience and hazard mitigation into upgrades.
Long-term Monitoring (Qualitative / Quantitative Indicators)	Provides measurable data across the above domains to track changes over time and support evidence-based decision-making	○ Watershed Health Score (composite) ○ Water Quality Index ○ Per capita water availability ○ Slope stability ○ Erosion Management ○ Documentation of co-produced data ○ Integration of LEKJ/LIK inputs ○ Qualitative indices of community trust / reciprocity in data sharing	**Challenges**: Data gaps; Outdated monitoring systems (Luhring-González et al., 2023). **Strategies**: Expand socio-ecological monitoring integrating SEV and EJ metrics.

3.3.3a Climate Change & Disaster Resilience

Climate change impacts (e.g., more frequent hurricanes of greater magnitude) not only exacerbate environmental and infrastructural vulnerabilities, but also amplifies existing social inequalities, disproportionately impacting children and marginalized populations (UNICEF, Office of Research, 2014). Adaptation strategies must therefore integrate rights-based, intergenerational, and cross-sectoral approaches to prioritize systemic resilience, including equitable access to water, food, education, and disaster risk reduction systems. Global frameworks such as the 2030 Agenda for Sustainable Development emphasize collaboration, accountability, and adaptation to national realities across health infrastructure, equity, and climate action (UN, 2015; UNDP, 2023; UNDRR, 2015). The UN disaster risk management handbook for practitioners further stresses integrating disaster risk management (DRM) with climate change adaptation (CCA) to avoid creating new vulnerabilities and to empower local resilience (Iglesias, 2013). Building on this, adaptation must include both resistance and resilience strategies to manage the impacts of increasingly nonlinear climate variability (Gregg et al., 2018) (Table 3-7).

Despite global commitments like the Brisbane Declaration, the gap between environmental water policy goals and implementation persists, limiting adaptive water governance (Horne et al., 2017). Recognizing these gaps, ecosystem-based approaches and EbA frameworks have emerged as critical strategies, integrating ecological processes into flexible, locally adaptive responses to climate extremes (Gupta & Nair, 2012; Lo, 2016). Recent research further highlights the role of NbS in disaster risk reduction by enhancing ecosystem services, reducing socio-ecological vulnerability, and improving community resilience to extreme events (Bridges et al., 2015; Ruangpan et al., 2023) (Table 3-8).

The Caribbean's vulnerability to hurricanes, droughts, and sea-level rise underscores the need for resilient watershed governance. Climate adaptation efforts are often hindered by high infrastructure costs and restricted financial resources (World Bank, 2016; World Bank, 2018) (Table 3-8). Climate projections for the Caribbean anticipate increased frequency and magnitude of hurricanes, increased drought frequency, and coastal impacts, intensifying risks to water availability, wetland integrity, and socio-economic systems (Hill, 2023; US Global Change Research Program, 2018). Recent frameworks emphasize that bridging DRM and CCA proactively rather than reactively is essential for watershed governance under future climate scenarios (Begum et al., 2014; Murry et al., 2019). Managing these impacts demands adaptive governance that incorporates localized knowledge systems and fosters participatory management (Agrawal, 2008).

3.3.3b Institutional & Governance Challenges

Financial limitations severely impact and constrain watershed protection and hazard mitigation efforts (FEMA, 2020; Inter-American Development Bank, 2010; United Nations Convention to Combat Desertification, 2022). Funding shortages often delay critical infrastructure resilience projects, including erosion control and pollutant management (World Bank, 2018). Global evaluations highlight persistent challenges to watershed governance, especially in integrating risk-informed approaches and climate-resilient approaches (UNDP, 2023; UNDRR, 2015; United Nations, 2015). Education and stakeholder diversity are essential to reduce pollution, promote sustainable resource use (i.e., land use and infrastructure management that affect rates of erosion and hillslope stabilization), and address inequitable water access (World Bank, 2018; Murry et al., 2019; Smajgl & Ward, 2013). However, multi-scalar governance systems often exclude local communities and overlook social vulnerability, limiting adaptive capacity (Baptiste et al., 2019; Rivera-Rentas & Figueroa-Albelo, 2016; Stablein et al., 2022) (Table 3-8). Practical tools emphasize the importance of collaborative frameworks that prioritize equity, transparency, and co-management among diverse user groups (The Nature Conservancy, 2016) (Table 3-8).

In Puerto Rico, effective watershed governance depends on local involvement, awareness, and education, yet public engagement remains low, reflecting governance gaps common across Caribbean watersheds (Rodríguez-Martínez et al., 2004; US EPA, 2020; Viqueira Ríos, 2022). Across the island, inconsistent regulation, limited technical capacity, and post-disaster workforce loss (e.g., post-Hurricane Maria diaspora) continue to exacerbate governance instability and reduce capacity for resilience (Adams & Sastry, 2020; Baptiste et al., 2019; Center for Puerto Rican Studies, 2018; Invest Puerto Rico, 2021) (Table 3-8).

3.3.3c Ecosystem Services & Needs

Across Puerto Rico, balancing the water needs of human populations and ecological systems remains a persistent challenge (López et al., 2001; Murry et al., 2019). Increased urbanization intensifies pressure on freshwater sources, leading to conflicts that prioritize human consumption, especially in urban interfaces, over ecosystem requirements (Ortiz-Zayas & Scatena, 2004). This imbalance often compromises wetland integrity, biodiversity, and essential ecosystem services such as water filtration, habitat provisions, and flood mitigation (López et al., 2001; Murry et al., 2019) (Table 3-8). Historical patterns of land use conversion from forests to agriculture, and subsequently urban development, have further stressed natural recharge areas, reduced surface water infiltration, and heightened runoff and erosion risks (López et al., 2001; Murry et al., 2019; Ortiz-Zayas & Scatena, 2004).

For example, the Guánica Bay Watershed, located in southwestern PR, spans portions of several other HUC 10 watersheds including the RGA, Río Loco, and Río Yauco (Figure 3-1). It faces many of the same systemic pressures as the RGA watershed such as significant land use change contributing to erosion from poorly managed agricultural expansion and road construction (Viqueira Ríos, 2017). Inadequate erosion control has led to increased rates of sedimentation and nutrient loading (Center for Watershed Protection, 2008; Viqueira Ríos, 2017). Excessive runoff containing fertilizers, wastewater, and agricultural effluent contributes to eutrophication and coral reef degradation downstream (Center for Watershed Protection, 2008; Smith et al., 2017). Altered hydrology, degraded coral reefs, climate change impacts, and a decline in ecosystem services also challenge effective management (Guzmán-Morales et al., 2024; Smith et al., 2017). Proposed strategies include targeted erosion and sediment control practices, improved nutrient management through agricultural best management practices, and restoration of hydrological connectivity using natural filtration systems (Smith et al., 2017; Viqueira Ríos, 2017) (Table 3-9).

Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

FIGURE 3-1. Map of watersheds across the islands relative to the RGA watershed.

3.3.3d Infrastructure & Resource Constraints

Across the island, following Hurricane Maria, communities combated both aging and destroyed infrastructure resulting in added impact to livelihoods as well as the vulnerability of communities to further disasters and extreme weather events. Complicating water resource management is aging water infrastructure combined with high water loss through leaks throughout the island (Stablein et al., 2022). These challenges undermine effective management, equitable distribution, and disaster risk reduction (Table 3-8). The infrastructure issues, including high sedimentation rates in reservoirs and limited storage capacity, complicate efforts to maintain adequate water supplies during dry periods, further straining human and ecological water needs (Murry et al., 2019).

(Espacios Abiertos, 2020; Flores-López et al., 2014; Torres de Durand, 2018) (Table 3-8). Limitations on institutional or formalized governance restrict the application of new technologies (Gallick, 2019; Internet of Water, 2020; U.S. Water Alliance, n.d.; Voulvoulis, 2023). In Puerto Rico, efforts to evaluate and introduce new technologies relatively recent, with a strong surge apparent following the devastation of Hurricane Maria (National Science Foundation (NSF), 2023a; NSF, 2023b, National Renewable Energy Laboratory, 2023; RAND Corporation, 2018; University of Pennsylvania, 2023). Only in regions where watershed scale processes became unified under research projects (few exist on island) have efforts at governance largely incorporating community involvement, outreach education, and a call for more representative and inclusive governance (Luhring-González et al., 2023) (Table 3-8).

Like the RGA, the Rio Grande de Arecibo watershed is characterized by socio-economic conditions that are distributed in a spatial discontinuous manner across the watershed, with some areas experiencing disadvantageous conditions associated with water infrastructure development for urban centers (Álvarez-Berríos et al., 2013; Colón-Mercado & Ramos, 2007; FEMA, 2018c; Ramos-Scharrón et al., 2014; Torres-Pulliza et al., 2020). Additionally, scale greatly drives the dynamics of the socio-ecological complexities between urban and rural areas. These inequities also tell a story of institutional and governance challenges.

3.3.3e Long-term Monitoring (Qualitative and Quantitative Indicators)

WHA methodologies reviewed as a part of Literature Review I emphasized biophysical indicators, but at the expense of integrating more comprehensive SES dynamics (Binder et al., 2013; Liu et al., 2007; Parkes et al., 2010). Typical indicators include water quality metrics (e.g., nutrient concentrations, turbidity), sediment and erosion rates, streamflow patterns, and basic socio-economic variables such as water access and land use conflicts (Duan et al., 2022; Hazbavi et al., 2018; Hazbavi et al., 2020; Tsai et al., 2021; US EPA, n.d.; US EPA, 2003; US EPA, 2013) (Table 3-7). Sediment and erosion metrics may be assessed by examining soil erosion rates, sediment yield/load, sediment accumulation in streams and reservoirs (Duan et al., 2022; Hazbavi et al., 2018; Hazbavi et al., 2020; Tsai et al., 2021)

While some models such as SWAT integrate multiple processes (e.g., hydrologic, sediment transport, and nutrient cycling), many standard approaches still treat sediment/erosion and hydrologic dynamics separately (Arnold et al., 1998; Gassman et al., 2007; Neitsch et al., 2011). For example, the Minnesota Watershed Health Assessment Framework (WHAF) demonstrates how integrating biological, hydrological, geomorphological, and water quality indicators can provide a multi-scalar understanding of watershed resilience and degradation (Minnesota Department of Natural Resources, 2014). Distinguishing these components ensures more targeted evaluation of land degradation processed and water system behavior, both critical for SES-based watershed management (Table 3-9). Colon Lopez and Restrepo (2019) assessed water quality trends and socio-economic linkages in the Rio Grande de Arecibo watershed, revealing how localized conditions shaped vulnerability across space and time. Similarly, Luhring-González et al. (2023) highlight the importance of assessing social system metrics alongside biophysical indicators to promote equity and resilience in watershed governance (Table 3-9).

3.3.4 Application to RGA

The following sections review the results of applying the SES WHA Framework to the RGA. This application evaluates the current integration of resilience, governance, ecosystem service preservation, and resource management within the RGA's socio-ecological context. Table 3-10 summarizes the key findings from each assessment category, offering a comparative evaluation of system performance and pinpointing strategic areas for intervention that can be applied at multiple scales. A primary result of this application is the identification of current data gaps and limitations across both social and ecological systems.

TABLE 3-10. Summary of key findings and recommendations from the application of the SES WHA Framework to the RGA.

Assessment Category	**Data Used**	**Key Findings**	**Data needed/missing**	**Recommendations / Strategies to Advance SES Watershed Health**
Climate Change & Disaster Resilience	✓ Municipal HMPs ✓ FEMA Floodplain Maps, hazard zone designations ✓ Peer reviewed studies ✓ Ethnographic fieldnotes	▪ Limited hazard mitigation funding ▪ High post-event instability ▪ Ongoing ecological vulnerability (landslides, erosion, coastal degradation).	○ Updated mapping natural buffers ○ Longitudinal flood/drought monitoring tied to SES outcomes ○ Tracking of Municipal HML Implementation' ○ Systemic data on NbS / EbA adoption/effectiveness ○ LIK/LEK ○ Updated hydrologic and streamflow datasets (including from extreme storms) ○ Risk & vulnerability assessments	○ Strengthen hazard mitigation funding ○ Integrate NbS ○ Promote community-led resilience initiatives.
Institutional & Governance Challenges	✓ Municipal HMPs ✓ Federal policy documentation ✓ Watershed council documentation ✓ Ethnographic fieldnotes ✓ Peer-reviewed/Gray Literature	▪ Highly fragmented governance ▪ Limited institutional coordination ▪ Reliance on informal, reactive measures ▪ Mistrust of institutions.	○ Participation and inclusivity metrics (including for LIK/LEK) ○ Watershed scale management plans ○ Funding and budget tracking ○ Regulatory enforcement records	○ Foster cross-municipality watershed governance councils ○ Build capacity for participatory planning ○ Promote trust-building mechanisms with communities.

	✓ GIS mapping of municipal and watershed boundaries		o Risk and vulnerability assessments	
Ecosystem Services & Needs	✓ Peer-reviewed studies ✓ Geologic and hydrologic reports/maps ✓ Ethnographic fieldnotes ✓ GIS mapping of land use/cover, hydrology, geology, built infrastructure	▪ Sediment runoff from development and repeat slope failures ▪ Tourism pressure exacerbating erosion and deforestation ▪ Road network increases vulnerability of slopes to failure ▪ Reliance on low-capacity aquifers ▪ Ecosystem degradation (harm to ecological services and socio-economic stability)	o Updated land cover/land use datasets post 2017-2024 o High resolution remote sensing change detection analysis o Long-term biodiversity monitoring datasets o Sedimentation rate monitoring/modeling (post 2017) o Water quality datasets (post 2017) o Ecosystem services valuation studies o Tourism impact data	o Implement land-use planning integrating ecosystem service protection o Restore critical habitats (e.g., wetlands, coral reefs) o Manage tourism impacts through regulation and education. Expand biodiversity and water quality monitoring to cover upland-coastal linkages
Infrastructure & Resources Constraints	✓ Post-disaster risk and vulnerability assessments ✓ Peer-reviewed technical studies and analysis ✓ Hazard and built infrastructure datasets	▪ Repairs and slope stabilization remain incomplete ▪ Funding is limited, delayed undermining long-term stabilization ▪ High water loss	o Updated infrastructure inventories w/ condition assessments o Service reliability datasets o Slope stabilization monitoring data; Landslide susceptibility maps at scale	o Prioritize repair and modernization of critical infrastructure o Invest in decentralized, climate-resilient systems o Integrate slope stabilization and hazard mitigation into infrastructure planning

	✓ Ethnographic fieldnotes ✓ Municipal HMPs	▪ Limited application of new technologies post-Maria ▪ Uneven capacity across municipalities. ▪ Damaged, aging infrastructure complicating recovery	o Funding pipeline transparency o GIS data of critical facilities	o Develop transparent funding pipelines and reporting mechanisms.
Long-term Monitoring (Qualitative / Quantitative Indicators)	✓ Peer-reviewed studies on flood frequency/hydrologic disturbance ✓ Water quality evidence ✓ Ethnographic fieldnotes	▪ Chronic flood disturbance (valley/coastal inundation) ▪ Downstream water quality degradation linked to upland erosion, ag inputs, sewage failures ▪ Urban sprawl impacts ▪ Incomplete / discontinuous ecological datasets.	o Continuous stream-gauge records o Updated rainfall intensity-duration-frequency for RGA o Routine water quality monitoring o Sediment monitoring o Slope stability assessments o Supple-demand metrics on water availability	o Develop integrated watershed monitoring programs o Establish open-access data portals for decision-making support. o Pair agency monitoring with community science to ensure data interoperability for SES health assessment

3.3.4a Climate Change & Disaster Resilience

Distribution of federal hazard mitigation funding across Puerto Rico remains limited, heightening the need to assess socio-ecological vulnerabilities within the RGA watershed. Watershed management efforts face challenges in supporting post event recovery, from landslide-inducing sediment loading in mountain regions to coastal erosion and habitat loss along the coastline. In Rincón, ongoing recreational use in damaged areas has further hindered ecological succession and stabilization (Viqueira Ríos, 2022).

Hazard mitigation plans (HMPs) for several RGA municipalities (e.g., Adjuntas, Añasco, Las Marías, Maricao, Mayagüez, Rincón) acknowledge persistent ecological instability following Hurricane María, subsequent year-long, daily earthquakes, and Hurricane Fiona (Municipio de Adjuntas, 2020; Municipio de Añasco, 2020; Municipio de Las Marías, 2024; Municipio de Maricao, 2021; Municipio de Mayagüez, 2020; Municipio de Rincón, 2020). The HMP for Lares is unavailable at the time of this writing. The Añasco HMP, for example, highlights critical needs related to watershed management, erosion and sediment control, forest and vegetation management, preservation and restoration of wetlands, habitat preservation, and stabilization of hillslopes (Municipio de Añasco, 2020).

3.3.4b Institutional & Governance Challenges

The RGA watershed is characterized by fragmented governance, limited institutional coordination, and a lack of reliance on formal resources (Orengo-Aguayo et al., 2019; Rodríguez-Madera et al., 2021). Cultural, demographic, and economic barriers reinforce this fragmentation, resulting in localized, reactive management strategies rather than unified, watershed-scale planning. In many cases, hazards are not addressed until significant property loss or life-threatening conditions occur. These challenges are not a condemnation of communities or municipal governments, but rather a reflection of systemic resource limitations, institutional disconnection, and socio-economic stressors.

Recent developments, including the termination of FEMA's Building Resilient Infrastructure and Communities (BRIC) funding for Puerto Rico (Fiscal years 2020-2023), further undermine recovery and resilience efforts (Central Office of Recovery, Reconstruction and Resilience [COR3], 2025; Centro de Periodismo Investigativo, 2025). The abrupt cancellation of these funds at the national level not only disrupts hazard mitigation projects, but also deepens existing challenges related to consistent monitoring, implementation, and institutional trust. These cumulative factors limit the ability of watershed governance systems to operationalize SES resilience strategies and maintain public confidence in recovery and adaptation initiatives.

Watershed management tends to be restricted to municipal boundaries only and largely reactive, hindered by constrained financial and human resources and compounded by public mistrust of agencies (e.g., PRASA - Puerto Rico Aqueducts and Sewers Authority and Aquaducto). Chronic socio-political stressors (e.g., economic instability, wealth disparities, and aging infrastructure) further strain governance capacity (Figueroa & Roque, 2024; Gearing, 2023; McBride et al., 2020; Nelson et al., 2023). Efforts to improve watershed governance have emerged, such as the Iniciativa de Cuencas del Oeste, a multi-partner watershed council for RGA and Yaguez watersheds, in which the author participated for two years. The working group identified several major challenges that highlight significant research and operational gaps throughout the RGA watershed (Table 3-8).

Further complicating governance are administrative mismatches in that most agency jurisdictions align with municipal boundaries, not watershed boundaries. A significant portion of the population remains unofficially registered or entirely outside formal systems, complicating monitoring, early warning systems, and hazard mitigation efforts. Informal property ownership, land use practices, and unregulated development (e.g., informal roads, housing construction) exacerbate socio-ecological vulnerabilities. Finally, limited institutional outreach, restricted by funding and demands of a multi-hazard landscape, further weakens community engagement and trust. Mistrust of institutions, fueled by political instability and corruption, undermines the formation of strong watershed-scale governance networks need for integrated, resilient management.

3.3.4c Ecosystem Services and Needs

In Rincón, particularly in the region encompassing Maria's Beach, poorly planned development and land-clearing activities have led to significant sediment runoff into marine environments, degrading water quality and impacting sensitive ecosystems like coral reefs, seagrass beds, and mangroves (Viqueira Ríos, 2022). As Rincón, located along the coast at most northeastern point of the watershed, serves as a major tourism center for the western side of the island, understanding the impacts of tourism-driven land use is essential for watershed scale management (Chapter 2, Figure 2-1). Viqueira Ríos (2022) found that high visitation rates resulted in illegal parking, deforestation, and uncontrolled land use, exacerbating erosion and ecosystem degradation. This underscores the challenge of balancing public access with ecosystem preservation. Additionally, in Mayagüez, located at the southeastern boarder of the watershed, the geology limits groundwater development, as fractured rock formations offer low storage capacity (Figure 3-1) (Gómez-Gómez et al., 2014; Mattson, 1960; Rodríguez-Martínez et al., 2004). This constraint forces reliance on surface water sources that are vulnerable to seasonal fluctuations, necessitating careful management of water resources to avoid over-extraction during dry periods (Rodríguez-Martínez et al., 2004).

3.3.4d Infrastructure and Resource Constraints

Following the impact from Hurricane María, there was a surge in research and federally supported efforts aimed at evaluating hazards impacts and mitigation approaches (Bessette-Kirton et al., 2018; Bessette-Kirton et al., 2020; FEMA, 2017; Feng et al., 2020; Lin et al., 2020; National Institute of Standard and Technology, 2022; Orengo-Aguayo et al., 2019; Rodríguez-Madera et al., 2021; Scott et al., 2024; Tyson et al., 2023; U.S. Army Corps of Engineers, n.d.; USGS, n.d., West et a., 20210). However, despite these efforts, implementation of infrastructure repairs and slope stabilization remains limited, incomplete, and highly challenging across both watershed and island scales. The recovery and prevention processes are hampered not only by the island's complex topography and multi-hazard, but also by persistent delays in funding for hazard mitigation and long-term SES stabilization.

3.3.4e Long-term Monitoring (Qualitative and Quantitative Indicators)

The climate, topography, and land use practices in Puerto Rico all contribute to the complex flood disturbance regimes on the island (Birdsey & Weaver, 1982; Clark & Wilcock, 2000; Daley et al., 2003; Staes et al., 1994; Woodruff et al., 2008). Due to poor drainage systems throughout the watershed, inundation of streets in the valley to coastal zones is common (on a near daily basis) during the bimodal rainy seasons, as observed during the author's fieldwork

(2018 – 2024). High frequency flood peaks during the hurricane season months (June - November) further strain watershed resilience (Hernández Ayala et al., 2017). According to Harmsen and Goyal (2017), floodwaters fully inundate the Añasco valley floodplain 17 of 31 years or an average of once every 2 years. Extreme overland flow on saturated soils and river flooding during this period also contributes to the landslide disturbance regime (Larsen & Simon 1993; Larsen & Torres-Sanchez 1998; Scatena & Larsen 1991).

Compounding these flood risks are widespread water quality challenges across these ecosystems and the zones identified and described in Chapter 2. Runoff carrying agriculture chemicals (e.g., fertilizers, pesticides, and manure) and sediment from erosion and mass wasting events degrades water quality, impacting ecosystems, fisheries and coral reef health in Mayagüez Bay (Caribbean Coral Reef Institute, n.d.; Duque & Melesse, 2016; Ramos-Scharrón et al., 2014; Tyson, unpublished; USDA Caribbean Climate Hub, 2018; Warne et al., 2005). In urban centers like Mayagüez, illegal sewage discharges, malfunctioning sewer systems, and livestock runoff contribute to high fecal contamination levels, posing major public health and ecological risks (Rodríguez-Martínez et al., 2004). Additionally, land use fragmentation, accelerated since the widespread abandonment of agricultural lands in the 1950s, exacerbates stormwater management challenges (Castro-Prieto, 2013). Urban expansion and increased impervious surfaces overwhelm existing infrastructure, especially where municipal and watershed boundaries align.

3.4 Discussion

The findings of the literature reviews highlight the importance of adopting a systems-based perspective when assessing watershed governance challenges. This approach emerged from a cross-comparison of studies and frameworks that collectively emphasized the interplay between institutional shortfalls, ecological degradation, and governance complexity, particularly in the context of climate change impacts, land use/cover change, and stakeholder conflict/engagement (e.g., Armitage et al., 2009; Folke et al., 2005; Pahl-Wostl, 2009). One key theme identified across multiple sources is the need for inclusive, multi-scalar stakeholder networks that actively engage diverse communities, including women, children and youth, persons with disabilities, Indigenous groups, and migrants (Arora-Jonsson, 2011; Bennett et al., 2016; Ensor et al., 2015; Hiwasaki et al., 2014; Phadke et al., 2015; UNDRR, 2022). Integrated Watershed Health Framework (IWHF) incorporates ecological, socio-economic, policy, and cultural dimensions to better reflect complex drivers of resilience and degradation (Aredo et al., 2024) (Tables 3-1, 3-3, 3-6).

While the SES WHA Framework (Table 3-9) incorporates inclusion, it moves beyond the IWHF by and deepens this lens by emphasizing equity as a measurable dimension within both institutional design and indicator selection, particularly through the lens of team science and knowledge co-production. This inclusive orientation supports the co-creation of resilience strategies by leveraging diverse knowledge systems (LIK/LEK), priorities, and lived experiences of each group (Bennett et al., 2016; Ensor et al., 2015; Hiwasaki et al., 2014). This Framework also builds upon the existing categories by incorporating disturbance trajectories and compounding risk scenarios as central to watershed resilience analysis (Table 3-7, 3-8, 3-9). This advances a dynamic, adaptive governance system capable of responding to current and future socio-ecological challenges.

The application to the RGA watershed highlights how highly varied land use patterns across distinct topographic zones create complex governance challenges (Table 3-10). Sustainable watershed management requires dynamic approaches that account for local variations in cultural framing, ecosystem service dependencies (e.g., upland and lowland farming, irrigation, drinking water, forest cover), and land use pressures (Reference Map, Chapter 2, Figure 2-7). These localized factors, coupled with divergent perceptions of risk and connectivity across mountain, valley, and coastal communities, directly influence resilience capacity and social vulnerability (Schipper, 2015; West et a., 2021) (Table 3-9) (Reference Map, Chapter 2, Figure 2-3). Gaps in hazard mitigation, ecosystem preservation, infrastructure adaptation, and governance coordination reveal the need for integrated responses across interconnected zones in the RGA (Table 3-10). Strengthening ecological connectivity, such as managing upland erosion to protect downstream coastal resources, requires governance systems that operate beyond municipal boundaries and engage diverse community perspectives and knowledge systems.

Furthermore, the system interactions are not uni directional. Litterfall, downed stands, slope failures, forest fragmentation resulting from landslide and wind impact, and increased sedimentation to rivers directly and indirectly negatively affect local economies and infrastructure across the island (Scatena & Lugo, 1995; Shiels et al., 2008). Conversely, land use practices such as the building of roads can segment slopes influencing susceptibility to failure. Likewise, agriculture contributes to reduction of stands, patch dynamics, species distribution, and erosion rates (Larsen & Torres-Sánchez, 1998; Walker et al., 1996). An evolutionary analysis of dominant and explanatory response variables incorporates such complex feedback loops within a socio-ecological system. An adaptive, integrated management approach is therefore more responsible to the multi-system impact of punctuated events on the scale of Hurricane Maria (Lugo, 2018) (Table 3-7, 3-9).

Burgos-Rodriguez (2020) speaks to the financial challenges affecting social system resilience and adaptive capacity through a historical evaluation of the Puerto Rico Oversight, Management, and Economic Stability Act (PROMESA). PROMESA established a federal Oversight Board to manage Puerto Rico's financial crisis, significantly affecting local governance. Historically, environmental considerations are marginalized under PROMESA's economic priorities, leading to diminished local authority over environmental regulation and policy. Burgos-Rodriguez asserts that Puerto Rico's Constitution includes a mandate to conserve and sustainably manage natural resources, but PROMESA's authority often supersedes local legislation. The article highlights the vulnerability of Puerto Rico's ecosystems to climate change, including reduced freshwater availability, rising temperatures, and intensified storms. Burgos-Rodriguez further argues that budget constraints under PROMESA hinder climate change mitigation and adaptation strategies, exacerbating environmental risks. Therefore, the assessment advocates for a balance between fiscal recovery and environmental sustainability, urging adherence to Puerto Rico's constitutional environmental mandates. Burgos-Rodgriguez (2020) calls for innovative governance that integrates environmental considerations into economic planning to ensure long-term resilience and compliance with federal environmental laws.

3.4.1 Role of Governance in Watershed Health

Effective disaster risk management is challenged by fragmented governance structures across the Caribbean region and including in the RGA (Eckstein et al., 2021; Mycoo & Bharath, 2021; UNDRR, 2022) (Table 3-10). Coordination among local, national, and international bodies is critical but often leads to disjointed efforts when institutional priorities and capacities diverge

(Baptiste et al., 2019; World Bank, 2018). For instance, varying priorities and institutional capacities between disaster risk reduction and sustainable water management create governance challenges in ensuring comprehensive planning (World Bank, 2018). Additionally, across Puerto Rico, there is a need for governance beyond traditional watershed boundaries (Murry et al., 2019; Smith et al., 2017). Inter-basin transfers and upstream land use decisions can produce significant downstream impacts, underscoring the need for integrated landscape-scale governance that addresses both local and global stressors such as climate change (Murry et al., 2019; Smith et al., 2017) (Table 3-8, 3-9). Though a highly systematized and institutionally supported watershed scale governance system prioritizing climate adaptation, inclusive of hazard mitigation, boasts many advantages of less well-developed systems of governance, it is not without its challenges. Over administration and investments underwritten primarily by corporate or profit based entities could bog down processes in bureaucratic inefficiencies, competing goals between stakeholders, and introduce ethical considerations. It is then up to a healthy institution as well as the social system to address and ensure transparency and integrity in the processes and approaches.

In hazard-prone regions, effective watershed governance is characterized by stakeholder engagement across multiple levels, from conservation organizations and government agencies to citizens and private entities. Broad participation strengthens accountability, enhances local risk awareness, and fosters willingness to invest in hazard mitigation. This may take the form of nurturing a culture of awareness through public outreach and education across multiple platforms (e.g., K-12; community organizations; local and state governments; materials readily and easily available on public facing websites). Institutional adaptability and public outreach are essential to support informed community decisions, early warning systems, and coordinated landscape management (Table 3-7, 3-9). Ground-up approaches offer critical pathways to strengthen socio-ecological resilience amid climate pressures and governance fragmentation.

Institutional frameworks with a long history of regulating local practices and flood prevention and mitigation measures assist in supporting the local controls on the landscape. Depending on the adaptability of the institutions, the incorporation of local risk perceptions may be enhanced or muted in the development of risk-informed governance. At the site level, approaches to governance based on rule of law and largely effective institutional involvement, socio-environmental controls impact or are impacted by the development, maintenance, and incorporation of early warning systems. This reflects both the effective implementation of technology and research/assessments and the social system decisions on where and how to build and interact with the environment. Public outreach by institutions informs site specific hazard control and management.

3.4.2 Implementing improved management beyond the SES WHA

Advancing sustainable management across the watershed will depend on scaling up the use of NbS, EbA, and CBNRM (Table 3-8, 3-9). These approaches offer critical opportunities to build long-term socio-ecological resilience, strengthen local adaptive capacity, and promote equitable risk-informed governance aligned with the integrated framework developed in this chapter. For example, rainwater harvesting is a NbS particularly useful in high hazard zones like the Caribbean. In the RGA watershed, this would have been a particularly useful socio-ecological solution when drinking water conveyance infrastructure failed and drinking water was unavailable post Hurricane María (Ruiz-Avilés et al., 2022). Collaborative approaches, like CBNRM, are well suited for regions particularly characterized by a backdrop of historic, disaster induced, and climate driven land use and cover changes, such as is the case throughout Puerto Rico. To evaluate the suitability of CBNRM as a resource management approach, it is increasingly important to examine and incorporate regional as well as historical context for the spatial, temporal, economic, political, and social character of the managed resources (Bajracharya et al., 2005; Leisher et al., 2012; Nolte et al., 2013; Sudtongkong & Webb, 2008).

Daily decisions on the landscape incorporate a risk informed community as well as commonly held awareness of regulations and a basis for controls. Multiple sectors (transportation, water, utilities, construction, etc.) are governed by regulations and this trickles down to community level understanding and alignment of practices. This is typified by household level adoption of flood prevention, erosion control and slope stabilization/mitigation measures (i.e., on agricultural lands). And, finally, there is an increase of trust in institutions and an awareness of processes upstream and downstream and impact of land use decisions. To move forward, unified, regulated, structured, but also adaptable, risk-informed, and sustainable watershed scale governance will require the encouragement of a watershed scale mindset by not only the municipal leadership, but also communities

This involves maintaining an updated repository of information on disaster risk, regularly evaluated and shared to accurately capture hazard exposure and vulnerability specific to each event. Such a knowledge base is intended to build a strong foundation of disaster awareness across all societal levels. A crucial component of the SES WHA Framework is implementing risk-informed strategies that address the needs of diverse demographic and socio-ecological interactions (Table 3-9). These strategies require thorough assessment of vulnerability, capacity, and exposure, incorporating a multi-sectoral perspective that extends into land use policies, urban planning, and land degradation evaluations. Urban landscapes, characterized by concentrations of people, infrastructure, economic activity, present levels of complexity that challenge socio-ecological climate risk mitigation (e.g., housing, infrastructure deficits, juxtapositions of wealth and poverty, heat stress, stormwater management, air pollution) (Revie et al., 2014). Additionally, urban, rural transition zones can be unstable areas due to rapid and sometimes unplanned change (particularly in the global south) (Aydın & Çetin, 2022; Marshall et al., 2022; Ravetz et al., 2013).

Promotion of transboundary cooperation further enhances this SES WHA Framework, with a focus on ecosystem-based approaches that manage shared resources effectively, especially along coastlines and river basins. This cooperation supports a regional approach to risk reduction, safeguarding environments that traverse political and geographic boundaries. Investment from both public and private sectors plays a pivotal role, driven by engagement from multi-sector entities including academia, scientific communities, businesses, local organizations, and research bodies. Diverse funding pipelines at all levels are encouraged to ensure adaptability and sustainability in resource allocation. The SES WHA Framework advocates for balanced participation with the inclusion of incentives and penalties to drive the implementation of NbS and adaptive management strategies (Table 3-9). A holistic approach to strengthening socio-ecological resilience underpins the entire framework, addressing areas such as food security, health, social safety nets, and business continuity, notably within local agriculture and tourism. This approach discourages unplanned habit changes and stresses the priority of reducing ecosystem degradation, supporting biodiversity, and fostering a shift from anthropocentric to nature-centered perspectives. By promoting this mindset shift, communities, land-use planners, and municipal leaders can better align development goals with ecological stewardship, reshaping human-environment interactions (Table 3-9).

3.5 Conclusions

In response to research question 1, this study demonstrates that current watershed management frameworks inconsistently and inadequately incorporate LEK, LIK, EJ, and SEV. While some global and regional guidance acknowledge these dimensions in principle, they are rarely operationalized or measured systematically. Through the literature review and case study application of the framework to the RGA, it becomes evident that fragmented governance structures, limited forma engagement of marginalized communities and insufficient integration of cultural and historical knowledge contribute to this gap. Identifying practical and conceptual strategies to better integrated LEK, LIK, EJ, and SEV into watershed health assessments and management addresses research question 2. These include co-creative processes such as CBNRM, participatory monitoring, NbS, and risk-informed, justice-centered planning. The SES WHA Framework developed here translates these concepts into actionable indicators and assessment domains, offering a structured approach to include place-based management.

In answering research question 3, this research presents a transferable, interdisciplinary framework grounded in resilience, equity, and systems thinking. The RGA case study application highlights persistent challenges (e.g., inter-municipal coordination, limited hazard management capacity, and infrastructure vulnerability) while also identifying pathways to strengthen resilience through CBNRM and NbS integration. These findings offer a transferable model for applying SES frameworks in similarly complex or data-limited contexts and embeds vulnerability and justice as core assessment criteria. Additionally, the framework presented in this chapter is applicable to multiple scales of assessment, from individual municipal/county levels to the entirety of the watershed. The primary challenges facing watershed management at the watershed scale, encompassing both environmental and social complexities, highlight the need for an integrated approach to address these issues effectively. Given the acute challenges facing the region, integrative watershed management and NbS are poised to strengthen adaptive capacity in the face of modelled escalating climatic extremes (Mycoo & Bharath, 2021; Mycoo & Roopnarine, 2024). Murry et al. (2019) highlighted the interconnectedness of governance, socio-ecological challenges, and management strategies, underscoring the need for inclusive, adaptive, and multi-disciplinary approaches to sustainably manage watersheds in Puerto Rico and the Caribbean. I argue for the inclusion of not just the literature exemplifying approaches to assessing watershed health, but also the international guidance from the UN, UNDRR and the SDGs to center equity, participation, and knowledge pluralism. The RGA case study serves not only to demonstrate the practical application of the framework, but also a baseline for ongoing SES watershed health assessments, complementing related assessments presented in Chapter 4, Assessing Socio-Ecological Vulnerability: A Holistic Approach.

Though the RGA watershed encounters its own unique socio-ecological challenges from ridge to coast, I offer that it is relevant, if not essential, to evaluate the assessment criteria based on, in part, assessments and studies conducted in other watersheds across the island as well as to draw on this international body of literature. The degree of resource sharing and limitations across municipalities, shared burdens and challenges, particularly following extreme events, and complexities of managing from ridge to coast offer an opportunity to learn from challenges and approaches identified in other locations. Ultimately, examining watershed health from a SES perspective contributes to the climate justice literature by highlighting how environmental impacts and management strategies intersect with social equity concerns. This SES WHA framework aligns with current global thinking in sustainability science, disaster risk reduction (e.g., Sendai Framework, SDGs), and climate adaptation. It's built not just to measure, but to inform better, more inclusive governance and action through deepened understanding of watershed management as interconnected systems that support both human and ecological well-being, fostering more holistic and equitable management practices.

3.6 References

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CHAPTER 4 – ASSESSING SOCIO-ECOLOGICAL VULNERABILITY: A HOLISTIC APPROACH

4.1 Introduction

Puerto Rico, the smallest and easternmost island of the Greater Antilles in the Caribbean, is characterized by an increasing magnitude of hurricanes, frequent landslides, intense rainfall, and dynamic land use changes. Extremes of wealth and poverty further complicate the implementation of sustainable land use planning and climate adaptive, integrated watershed management. Historically, landslides and high rates of erosion occurred with high frequency throughout the island annually, particularly due to the compound effect of heavy anthropogenic modification (primarily agriculture and roads) (Colon & Anaya, 2000; Jibson, 1987; Larsen, 2012; Larsen & Torres-Sánchez, 1998; Larsen & Santiago Román, 2000; Larsen & Webb, 2009). Agricultural practices vary from small farms, supporting crops for local consumption and small to mid-size coffee plantations (some with export operations), to large scale agricultural commercial production. Several biotech and bio-agricultural companies contribute to land use practices and the local economy maintain operations on the island, capitalizing on the extended tropical growing season, fertile soils, and tax incentives (e.g., 2008 Act 73). These interrelated factors, within a socio-ecological system (SES) already vulnerable to extreme weather events, necessitate proactive hazard mitigation strategies that enhance resilience against climate-driven hydrological disturbances and geomorphic instability.

The combined impact of hurricanes Irma (September 7, 2017) and María (September 16, 2017), the strongest storm to hit Puerto Rico in more than 80 years, caused an unprecedented number of landslides and extensive damage to roadways, power, and communication networks

(Montoya-Rincon et al., 2023; Scott, 2018). The storms also caused widespread geomorphic change affecting short and long-term water supplies throughout the island. The affected river networks, aquifers, and reservoirs are essential for drinking water and irrigation (Scott, 2018). 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). Subsequently, between 2019 and 2022, Puerto Rico faced challenges from year-long, daily earthquake tremors, the COVID health crisis, and the impact of Hurricane Fiona (September 18, 2022). These added stressors further impair SES, recovery, and mitigation.

Beyond the physical system impacts, the agricultural sector also experienced severe impact. The economic loss related to agricultural yield across the island as a result of Hurricane María measured over $780 million (Marrero et al., 2022). Before the storms, 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 María, this dependency increased as farmers struggled to recover from the ~$2 billion in total losses (Rodriguez-Cruz and Niles, 2021). Institutions across Puerto Rico continue to strive to address the challenges of the government-debt crisis that began in 2014 and complicated by the impact of repeat crisis (Financial Oversight & Management Board for Puerto Rico, n.d.).

Within the Río Grande de Añasco (RGA) watershed, the impact of the storms and the resulting extreme and paired hazards on systemic complexities and the socio-ecological landscape are as diverse as the watershed which rises from the coast to mountains. For example, while the vast majority of landslides, 16,000 in total, occurred within areas dominated by forest land cover, over 1,000 landslides occurred within areas designated by crops in lowland and mountain farming communities. Flooding and sediment deposition from widespread slope failures (>70,000 island-wide) decimated valley and mountain crops beyond normal, and already high, rates of sediment yield and mass wasting and included the mobilization of agricultural sediments along the central channel, the Añasco River (Bessette-Kirton et al., 2019; Nilawar et al., 2017; Clark and Wilcock, 2000; Hughes & Schulz, 2020). 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). Post-María risk and hazards studies primarily focused on island-scale analysis, leaving integrated, socio-ecological assessments of geomorphic change, sediment yield, slope stability, and carrying capacity at the watershed scale underexplored.

Within disaster risk reduction studies, landslide susceptibility, impact, and risk tend to be evaluated in isolation from assessing social vulnerability and capacity for resilience. This chapter offers unique insights that are not captured through traditional quantitative modelling or geospatial analysis (Schenk, 2015). The integrative approach to dynamic, relational assessments of these systems through a study of the spatial correlation between the distribution and density of the landslides and slope, soils, road networks, river channels, and land use/land cover. Comparing these results with those of a social system vulnerability spatial analysis, identifies coupled system feedback loop and advances traditional erosion risk analysis. To address this shortfall in localized and watershed scale assessments, the research presented undertakes the following research questions:

- How do slope gradient, soil characteristics, proximity to road networks and river channels, and patterns of land use/land cover correlate with the spatial distribution and density of landslides?

- How can spatial identification and characterization of discrete points of susceptibility and vulnerability across built and natural landscapes generate data that contribute to hazard mitigation and ecosystem management efforts?
- How does including social vulnerability data in a geospatial landslide impact analysis advance understanding of social-ecological vulnerabilities and capacity for climate adaptation?

4.2 Methods

4.2.1 Analysis Framework: Landslide Impact Analysis (LIA) and Social Vulnerability

Assessing landslide impact and distribution reveals key areas of concern within the physical landscape. The Landslide Impact Analysis (LIA) presented here utilizes a multi-stage geospatial analysis to assess landscape susceptibility, risk, and vulnerability. It visualizes the spatial relationships of several key variables common to landslide assessments and landslide susceptibility analysis as well as variables unique to the built and managed environment of the watershed (e.g. distribution of clay dominant soils, slope (particularly strong to extreme), roads, stream input points, and land use). This exploration enunciates the impact of landslides on the landscape through identification of areas of vulnerability at the watershed, municipal, and barrio scale. However, to achieve the goal of a systems level evaluation of socio-ecological interactions, it is necessary to integrate the LIA with an assessment of social vulnerability (Figure 4-1).

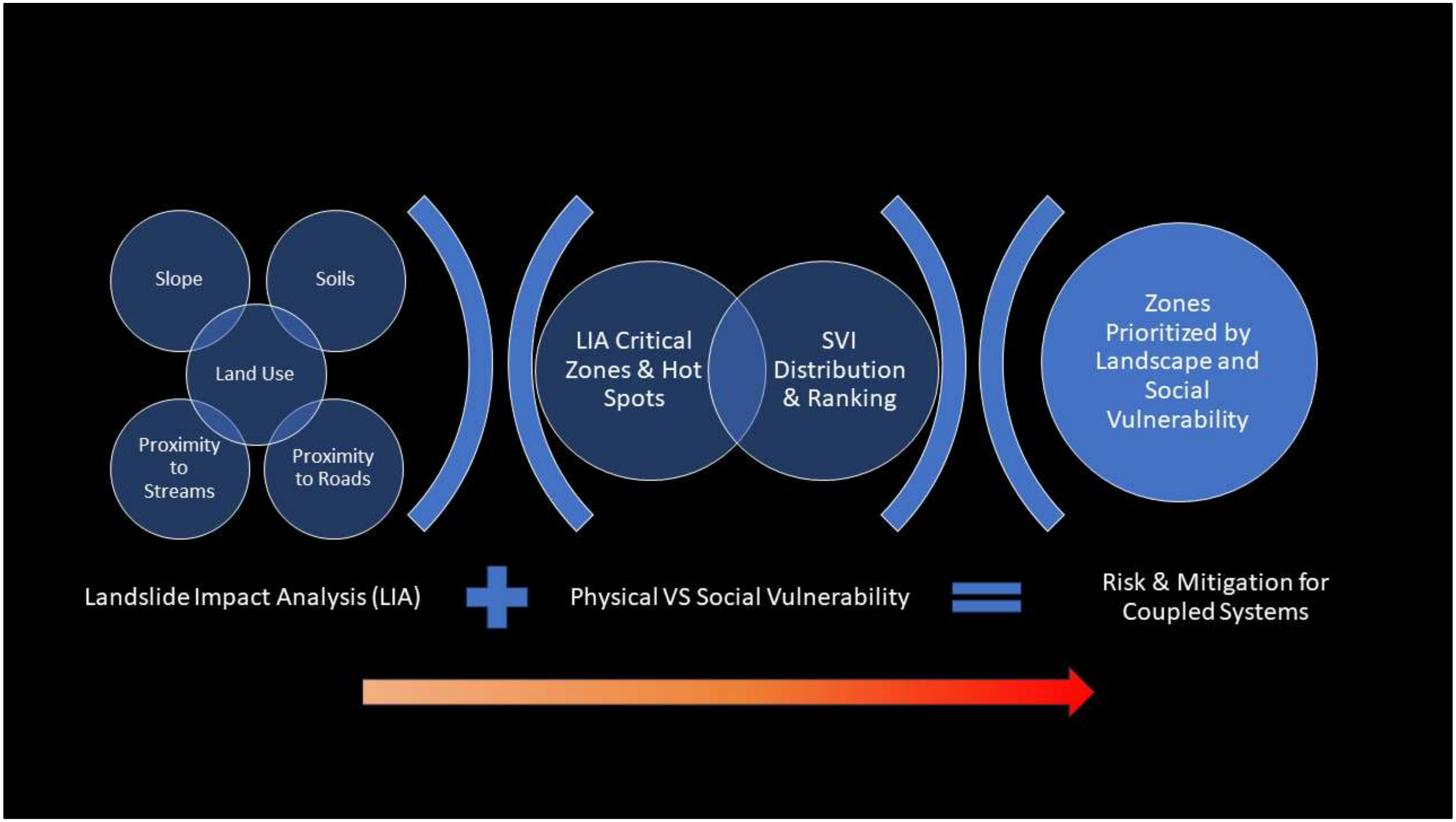


FIGURE 4-1. Diagram illustrating the overall coupled systems analysis assessing impact, susceptibility, and vulnerability.

The LIA analysis was conducted using ESRI ArcMap and ArcPro using a four-phase spatial workflow (Figure 4-2). Phase I spatially evaluated landslide distribution and landslide density relative to slope. Phase II incorporated a spatial analysis of the correlation between landslide density, slope, and soil type. Phase III evolves the analysis to include an assessment of the spatial correlation between landslide and roads (where slides > 50) within a ~100m (~325ft) buffer and streams within a ~150m (~500ft) buffer. The results of these geospatial analyses are combined to identify hot spots of vulnerability. Phase IV further evaluates impact and vulnerability through a spatial analysis of the correlation between landslide density, previously identified vulnerable stream segments and landslide density.

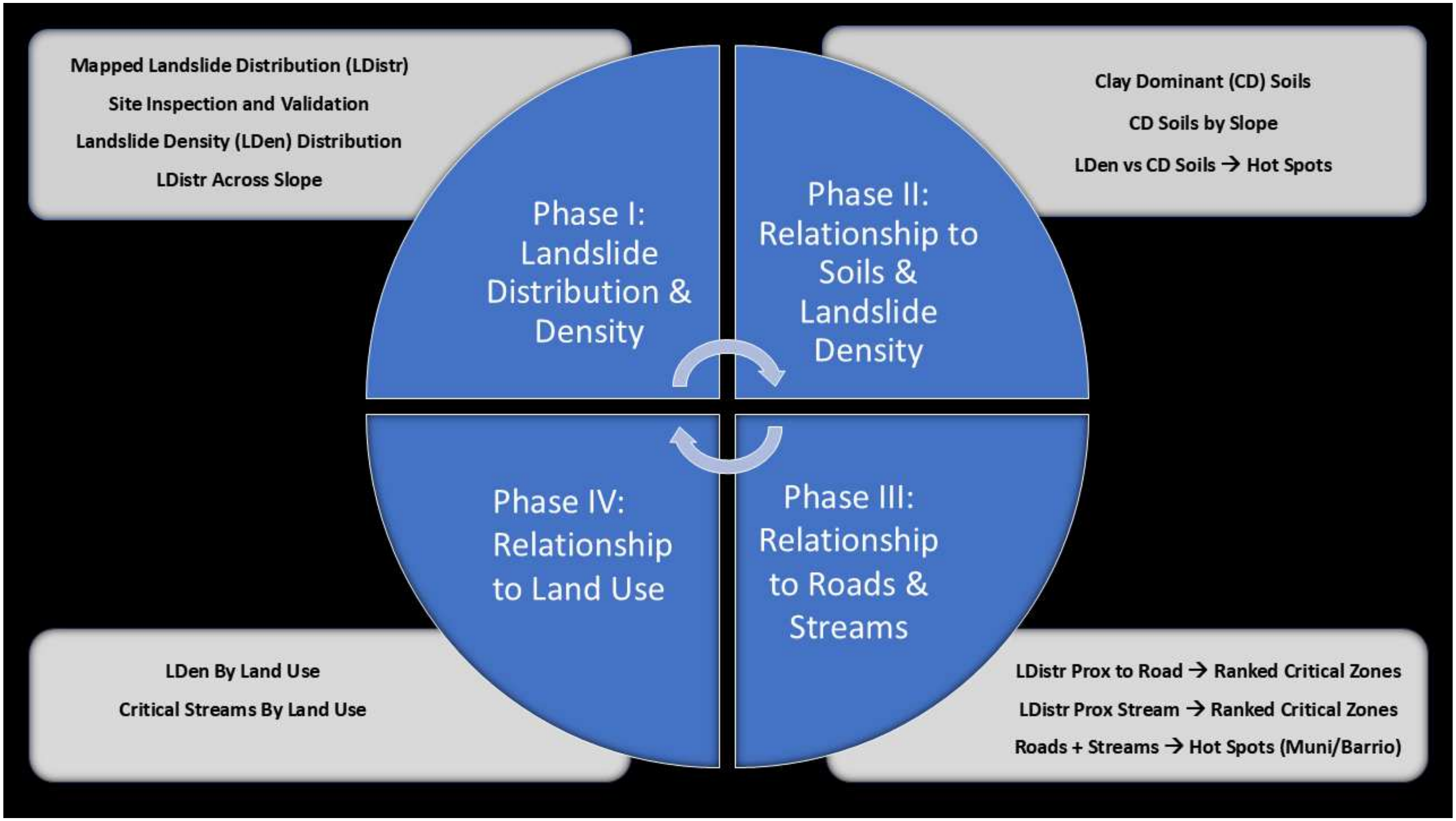


FIGURE 4-2. Diagram illustrating the four phases of the LIA.

Data processed for use throughout the phases detailed in the above figure are listed in the table found in Appendix B. Association of data layers with the listed Analysis Phase is based on whether the layer was used as an input to the analysis. Other layers may have been used to display the results in the final map. Data sources include field validated landslide site assessments.

A spatial analysis examining social vulnerability within the RGA Watershed was conducted using data from the CDC Social Vulnerability Index (SVI), Theme 1, including data from 2014, 2018, and 2022. The analysis aimed to assess social-ecological vulnerability in relation to built infrastructure (roads) and ecosystems (impacted streams, soils, slope and land use/cover). To identify areas of combined physical and social risk, the SVI data was spatially integrated with results of the LIA. Considering social vulnerability unveils patterns in the distribution of data relative to the management and role of the built environment and land use. It also provides a starting point for understanding social systems factors driving land use practices and feedback loops inherent to a municipality or barrio's capacity to prepare for and respond to landslide hazards. This coupled systems analysis facilitates targeted, place-based prioritization of areas where resource allocation for sustainable hazard mitigation and enhancement of community-based capacity building may be maximized.

4.2.1a LIA, Phase I: Landslide Distribution and Density

To assess landslide distribution relative to slope, a slope map was derived from a prepared Digital Elevation Model (DEM) layer clipped to the bounds of the watershed (Appendix D.1.1). To accomplish this, the ArcGIS Spatial Analyst Slope function evaluates the data using a 3X3 roving window over each cell using neighboring values of the raster cells to determine its slope (e.g. gradient or steepness). This analysis assessed slope as a percentage where flat elevation might receive a classification of 0% slope and a 45-degree surface is 100% slope.

A landslide density map was derived from the landslide point data layer. Using the ArcGIS Spatial Analyst Point Density tool (ArcGIS 10.8.2), a slide density map is computed by calculating the magnitude-per-unit area (km/km^2), or the number of point features that fall within a neighborhood around each cell. Analyzing using density creates a continuous surface layer that shows the concentration spread or distribution of point features across a landscape.

Phase I also included a field component. This involved mapping of the landslide data (pre-publication) across the watershed and identification of a range of sampling sites for ground validation. Landslide field assessment sites were identified across ranges of elevation, slope, topography, land cover, escarpment type, and proximity to streams and roads. Initial field assessments were conducted prior to current island scale landslide mapped assessments (Bessette-Kirton et al., 2019b; Cerovski-Darriau, 2022; Hughes & Schulz, 2020; Ramos-Scharron et al., 2020). These field data (GPS point and site observational data) were collected during a scoping trip in June 2018 and then throughout 2019-2020. The initial field evaluations occurred prior to publication and release of the full dataset for the island by Bessette-Kirton et al. (2019a) and were validated against data from FEMA (Federal Emergency Management Agency) and IITF (International Institute of Tropical Forestry). This was necessary in order to perform a higher resolution and ground evaluation of the data and the ecosystem response. Subsequent site visits (2023) assessed key sample sites to verify ecological response (vegetation regrowth) and stabilization without human intervention.

4.2.1b LIA, Phase II: Relationship between Soils and Landslide Density

A more critical examination of the role of soil type with reference to slope failures within the Añasco watershed required geoprocessing, reclassification, and analysis of SSURGO soils data. The data was obtained through the NRCS Soil Data Viewer, merged to obtain one soil data layer for the island. The data for the watershed was extracted using the Clip geoprocessing tool with a watershed layer as the boundary. Using the Spatial Join function in ArcMap, the raw spatial data was joined with soil texture class descriptions provided in a MSAccess database. The classes were aggregated and ArcMap Field Calculator used to assign a new value. The final soils maps required reclassification in order to streamline the data to within a more generalized sand, silt, clay classifications.

Isolating for the distribution of clay soils across the watershed, the analysis was further refined to identify those areas where the percent clay exceeded 40%. Following selection of clay only data from the full dataset, the data was further refined by reclassifying the data to rank the % clay from which those polygons with % clay greater than 40% were isolated and a new layer generated. A spatial join based on spatial location and a sum count of points per polygon area between the resulting data layer (polygon feature layer) and the landslide point feature layer dataset. Then, those areas containing landslide points greater than or equal to 300 were extracted for the final map layer.

To further refine this analysis as relates to slope, areas where clay soils dominated (over silt and sand) by greater than 50% were extracted. Using a spatial join, this new feature layer was correlated with the polygon feature classified slope layer. The goal of this step in the phase was to achieve a ranked designation and relationship between clay dominant soils and slope illustrating which municipalities may need to account for soil type as a significant variable in slope stabilization.

4.2.1c LIA, Phase III: Relationship to Roads and Streams

The third phase of the landslide impact analysis evaluated the relationship between slope failures and road infrastructure and fluvial channels. The goal of this analysis was to identify critical potential points for mobilization of sediment that could impact streams and stream morphology and thus potential volume sediment transport downstream. However, this analysis does not estimate volume of sediment mobilized. To assess the relationship between landslide occurrence and slope stability to stream segments across the watershed, a proximity analysis was used to identify landslide point data within a ~150m (~500 ft) buffer of a given stream segment where the number of landslides was >50. To assess the impact and risk to the road infrastructure, a geospatial proximity analysis was used to identify those road segments within a ~100 m (~325 ft) buffer to landslide points where the number of landslides was >50. This yielded a spatial and ranked distribution of impacted primary road segments.

Support for the buffer distances selected is supported by research specific to Puerto Rico as well as by international landslide assessments (Heijenk et al., 2021; Hughes & Schulz, 2020; Pasang & Kubíček, 2020; Rahman et al., 2020). Hughes and Schulz (2020), at island scale found that 50% of the land area of the island is in proximity of between 100 – 400m to a channel and 30% within 100m. The RGA is no exception. Underlying lithology, degree and type of established vegetation, and slope became a controlling and balancing force resisting failure beyond the 150m buffer (streams, particularly primary tributaries to the Añasco River). The buffer distances selected for both streams and roads were also determined via a mixture of field assessments (across elevations, land use and cover types, and landslide movement types) identifying linear distance to stream input points as well as field-based measurements of the range of escarpment sizes and depth of scars across slope, elevation, and slide type. This also ensured that the runouts were included given the high variance in landslide types and sizes were included. The field assessments also identified a high frequency of both upslope and downslope failures (with unstable fill). Notably, there is no shoulder along the majority of roads throughout the upper, mountain regions of the watershed which increases the impact to both roads and housing located within 3-5m of the road.

4.2.1d LIA, Phase IV: Relationship to Land Use / Land Cover

This phase of the analysis involved an evaluation of the spatial relationship between soil type, land cover, and proximity to landslides. Agricultural land use/vegetation cover are key factors in sediment production and landslide incidence across multiple elevations and slope gradients. This 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). As previously stated, the relationship between land use/land cover and slope stabilization and sedimentation rates is well documented. In the Río Grande de Añasco watershed, the chief factors influencing these relationships are exposed soils due to agricultural activities and roads, particularly clearing for informal roads in higher elevations. Picón Ruíz et al. (2018), found that the extent of exposed, bare soils on agricultural lands in the RGA watershed post Hurricane María increased from 0.1 ha to 1.3 ha, ~52% of all total bare soils. Natural forests (~78%) and land used for agricultural activities (~9%) constitute the primary forms of land use (Duque & Melesse, 2016).

Data obtained from NOAA (2019 Landsat Imagery) was processed and refined to the watershed boundary using the Clip geoprocessing function in ESRI ArcMap. The resulting data was compared against the multiple GAP Analysis results (Gould et al., 2017, Gould et al., 2008) in order to resolve disparities between number of classes and nominal differences for class assignment of land cover/land use (Appendix C). For the purposes of this analysis, those areas classified as “Pasture/Hay” are grouped with “Cultivated Crops” classification to signify Agriculture. .No data cells were removed (using the Extract function in ArcMap) and several categories consolidated to be more meaningful through Reclassification of the data.

This analysis also includes an assessment of the relationship between upland forest, agricultural, and base land use classes and landslide density as well as those slides within 50ft of tributaries. These land cover/use classes were extracted from the final land cover/use dataset. A simple overlay between the landslide density map and the reclassed land use/cover visualizes the relationship. Then, the Intersect function was used to identify relationships between slides, land cover, and the stream network. This identifies critical stream segments that are either at risk or contributing to upslope and downstream susceptibility.

4.2.1e Social Vulnerability Assessment and Integration with LIA

The CDC/ATSDR Social Vulnerability Index (CDC ATSDR, 2018) provides a basis for examining spatial distributions of social vulnerability. The CDC defines social vulnerability in terms of the impact of external stressors on human health and seeks to apply a metric to a community’s capacity for resilience (https://www.atsdr.cdc.gov/placeandhealth/svi/index.html). The index incorporates 15 variables derived from US Census data. It was originally developed to assist public health officials and emergency response planners in prioritizing relief and response efforts. For the purposes of this analysis, the 2018 CDC/ATSDR SVI geospatial dataset was used though at the time of this writing, the 2020 data had been released. Assessment of the 2020 Census data by the U.S. Census Bureau revealed significant overcounts and other “erroneous enumerations” (U.S. Census Bureau (2022, March; 2022, April).

Theme 1 evaluates socioeconomic status and incorporates census data for income, individuals living below poverty, employment status, and education (those unemployed over the age of 16 and seeking employment) variables. Those individuals comprising these groups are considered out of the total population within a given census tract or county. Percent of individuals below poverty identifies those individuals below the federally defined poverty line at 50% below, 50-74%, and 75-99%. The threshold for the value ranges may vary based on size and age composition of the household. Additionally, the source data offers layers of analysis and refinement at Municipal and barrio scales. While that scale of analysis is beyond the scope of this paper, the methods and overarching approach outlined in this section and in the LIA provide guidance should planners and Municipal governance wish to analyze the particular impact one variable might have over another.

There are known limitations to using U.S. Census Data as a proxy for analyzing social capacity, risk, and vulnerability. Historically marginalized communities, indigenous communities, and Tribal Nations are notably under-reported by the Census. As previously noted, the 2020 Census was found to contain statistically significant errors in reporting (U.S. Census Bureau, 2022). Another limitation of using census data is the rapidly changing composition of some small-area populations in the intercensal years. To supplement the 2018 Census Data used, the validation of the data and results of analysis were informed by informal ethnographies, meetings, and interviews with local organizations and organizations and individuals connected through their trusted network as well as field visits to barrios (neighborhoods), farms, in particular. Using Census data can be a starting point but should not supplant field validations.

Additionally, a spatial comparative analysis of the distribution of SVI, Theme 1 was conducted to assess changes in social vulnerability prior to hurricanes Irma and María (2014), shortly after the disasters (2018), and in the longer-term post-disaster period (2022). The goal of this analysis was to illustrate shifts and patterns in social vulnerability ranking at the municipal level. To further integrate social and physical vulnerability, landslide density was used as a proxy for physical/ecological vulnerability. For this phase of this analysis, the SVI data for 2018 was selected and spatially analyzed with landslide density as a proof of concept.

The landslide density analysis was refined by calculating kernel density using mapped landslide points, with a search radius of 50 m to capture localized clustering. The resulting density raster was classified into a binary data layer, identifying areas of moderate to high landslide density areas based on a threshold analysis and distribution of the data. These high-density areas were then converted into vector polygons and spatially joined with the SVI data to identify intersections between social vulnerability and landslide risk. This proof-of-concept map offers a valuable tool for identifying hotspots where moderate to high social vulnerability coincides with significant landslide density, offering insights into which municipalities and barrios should be prioritized for hazard mitigation activities.

4.3 Results

4.3.1 Phase I: Landslide Distribution and Density

Mapping distribution of slides aided in the process of identifying field sites for data validation and yielded additional characteristics about the type and range of slides (Figure 4-3).

The ranked distribution of landslide occurrences by municipality and barrio reveals the highest percentage of landslides occurred in Maricao, followed by Las Marías and Lares. (Table 4-1; Figure 4-4). The highest total landslide counts per barrio are recorded in Indiera Fría, Bucarabones, and Indiera Alta (Maricao) (Table 4-1).

TABLE 4-1. Distribution of slide (percent and count) by municipality and barrio. Based on data from Bessette-Kirton et al., 2019a.

Municipality	Total # Slides (% Total)	Barrio / Highest # Slides
Maricao	5117 (32%)	Bucarabones (1355)
Las Marías	3207 (20%)	Añones (431)
Lares	2559 (16%)	Río Prieto (637)
Adjuntas	1995 (12%)	Guillarte (427)
Añasco	1313 (8%)	Corcovada (248)
San Sebastián	833 (5%)	Guacio (292)
Mayagüez	649 (4%)	Río Cañas Arriba (287)
Yauco	500 (3%)	Río Prieto (494)
Rincón	3 (<1%)	Jagüey (2)

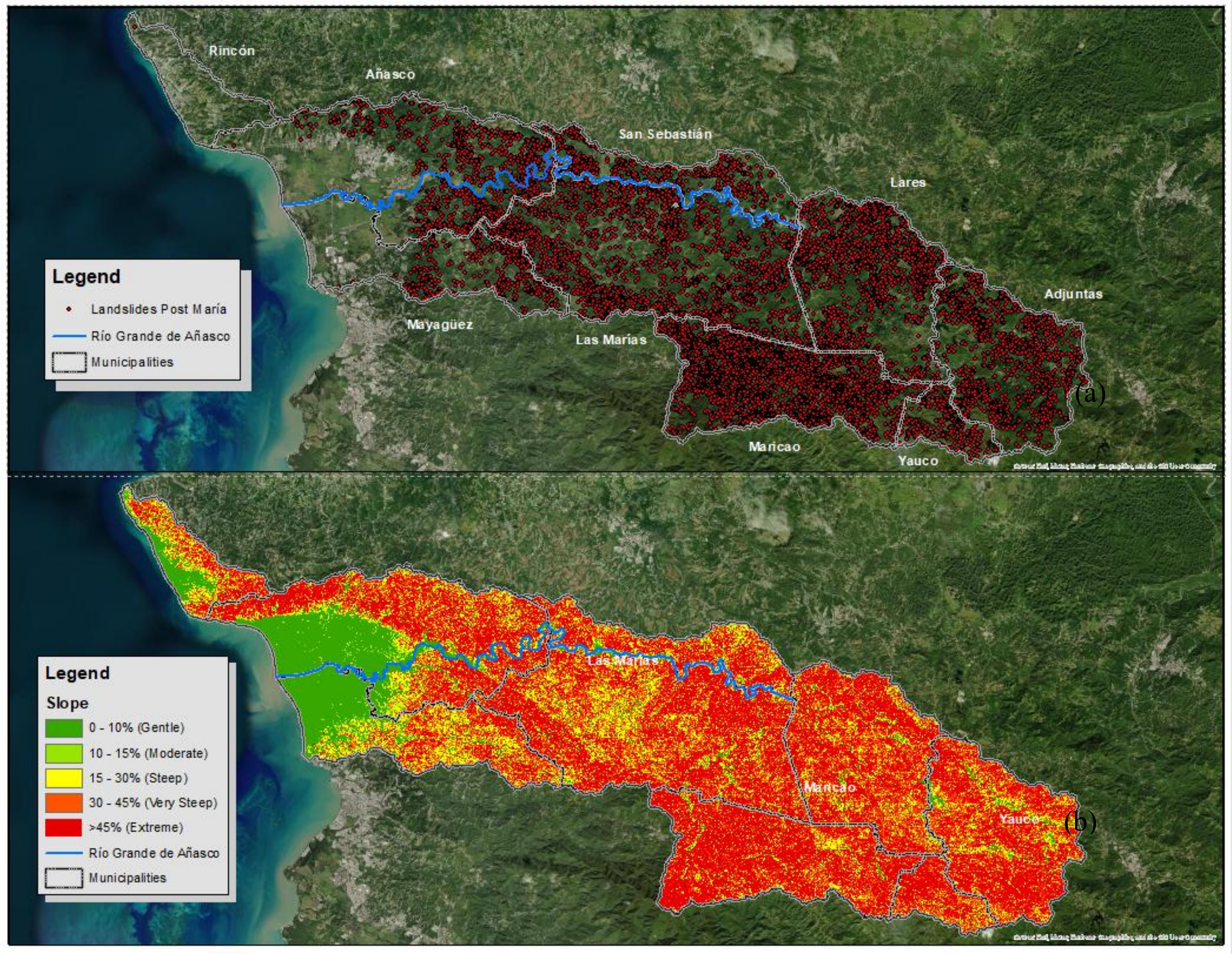


FIGURE 4-3. Distribution of landslides across watershed (a). Slope distribution map (b).

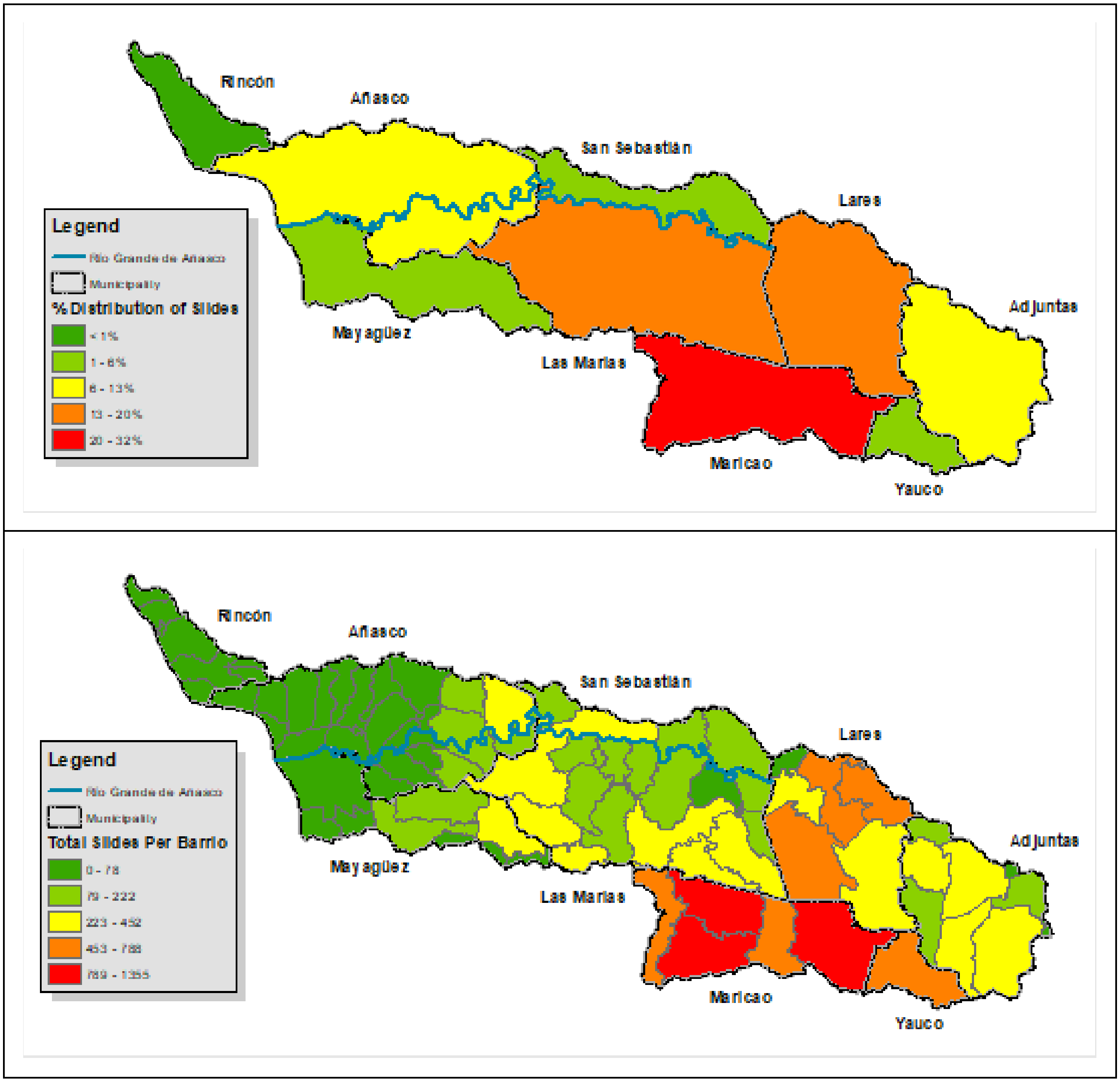


FIGURE 4-4. Ranked distribution of landslide counts per municipality and barrio.

The mapped analysis reveals that the highest proportion (20-32%) of landslides are concentrated in Maricao, making it a major hotspot. The adjacent municipalities, Lares and Yauco also show a high percentage (13-20%). Moderate distribution (8-13%) of landslides can be found in San Sebastían, Las Marías, and Adjuntas. Low distribution of landslides occurred within Mayagüez, Rincón, and Añasco (<8%). These spatial patterns suggest topographic and geologic factors may influence landslide distributions as more slides were identified in mountainous or steep terrain areas.

The slope map produced during Phase 1 (Appendix D.1.2) illustrates a pronounced transition in terrain morphology, revealing that the majority of the watershed exhibits increasingly rugged and heterogeneous topography east of the Coastal Zone, extending toward the headwaters. Building on the findings in Table 4-1, Figure 4-3, and Figure 4-4, Table 4-2 demonstrates the relationship between steep and extreme slopes and increasing numbers/percentages of slides. 96% of the slides identified by the USGS post Hurricane Maria were found in very steep and extreme landscapes.

TABLE 4-2. Classification of the count of landslides per slope class per municipality.

Slope Class	Municipality								
	Rincón	Añasco	Mayagüez	Las Marías	San Sebastián	Maricao	Lares	Yauco	Adjuntas
Gentle (0 – 10%)	0	3	2	10	4	11	4	1	10
Moderate (10 – 15%)	0	5	3	22	4	22	16	3	9
Steep (15 – 30%)	0	19	31	90	33	124	95	17	75
Very Steep (30-45%)	0	123	72	314	93	383	284	61	245
Extreme (> 45%)	3	1169	539	2771	696	4572	2165	416	1655

Targeted visualizations of slope distribution in relation to mapped landslide occurrences were generated by overlaying landslide point data onto the Phase 1 slope raster and extracting zoomed-in views of selected areas within the municipalities of Añasco, San Sebastián, and Lares. Appendix D.1.3 presents close-up visualizations of slope and landslide distribution in the municipalities of Añasco and San Sebastián, highlighting landslide polygons situated on steep to extreme slopes upstream of the RGA. In Lares, increasingly larger landslide polygons are observed, predominantly in rural communities adjacent to agricultural areas. Vegetative cover, proximity to roads and streams, and land use also influence the size and spatial distribution of slides. These characteristics influencing distribution will have even more significance when compared against specific land use/land cover classes (agriculture, bare soil, forests) in Phase IV.

The landslide density analysis revealed concentrated high-density zones ("hot spots") within the municipalities of Maricao, Las Marías, and Lares (Figure 4-5). Notably, these hot spots are not confined to mountainous terrain; additional concentrations are evident in lower-elevation areas of Las Marías, indicating that landslide susceptibility extends beyond steep slope zones. It is helpful to locate areas of high concentrations or clusters distributed across space that may not be realized through a simple distribution map.

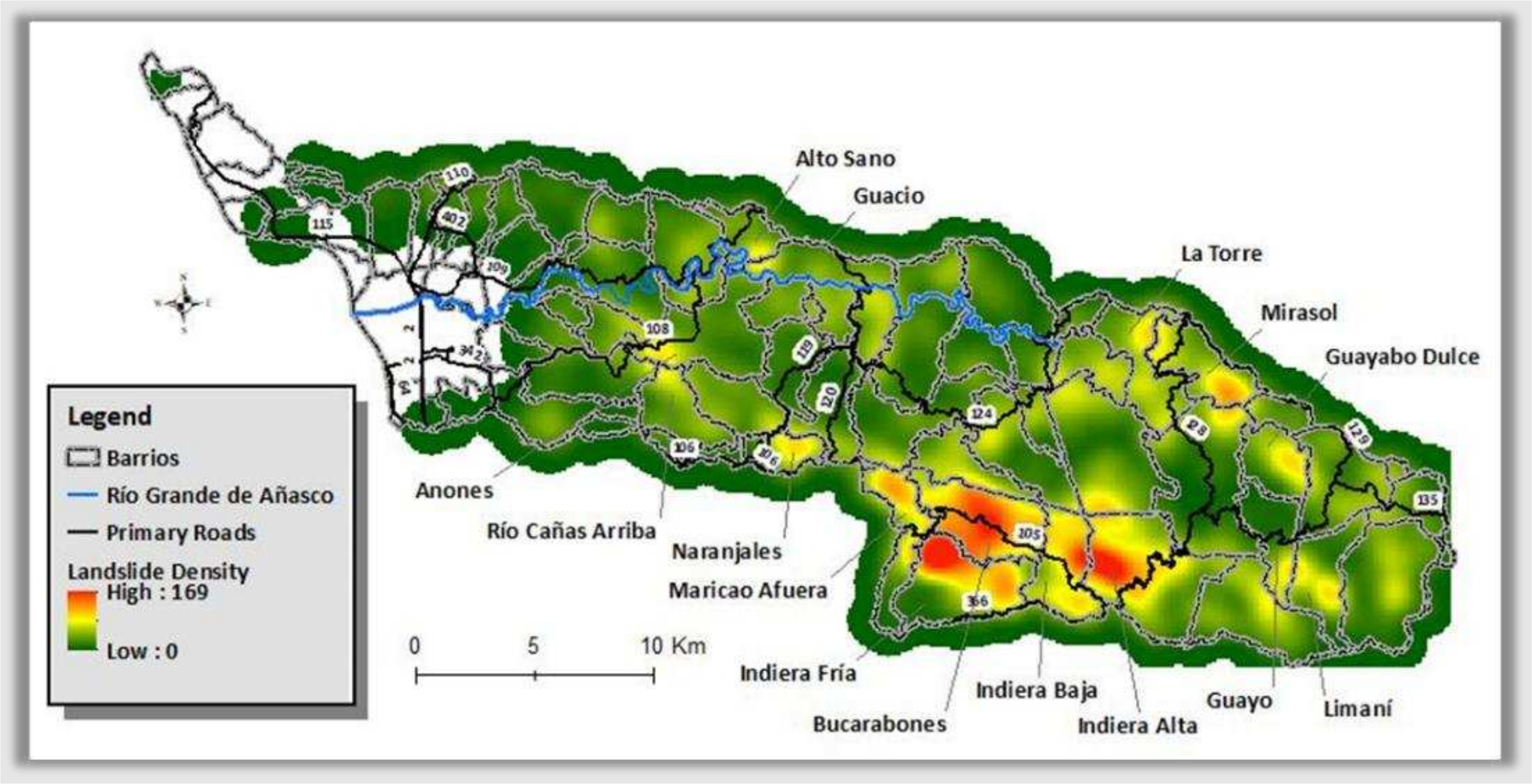


FIGURE 4-5. Landslide density map identifying "hot spots" of particularly dense clusters of landslides per municipality and barrio.

Three-dimensional fly-through visualizations, generated using ArcMap's 3D Analyst Fly tool, were employed to examine spatial relationships between infrastructure and geomorphic features across the study area (Appendix D.1.4). When oriented northeast from Añasco toward San Sebastián, the visualizations reveal emerging spatial patterns between road networks, stream channels, and zones of moderate to high landslide density. Similarly, in the upper watershed regions of Maricao, Adjuntas, and Lares, the alignment of roads relative to high-density landslide zones is particularly evident.

Phase I of the LIA revealed underlying spatial patterns and correlations consistent with field assessments of landslide density and historical frequency of events. For example, in Maricao the potential for sedimentation given both the distribution of slides relative to slope and the density relative to the rest of the watershed, indicates that the potential for release of sedimentation is the highest among all the municipalities

4.3.2 Phase II: Relationship Between Soils and Landslide Density

After initial analysis of distribution of clay soils across the watershed, the subsequent focus on clay dominant regions (>40%) relative to slope revealed that the municipalities of Adjuntas, Yauco, Lares, and Maricao evidence a spatial relationship between steep to extreme slope and clay dominant landscapes (Figure 4-6). However, some new spatial patterns also reveal areas of sudden changes in slope in the Transition Zone (see Chapter 2), namely northeastern regions of Las Marías and Añasco.

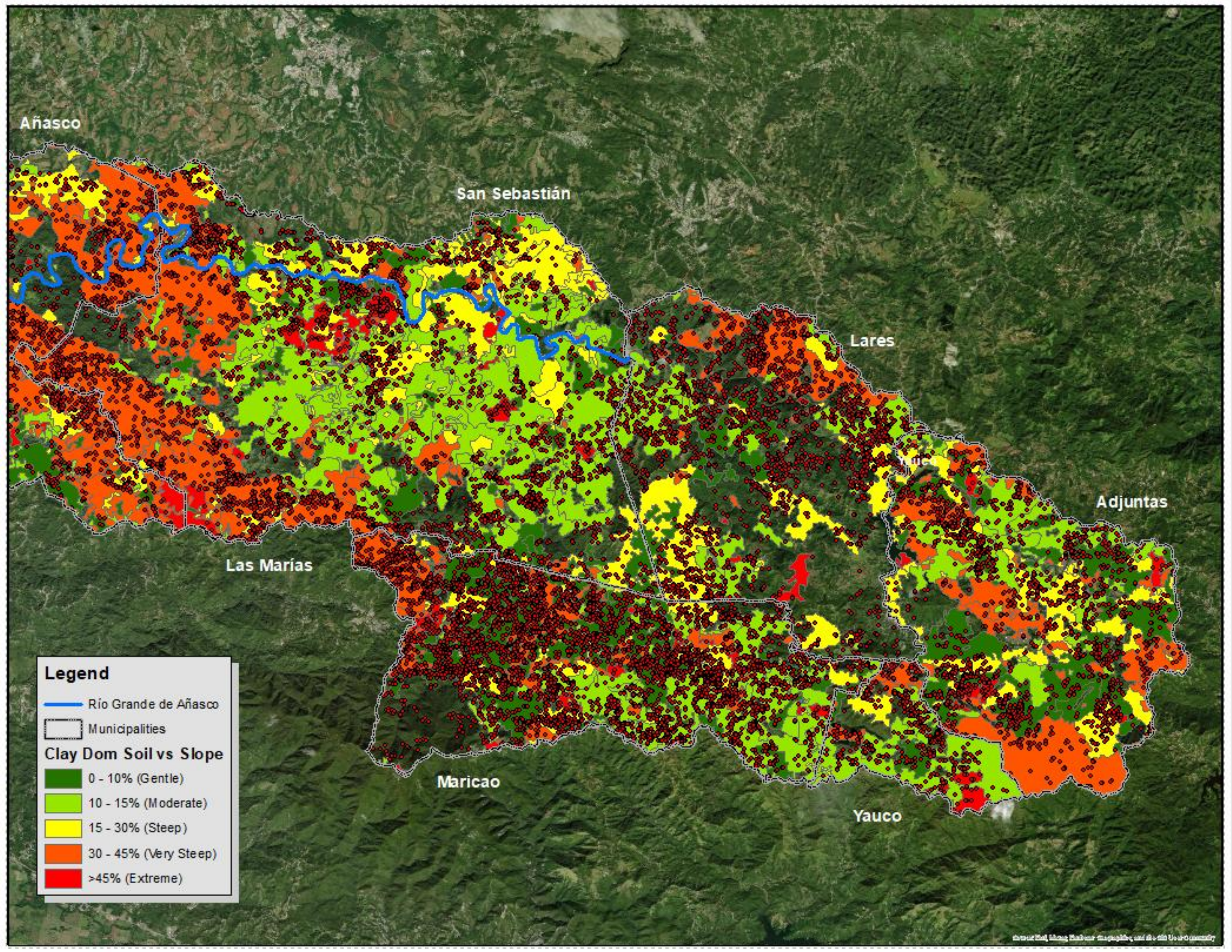
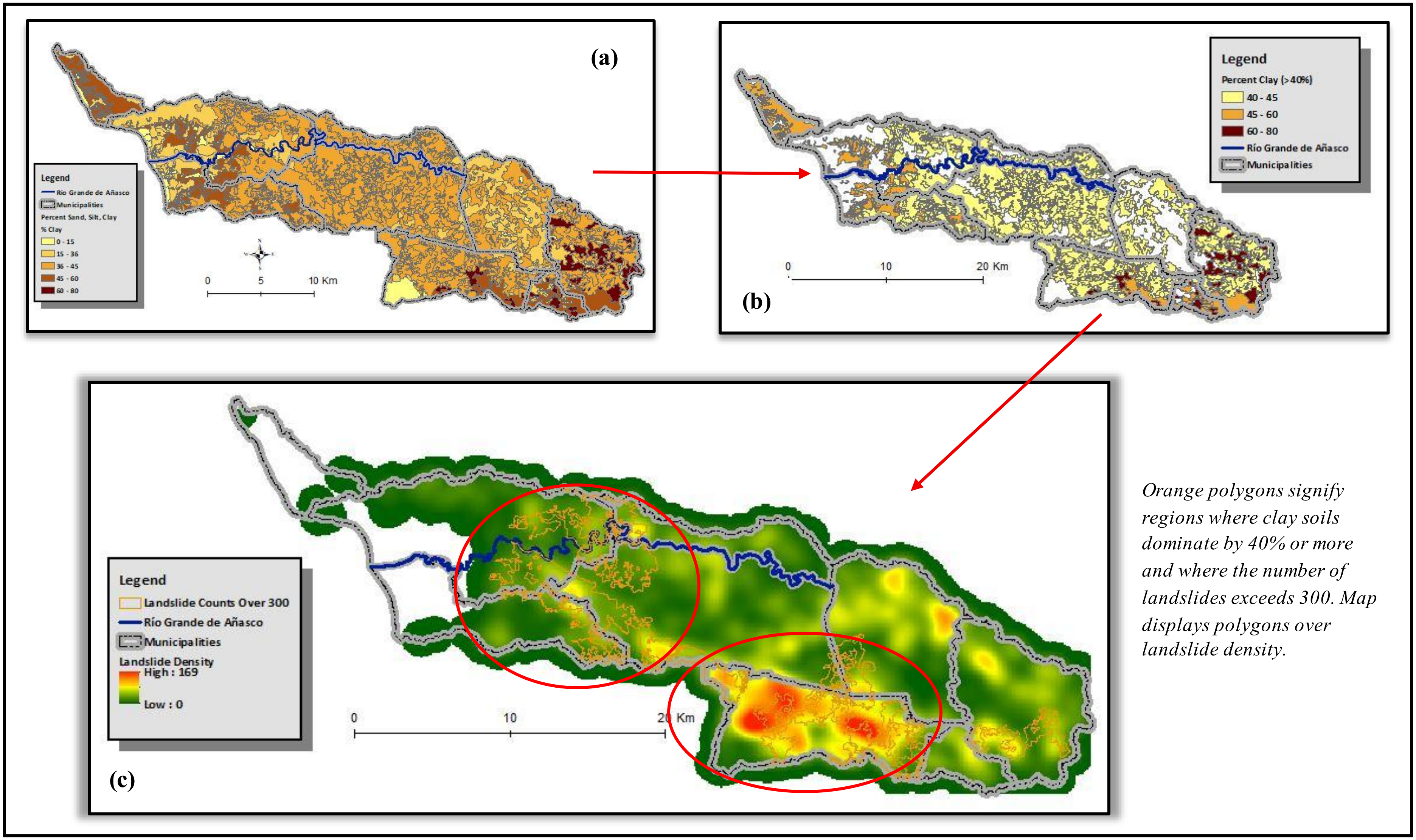


FIGURE 4-6. Regions where soils dominate by greater than 40% over silt and clay (including loamy soils) soils relative to slope.

The map is zoomed to a portion of the watershed based on the results of the analysis to enable increased focus on chief areas of concern. Integrating landslide density resulted in refinement of the analysis to reveal discrete polygons where these spatial relationships are highest. The majority of these polygons of concern are situated within Maricao and, secondarily along an area of transitioning slope between the Coast Zone and the Transition Zone, at the edge of Mayagüez and Las Marías (Figure 4-7). This supports the validity of this phase of the analysis to assess the distribution of soils where clay dominates >40% (map of soils >40%) relative to slope and landslide density.



Orange polygons signify regions where clay soils dominate by 40% or more and where the number of landslides exceeds 300. Map displays polygons over landslide density.

FIGURE 4-7. 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 frequency to reveal potential priority regions for slope stabilization.

4.3.3 Phase III: Relationship to Roads and Streams

Phase III examined the spatial relationship between landslide distribution and the roads and stream network resulting in ranked critical zones for impact. This analysis yielded a spatial and ranked distribution of impacted streams across the watershed from low to high vulnerability relative to potential critical points vulnerable to sediment loading (given local geology, soil structure, land use, and vegetation cover) as well as potentially contributing to the continued destabilization of slopes. The analysis identifies (by municipality) hot spots where the compound high impact to both stream and road segments exists (Figure 4-8).

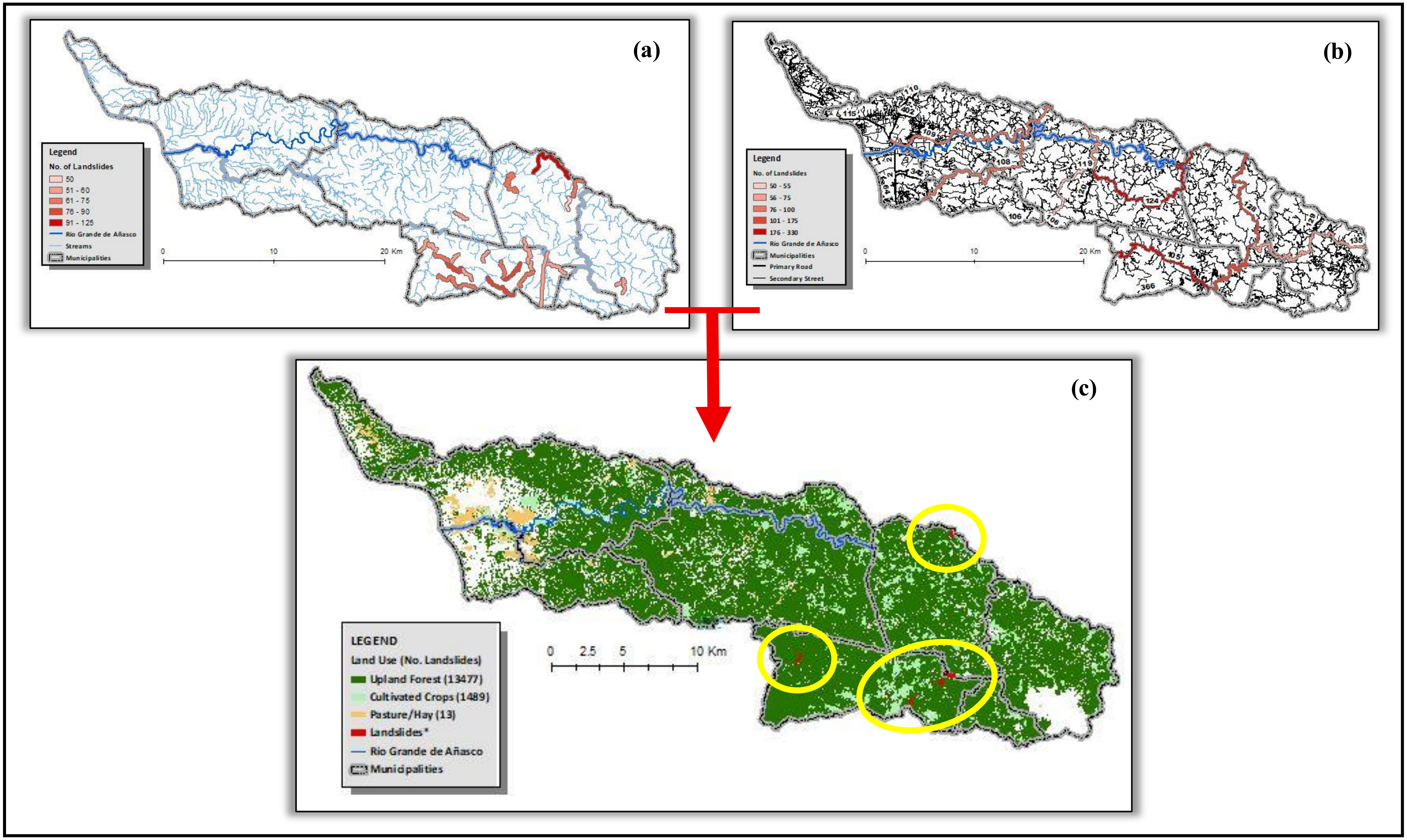


FIGURE 4-8. Diagram of risk analysis evaluating proximity of slides (where number of slides >50) to surface water networks (a) and roads (b) and resulting composite of highest risk regions relative landcover/land use (c).

The municipality with the highest density can be found in the northern area of the watershed in Lares and with less distance for sediment to travel to the main channel, potentially overloading smaller streams. Note that in Lares, another hot spot, the dominant soil type does not appear to be the dominating factor in the distribution of slides. This suggests that slope and land use may play a larger role. The most at-risk road segments lie in Las Marias and Maricao, followed by Lares (Figure 4-8b). This analysis clarified those road segments not previously identified as located within high-density regions of landslides. The most at-risk regions for BOTH streams and roads lie in Maricao and Lares (specific polygons identified). Lares has a higher density stream network and less distance for sediment to travel to tributaries and the main channel. However, in this location, soil type was not a significant contributing factor suggesting that slope and land use may play a more important role.

4.3.4 Phase IV: Relationship to Land Use / Land Cover

As shown on the map below, hot spots of high landslide density occur in proximity to forested (Upland Forest) and agricultural (Cultivated Crop and Pasture/Hay) land use types (Figure 4-9). The mapped result focuses on the upper reaches of the watershed to highlight key results. Based on the findings presented in Figure 4-9, these critical regions (San Sebastián, Las Marías, Maricao, Lares, and Adjuntas) exist within landscapes where agricultural production and upland forests dominate suggesting that it is critical to evaluate the relationship between management of these lands and their susceptibility for failure. The findings in this analysis also reveal spatial correlations between landslide density, roads, and land use. The majority of the primary roads located in municipalities in the upper reaches of the watershed connect small, rural, farming communities. In Maricao, for example, a mountainous landscape and home to several small to medium-scale coffee plantations and operations, the incidence of slides within proximity to roads is also high.

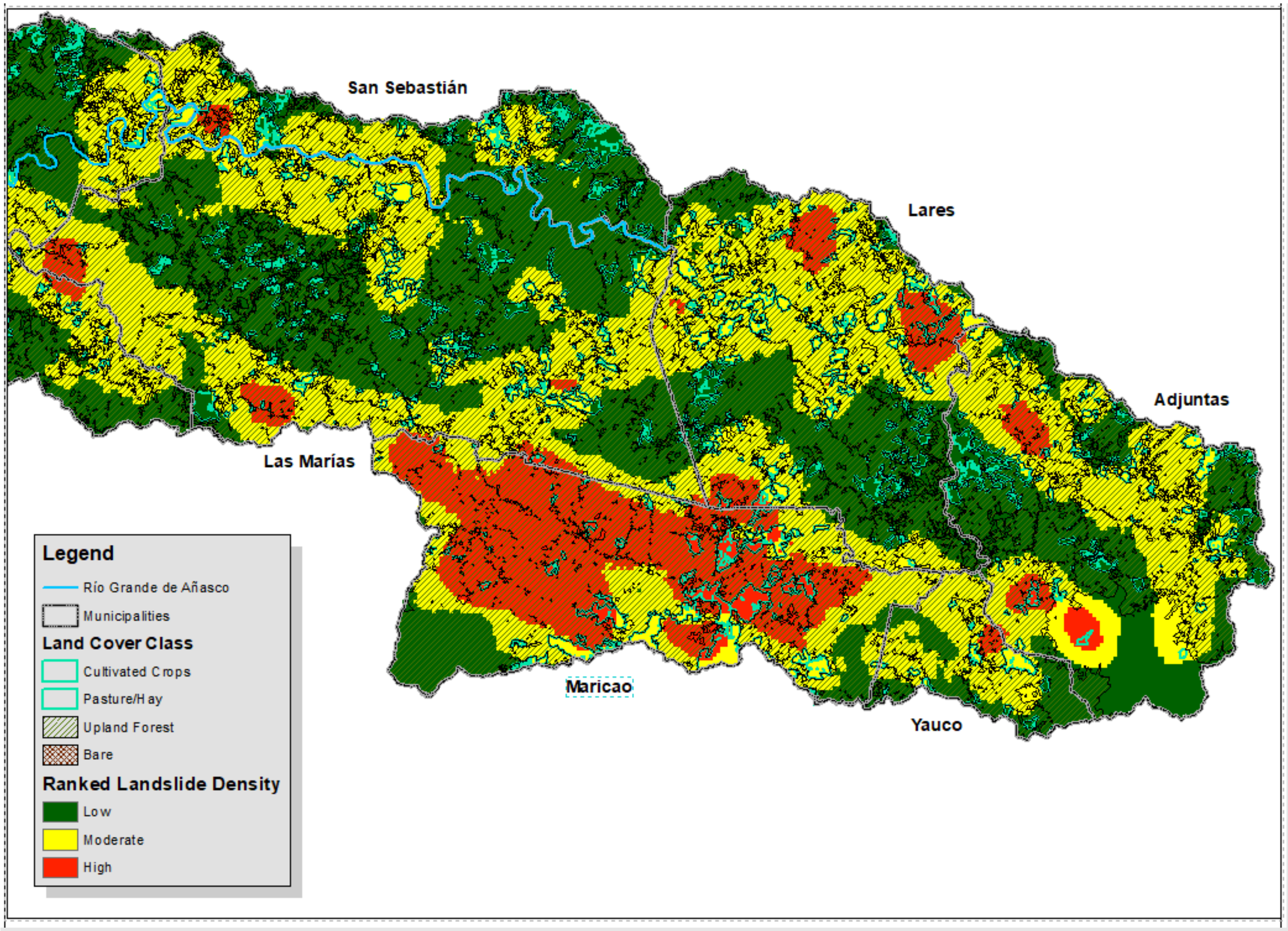


FIGURE 4-9. This map displays the relationship between select dominate land cover/use classes and landslide density.

Evaluating the impact to stream segments relative to land use also identifies critical relationships. The results of this analysis demonstrate a correlation between land dominated by agricultural activities and landslide distributions within 50ft of a stream. Of note is the cluster of landslides along tributaries feeding the upper reaches of the main channel along the border of Las Marias and San Sebastian and also located downslope from cropland (Figure 4-10). The map focuses on the municipalities shown to enable focus on stream channels of priority concern resulting from the analysis. The prioritization of critical regions by municipality resulting from this phase of the analysis expands municipal land use plans and hazard mitigation plans to account for the role of land use in slope susceptibility and vulnerability. This particular phase of the analysis provides key information for development of sustainable land use practices, hazard mitigation efforts, and prioritization of those areas in need of support and focus by agencies and municipalities.

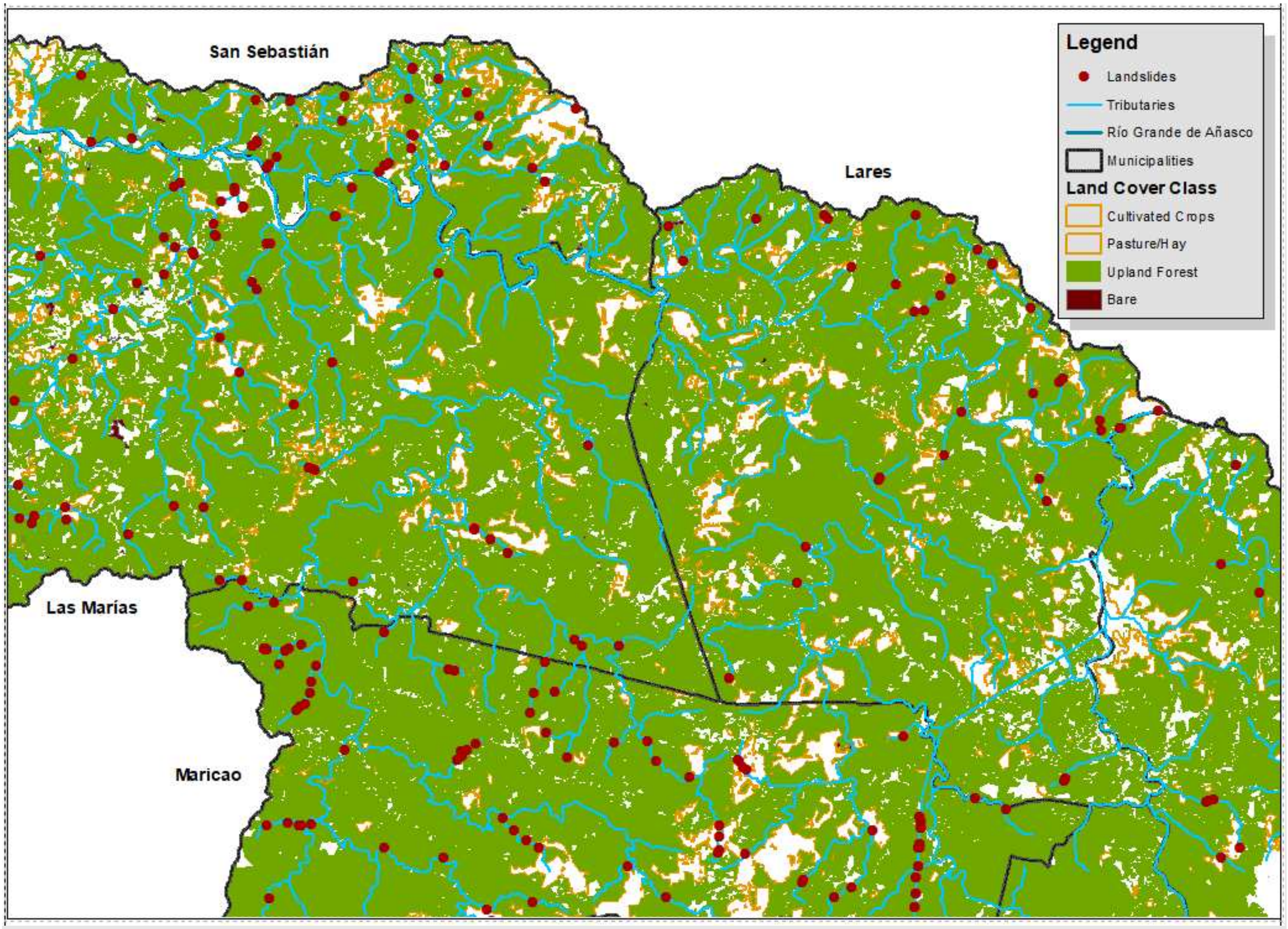


FIGURE 4-10. Map identifying locations of slides within 50ft of streams and the relationship to key land cover/use classes.

4.3.5 Social Vulnerability Assessment and Integration with LIA

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.). A comparison of the distribution of SVI, Theme 1 across the watershed over time (2014, 2018, 2022) reveals that the municipalities of Adjuntas, Lares, Maricao, and San Sebastían are repeatedly rank High (75-100%) levels of vulnerability across all years (Figure 4-11). This could indicate persistent institutional, economic, or infrastructure vulnerability (e.g., poverty, access to services, housing conditions, isolation).

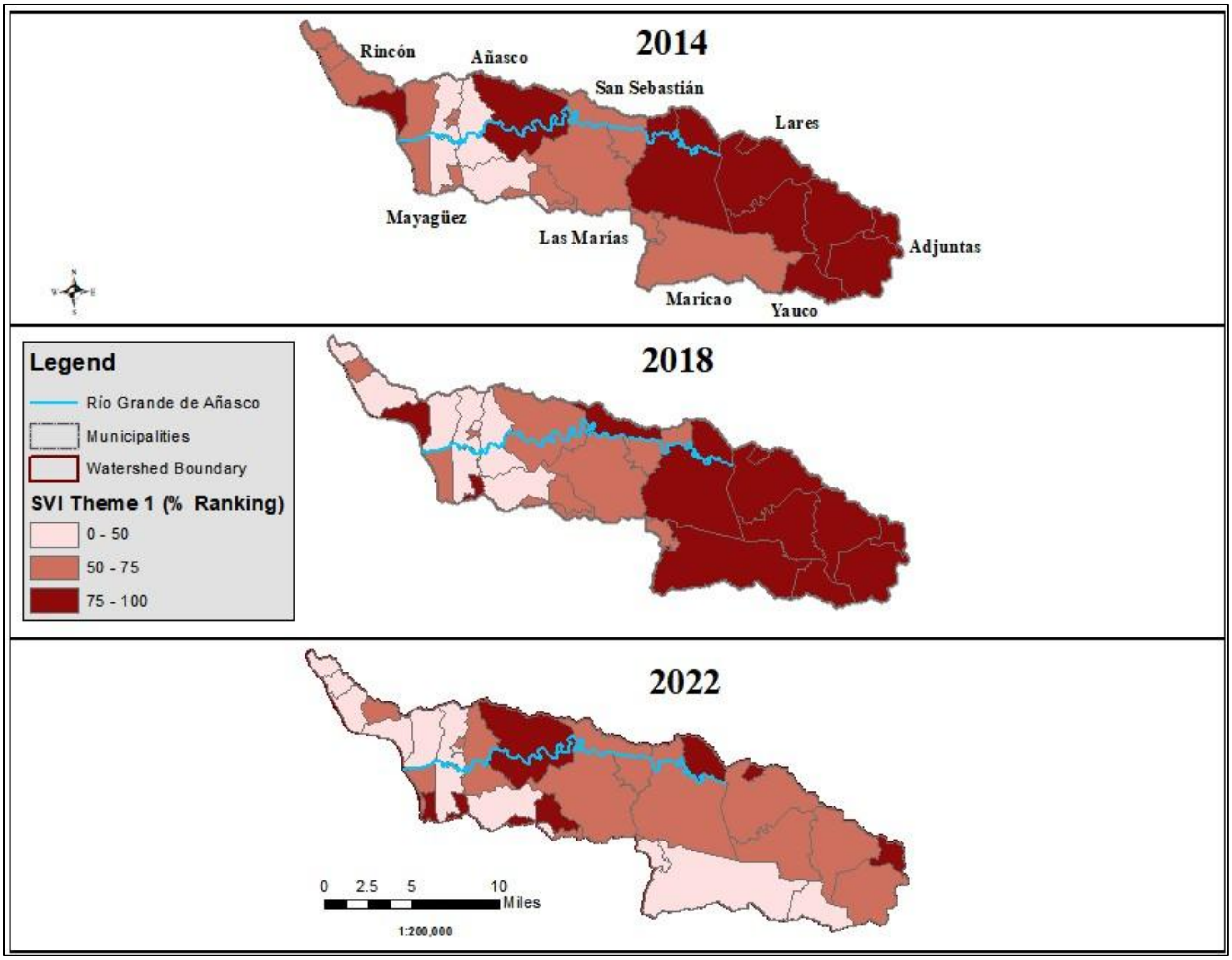


FIGURE 4-11. Distribution of SVI across the watershed – 2014, 2018, 2022.

2018 data, as compared to 2014, shows an overall increase in social vulnerability across all municipalities, particularly extending into Anasco and Mayaguez. This suggests that the period following Hurricane Maria may have had an impact on vulnerability due to the shocks to the SES. By 2022, there is an overall reduction in vulnerability for the most extreme category (e.g., High, 75-100%), particularly in the southwestern municipalities (e.g., Mayagüez, Maricao, and parts of Las Marías). However, norther municipalities such as San Sebastían and Añasco remain vulnerable suggesting limited recovery or structural change.

Additionally, the spatial relationship between landslide incidence and density relative to roads and streams at the headwaters and those municipalities with high social vulnerability offers opportunities for unique approaches to sustainable management of the landscape through economic, institutional, and educational enhancement of those rural communities. The majority of the primary roads throughout the municipalities located in the upper reaches of the watershed connected small rural communities, many of whom are also farming communities, and serve as primary transportation corridors. Overall, despite fluctuations, the mountainous regions of the watershed consistently rank high in vulnerability reflecting long-term socio-economic and infrastructure disadvantages (Table 4-3). The municipality of Añasco also ranks high across the years for vulnerability but is less vulnerable with respect to ecological, physical system variables.

TABLE 4-3. Top three municipalities ranked by comparison of susceptibility and vulnerability across SES variables.

Municipality	Rank							
	Landslide Distribution*	Most Affected Barrios	Relative to Very Steep / Extreme Slope**	Susceptibility of Soils & Slope	Land use/cover / Moderate to High Landslide Density	No. At Risk Stream Segments	No. At Risk Road Segments	SVI
Maricao	5112 slides	Bucarabones; Indiera Alta; Indiera Fría	383 (Very Steep) + 4572 (Extreme) = 4955 (96.9%)	1	Upland Forests; Cultivated Crops	1	2	3
Las Marías	3208 slides	Añones; Naranjales; Bucarabones; Cerrote	314 (Very Steep) +2271 (Extreme) = 3085 (96.1%)	2	Cultivated Crops; Upland Forests	N/A	1	2
Lares	5112 slides	Río Prieto; Buenos Aires; La Torre	284 (Very Steep) + 2165 (Extreme) = 2449 (95.5%)	3	Cultivated Crops; Upland Forests	2	3	1

*Data used assessed landslides immediately post-Hurricane María.; **Very Steep = 30-45% slope; Extreme = >45% slope

From the LIA, we know the relationship of landslides relative to roads is high in Maricao, Las Marias and Lares. These areas not only exhibit elevated landslide susceptibility, but are also characterized by significant social vulnerability, emphasizing their heightened risk profile. One notable are of intersection is the barrio of Bucarabones, which extends across both Las Marías and Maricao. This overlap suggested potential opportunities for cross-municiple collaboration aimed at hazard mitigation and community resilience. Within Maricao, the portion of Bucarabones recorded the highest number of landslides per area, further highlighting its status as a high-risk zone within the watershed.

Examination of those regions of moderate to high social vulnerability (SVI 2018) with moderate to high landslide density revealed that the highest concentration of combined social and physical risk occurs primarily in the municipalities of Maricao, Las Marías, and Lares (Figure 4-12). Bucarabones again emerges as a critical hotspot, but perhaps just as important is the delineation of smaller, yet significant areas of SES vulnerability in eastern Lares. This spatial clustering of high-density landslide areas and elevated social vulnerability underscores the need for integrated risk assessment and targeted mitigation efforts in high-priority zones.

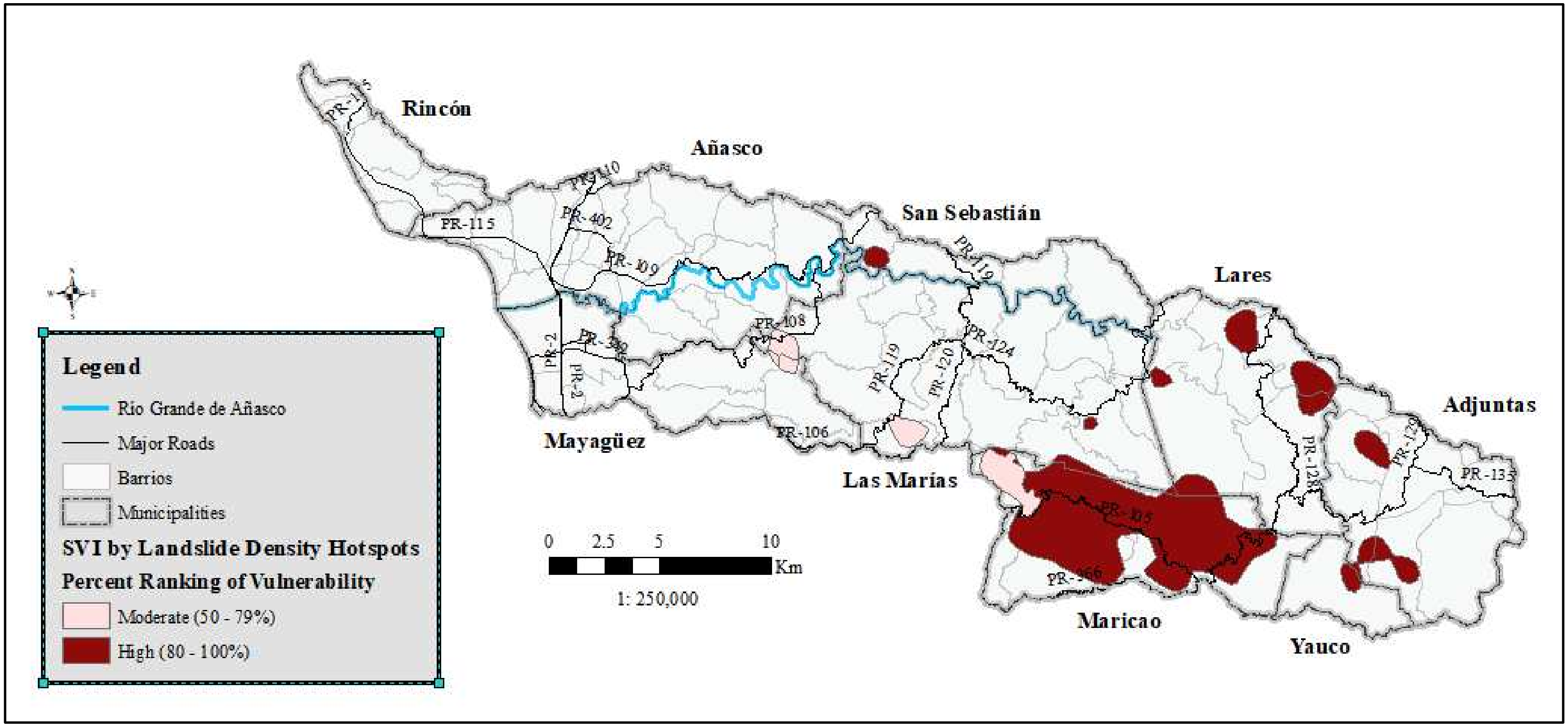


FIGURE 4-12. Risk map highlighting hotspots of Moderate to High social vulnerability (SVI 2018) coinciding with Moderate to High landslide density across the RGA Watershed. (Bessette-Kirton et al., 2019a; CDC, ATSDR, 2020).

4.4 Discussion

The impact of the storms and the resulting extreme and paired hazards on systemic complexities and the socio-ecological landscape are as diverse as the watershed which rises from the coast to mountains. For example, while most landslides occurred within areas dominated by forest land cover, over 1,000 occurred within areas designated by crops in lowland and mountain farming communities. Flooding and sediment deposition from widespread slope failures (>70,000 island-wide) decimated valley and mountain crops beyond normal, and already high, rates of sediment yield and mass wasting and included the mobilization of agricultural sediments along the central channel (Bessette-Kirton et al., 2019; Nilawar et al., 2017; Clark & Wilcock, 2000; Hughes & Schulz, 2020). The storms caused 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). This underscores the value of assessing impact to transportation networks and identification of landscape vulnerabilities with the goal of pairing hazard mitigation by road segments alongside supporting ecological stabilization. A landslide impact and vulnerability assessment include evaluating exposure to precipitation, slope, distance from water bodies, and complicating impacts from human disturbances such as land use and roads and the degree to which they do or do not influence erosion and slope stability. Examining these variables as contributors to landslide susceptibility and vulnerability, wherein susceptibility refers to the likelihood of repeat slope failure and vulnerability encompasses characteristics that might increase weakness and/or exposure. Susceptibility acts as a contributor to the understanding of degree of vulnerability. Risk incorporates the frequency and distribution of a hazard(s) and vulnerability.

Given the history of slope failures in both this watershed and across the island, there is already a known susceptibility. This was further documented at the island scale by Hughes & Schulz (2020). However, evaluating factors influencing susceptibility (e.g. history of failures/prior failures, distance to roads, elevation, land use that reduces vegetation) at the watershed scale further refines the degree to which these factors may influence susceptibility and the nuances of the variability that may be lost or homogenized at island scales. Such an analysis builds on the few and far between hydrologic modelling and watershed health assessments (water quality). The results of the LIA aid in prioritization of hazard mitigation efforts and maintenance of critical infrastructure (e.g. roads) and understanding the impact to and from stream channels. While Ramos-Scharron et al. (2020) developed a landslide density map at the island scale, to date, no watershed scale landslide density map exists for the RGA. Critical zones (by Municipality) and "Hot Spots" were identified across several variables (e.g. slope, soils, land use, proximity to roads, and proximity to stream input points). This analysis examined the impact of the landslides relative to land use practices (critical infrastructure such as roads) and physical system characteristics (such as soil type, slope, hydrology) essential to understanding landscape vulnerability and susceptibility.

The mass wasting events evaluated through the LIA contribute to sedimentation by exposing soils and parent material through mobilization 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. 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 & Walker, 1997). Evaluating these variables influencing landscape vulnerability through the lens of SES requires the inclusion of land use practices as well as social system vulnerabilities. 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.

Dominant soil textures range from moderately fine to fine, with clay dominant layers near the surface resulting from weathered Volcaniclastic rock in the mountains to coastal plains dominated by depositional sandy soils. Soils with higher cohesive properties (such as soils dominated by clay) are associated with higher susceptibility of a slope to failure in the form of a landslide (Batumalai et al., 2023). This is highly dependent on the degree of saturation of the soil. The antecedent moisture conditions caused by Hurricane Irma and preceding Hurricane María, overloaded these cohesive properties of the clay dominated soil, leading to a weakening of the soil's resistance to mobilization (Mecikalski & Harmsen, 2019; Mejia Manrique et al., 2021). Soil moisture content correlates with soil physical properties underscoring the value of analyzing the spatial relationship between those areas dominated by clay soils, particularly given the antecedent wet conditions due to Hurricane Irma weeks prior. Specifically, a typical soil property of clay soils is its ability to affect the magnitude of the gravitational force. Excessive wetting of these soils can decrease the cohesive properties and the internal friction angle as well as the soil shear strength.

The depth of the clay dominated soil horizon can also play a role when evaluating the relationship between the point of sediment mobilization and soil type. As summarized by Hunt et al. (2021), the depth, bulk density (which increases with depth), and permeability of clay soils affect the development of a transition point between the saturated upper layer and deeper dry layers and/or bedrock. This compound hazard variable increases the potential for transport of loose material downslope carrying with it pollutants deposited in the lower valley regions. These crucial factors, when combined with slope, land use, and vegetative cover, support the inclusion of the role of soil type in this analysis. This compound hazard variable increases the potential for transport of loose material downslope carrying with it pollutants deposited in the lower valley regions.

Additionally, rates of infiltration in mountainous regions of Puerto Rico tends to be slow to very slow (Duque and Melesse, 2016), creating an opportunity for flooding in lower elevations resulting from typically high runoff rates. Isolating those regions where clay soils dominate assists the process of understanding not only the role that this soil type plays in slope stabilization in extreme weather events, but also the geomorphic impact when such soils are detached, and soil banks are redistributed further down the watershed. This sudden redistribution and deposition within channel and on flood plains disrupts the typical landscape evolution process wherein redistribution might take place on decadal to century scales of soil development.

The USGS initial evaluation across the island found that most of the slides occurred at the soil and saprolite interface, ranged from centimeters to meters deep, and the majority transitioned to long debris runouts, debris flows, or coalesce (Cerovski-Darriau, 2022). Again, this analysis also builds on the USGS and Bessette-Kirton et al (2017; 2019a,b) assessments of landslides as well as pre-María island scale mapped analysis and inventory (Lepore et al., 2012). Prior studies examined the susceptibility of slopes to failure focused on an island scale (with some validation mapping in Lares) and identified soil classification as the most predictive variable for slope failure (Einbund et al., 2017). Evaluating the dynamics at the watershed scale reveals more information about the most vulnerable, susceptible and continually at-risk slopes. It also refines the understanding of other variables (such as vegetative cover, land use, relationship to road systems) and a higher resolution than can be identified at the aggregated island scale.

Location, density, and size of channel segments may aid in slope destabilization through erosion, under cutting, and saturation of material (Schulz et al, 2019; Sherrill et al., 2008). Groundwater, too, may play a significant role in both saturation of material and rate and direction of movement. The US Geological Survey maintains a stream gauge in the river near San Sebastián. The river morphology near this gauge 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 Mayagüez. The meander and sedimentation compromised the intake facilities during Hurricane María. Additionally, other reaches of the primary channel changed course significantly, causing downstream issues (e.g., scouring, deposition, unanticipated in channel morphology) for farms reliant on physical withdrawal of stream water for irrigation for valley farmland.

Floodwaters triggered by rainfall brought with Hurricane María led to significant shifts in channel width, depth, and course of the Anasco river. In some reaches the river shifted so far laterally that it disconnected access points for crop irrigation. Excess overland flow in this region drains quickly due in part to landslides leaving forest floors bare, roads, cropland in development, and steepness of slopes adding wood and organic material to streams. This contributes to buildup of material at bridges and narrow stretches of river, contributes to channel morphology and local ecosystems. Valley main and tributary channel beds are dominated by sandy soils over underlying limestone and are therefore prone to shifting unless there is in stream or vegetation along the bank. Alluvium deposited by floods contributes to sandy stream beds, high suspended clay sediments in stream, and high frequency of deposition on banks, in stream island development, and on cropland. The density of landslides following Hurricanes Irma and María increased in this zone and field site visits (2018, 201, 2020, 2023) revealed that some sites have continued to fail during both climatically heavy precipitation and punctuated by extreme events (Photos available via data repository: https://doi.org/10.5061/dryad.5mkkwh7jq).

Road placement and slope stability is a critical component of landslide and slope stability assessments, particularly when evaluated alongside proximity to stream networks (Hughes and Schultz 2020; Larsen & Torres-Sanchez 1992; Ramos-Scharron et al., 2021; Sherrill et al., 2008; van Westen et al., 2008). Roads contribute to an increase in shear stress and reduction of shear strength acting against the gravitational resistance of a slope to failure (Pradhan et al., 2022). This correlation is a result of stress redistribution from cutting and filling, and alteration of surface and subsurface drainage paths, all of which can result in decreased slope stability. In addition, many rural roads are not constructed using best practices for reducing slope instability (Larsen and Parks, 1997).

In Puerto Rico, this relationship is being examined with greater acuity following the notable impacts of hurricanes Irma and Maria and now since the added impact of Hurricane Fiona (2022) which brought heavy rains that contributed to renewed failures of slopes still in a state of susceptibility (Tyson et al., 2023). In the RGA, typical of other regions across the island, road type and density vary between established formal networks with high density in critical, high slope regions and informal roads connecting farms and otherwise disconnected rural barríos. Hughes and Schultz (2020) build on the role of formal and informal, unplanned road networks throughout the watershed in their assessment of the variables influencing slope stability post María. They and Larsen and Torres-Sanchez (1992) cite the increase in landslide susceptibility relative to roads. Currently, no full inventory of informal road networks relative to formal roads exists. The findings of the LIA reveal the need for further analysis, particularly concerning land use, road maintenance/mitigation, and transportation corridors for basic livelihood needs. 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.

Cruise and Miller (1994) and Ramos-Scharrón (2014) contributed to the sparse body of literature modeling land processes, focusing on sediment discharge variability and influences by interannual and seasonal changes as well as land use (particularly agricultural activities and urban expansion) in southwestern Puerto Rico. Cruise and Miller (1994) developed a hydrologic model for Guanajibo watershed located just south of the RGA watershed. The study indicates that controlling erosion in agricultural areas, especially in the northern foothills, is essential to manage sediment flow into Mayaguez Bay. The findings suggest prioritizing erosion control in deforested foothills to mitigate sediment discharge. I note this study as it supports the verity of assessing land use in deforested regions of the RGA. Agricultural land use/vegetation cover are key factors in sediment production and landslide incidence across multiple elevations and slope gradients. The results of the LIA demonstrate spatial relationships between land currently in use as agriculture, categorized as forested lands, and incidences of slope failures. The results of this analysis demonstrate a correlation between land dominated by agricultural activities and landslide distributions within 50ft of a stream.

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. For example, this analysis highlighted the potential for concern about the impact on coffee plantations and opportunities for coordination with local communities to stabilize slopes in Maricao. Assessments and responding approaches that support socio-ecological adaptation moves beyond mitigation measures and grounds such approaches in the relationship between humans and the environment (O'Brien & O'Keefe, 2014). 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 in 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 314 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 mitigation 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. The prioritization of critical regions by municipality expands municipal land use plans and hazard mitigation plans to account for the role of land use in slope susceptibility and vulnerability (Table 4-3).

At the heart of the international calls to action (e.g., Sendai Framework, Sustainable Development Goals, Millenium Development Goals, 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. 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. Visualizing the distribution of social vulnerability provides a starting point to evaluate the intersection between physical system impacts serving as indicators of ecological resilience and social system vulnerability indices serving as proxies for social system resilience and adaptiveness. 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 UNDRR (United Nations Office for Disaster Risk Reduction) 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" (n.d., https://www.undrr.org/terminology/vulnerability). 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.

Vulnerability to hazards increases risk and exposure which in turn has a direct impact on capacity for adaptative capacity. Within disaster risk reduction literature, the degree of adaptability of a system or component of a system correlates with resilience. This paper offers an integrative approach to dynamic, relational assessment of these systems through a study 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 distribution 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 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 loop and advances traditional erosion risk analysis.

Additionally, this consideration of social vulnerability highlights challenges to equitable resilience which may result from issues of access to power, resources, and risk informed knowledge and data (beyond TEK) necessary for climate adaptation. Imbalances in power and social and resource connection between communities born from inequities and/or obstacles burdens the social system's capacity for resilience. Multi scalar management of the watershed benefits from the identification of social system vulnerabilities and risk (Lv et al., 2024; UNDRR 2020; Zabaniotou et al 2020). Considering social vulnerability unveils patterns in the distribution of data relative to the management and role of the built environment and land use. It also creates a starting point for understanding social systems factors driving land use practices and feedback loops inherent to a municipality or barrio's capacity to prepare for and respond to landslide hazards. This coupled systems analysis provides targeted, place-based prioritization of areas where resource allocation for sustainable hazard mitigation and enhancement of community-based capacity building may be maximized.

There is a distinct pattern of distribution of the SVI metrics between lowland and upland municipalities. Community development is increasingly rural with an increase in elevation to the top of the watershed. Correspondingly, distances to basic livelihood needs and resources such as markets, medical facilities, and schools increase. The SVI metrics reflect the disproportionate challenge impoverished populations face in the wake of disasters (Flanagan et al., 2011). This inclusion of SVI metrics enables the comparison of communities faced with higher vulnerability and risk to slope failure alongside social system stressors of reduced access to resources. Road infrastructure in the upper reaches of the watershed is also more at risk due to historic and now repeat failures since Hurricane María. There is also a corresponding increase in the density of the informal road segments higher in the watershed complicating the socio-ecological vulnerability. The topography of the watershed visually disconnects communities which can hamper understanding of the relationship between upstream/downstream and upland/lowland land use practices, informal roads, and informal land clearing (for housing and/or roads). This adds challenge to the understanding of the benefits and advantages of developing holistic socio-ecological solutions to mitigate hazards and compound impacts from extreme weather events.

The SVI metrics chosen to examine social vulnerability reflect the recognition of the particular and disproportionate challenge impoverished populations face in the wake of disasters

(Flanagan et al., 2011). Populations financially and resource-limited by poverty may not have the means to recover or recover quickly. This can be scaled up to the municipal level in the watershed. Yet another challenge to watershed scale management in RGA is the limited application of resources, particularly if limited, to a given municipality. Hazard and disaster impact, however, do not know municipal bounds in addition to the upstream and downstream effects of land use and erosion mitigation measures. The SVI correlates education with income and poverty. Though this correlation is under examined and poorly understood, there is an underlying assumption that those with higher education, not unlike higher and more sustained economy, have access to more resources and networks and are less likely to be as burdened by the process of navigating bureaucratic processes (Tierney 2006; Morrow 1999). It is worth noting that analyzing these metrics of social vulnerability are merely the starting point for further and deeper assessment of a community's vulnerability and capacity for resilience and adaptation. The SVI does not, for example, capture cultural framings and characteristics that may aid in the creative development of solutions or that should at the very least be considered alongside quantitative metrics.

4.5 Conclusions

Climate predictions cite increases in frequency and severity of extreme storms (Harmsen et al., 2009; Larsen & Torres-Sánchez, 1998; Van Beusekom et al., 2018). Additionally, 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's 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). 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 & Canuti, 2009).

Within the socio-ecological landscape of Puerto Rico, there are numerous challenges surrounding extremes of wealth and poverty, disenfranchised populations, and disconnected systems. 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. The feedback loops in this compound hazard system challenge ecosystem resilience, particularly post extreme events increasing susceptibility of slopes to failure, impact of mass wasting events to farmland, changes to river meanders and flows, and ultimately impact to human system through impacts to farmland and critical infrastructure. For example, landslides and mass wasting can disrupt the soil catena, which in turn can affect seed banks. However, the loss of seed banks is often an indirect result of mass wasting rather than a direct outcome of soil catena disruption.

A multi-scale systems 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, I argue that the diversity and variability of that frequency are difficult to pinpoint 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 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. Impacted roads in an already socially vulnerably landscape adds a layer of vulnerability to the entire system due to the pre-existing social system limited capacity and access to resources resulting in an overall heightened potential for constrained capacity for resilience.

The analysis identifies discrete locations on the landscape as well as barrios and municipalities where slopes vulnerable to failure are influenced by slope gradient, soil properties, proximity to waterways, and prevailing land use / cover patterns. Examining across both natural and developed environments provides critical insights for enhancing hazard preparedness and supporting ecosystem-based management strategies. It also offers key assessments for use by national housing authority projects examining investments in reconstruction, repair, and potential relocation of communities out of high-hazard regions. Assessing the impact of landslides on transportation networks – key to both community function and livelihood – sets the stage for future analysis that measures more than physical damage. It calls for a broader perspective of other interrelated variables within the context of community resilience, connectivity, and sustainable infrastructure planning.

Evaluating social vulnerability also highlights challenges to equitable resilience which may result from issues of access to power, resources, risk informed knowledge and data necessary for climate adaptation, disaster risk reduction, and reducing risk to the most vulnerable. Identifying points of vulnerability across all systems serves the end goal of advancing an understanding of social-ecological systems' capacity to withstand large scale disturbances and disasters (Cutter et al., 2008). 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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CHAPTER 5 - EVOLVING BEST PRACTICES FOR TEAM SCIENCE IN POST-DISASTER RESEARCH SETTINGS

5.1 Introduction

The escalating frequency and severity of disasters demand urgent, interdisciplinary research and coordinated action. Climate change has intensified the frequency and severity of natural disasters, such as hurricanes, wildfires, floods, and droughts - disrupting ecosystems, displacing millions, and causing significant economic losses (Intergovernmental Panel on Climate Change (IPCC), 2021; World Bank, 2021). The number of disasters reported annually has nearly doubled over the past two decades, largely driven by climate-related events and increased vulnerability due to rapid urbanization, population growth, and unsustainable land and water resource use and management (United Nations Office for Disaster Risk Reduction (UNDRR), 2020). Significant gaps remain for funding, implementation, and the integration of equity and justice into disaster management practices (O'Brien et al., 2018; United Nations (UN), 2015). Additionally, the consequences are often more severe for vulnerable communities, whose reality is compounded by systemic inequalities (Cutter et al., 2014; UN, 2015). Disasters involve complex interactions between natural, technological, and human systems, requiring expertise from diverse disciplines such as engineering, social sciences, public health, environmental science, and emergency management. Studying the root causes of disasters (e.g., climate change, poor planning, systemic socio-ecological susceptibilities) and the impact of these events is essential to understanding contributing factors, implementing mitigation measures, and responding to risks to human lives, infrastructure, economies, and ecosystems.

Collaborative approaches enable researchers to integrate diverse perspectives, methods, and data to develop comprehensive solutions that address both the immediate impacts and long-term consequences of disasters and climate impacts (Bammer, 2013; Comfort et al., 2010; Maxwell & Julian, 2018; Stokels et al., 2008a). Team science supports a systems approach, integrating concepts and methodologies from multiple disciplines to address complex problems across physical and social landscapes. It can foster innovation by promoting cross-disciplinary dialogue and the co-production of knowledge, ensuring that research is both scientifically robust and responsive to the needs of affected communities and policymakers. In my own experience participating in a multi-institutional, post-disaster research project in Puerto Rico following hurricanes Irma and María, I observed both the promise and the pitfalls of team science in high-pressure, equity-sensitive contexts. These observations, discussed later in the chapter, helped shape the critical lens used to assess team science literature and its relevance to post-disaster settings.

The Science of Team Science (SciTS) literature broadly defines team science as collaborative, often cross-disciplinary research carried out by groups of individuals who integrate their expertise to address complex scientific challenges (Stokols et al., 2008a; Bennett & Gadlin, 2012). However, even within SciTS, definitions vary in emphasis, from the integration of disciplinary methods (Stokols et al., 2008a; Börner et al., 2010) to collaborative models that emphasize stakeholder engagement and the co-production of knowledge with communities (Bennett & Gadlin, 2012; Hall et al., 2012; Love et al., 2022). This variability underscores a central premise of this chapter: that the meaning and practice of team science must be shaped by the team itself and the framing of the research. This chapter examines this variability across disciplines, aiming to identify common practices, conceptual touchpoints, and challenges that might inform a more integrative, interdisciplinary understanding of team science in post-disaster settings.

When implemented successfully, team science can excel in complex, multi-sectoral work by building interdependent, diverse stakeholder networks - a key strength in disaster research and applied solutions (Bui et al., 2022; Ismail-Zadeh et al., 2017; Lahiri et al., 2021; Riet & Niekerk, 2012; van Niekerk, 2012). The approaches and methodologies that extend from defining collaborations as multidisciplinary, interdisciplinary, or transdisciplinary play an essential role in the prioritization given to certain best practices and ethical considerations over others (Chapter 1). Team science underscores the importance of team-based approaches for addressing dynamic problems that require big data, broad stakeholder inclusion, and innovative solutions across scales—including fields such as water resource management, climate adaptation, and disaster risk reduction (Baker, 2015; Bennett & Gadlin, 2012; Börner et al., 2010; Cheruvelil & Soranno, 2018; deHart, 2017; Falk-Krzesinski et al., 2010; Fasnacht, 2025; Fassnacht & Ma, 2020; Fiore, 2008; Hall et al., 2019; Love et al., 2022). However, without shared understanding and clarity on what "team science" entails across conceptual frameworks and in practice, teams risk misalignment that can hinder collaboration, limit effectiveness, and obscure the path to best practices.

Drawing on a systematic, interdisciplinary literature synthesis and practice-based reflection, this research explores the following questions:

- What best practices and strategies for overcoming implementation challenges in team science are identified through a multi-disciplinary meta-aggregation literature review?
- How does an assessment of best practices in team science enhance the understanding of effective collaboration while revealing overlooked barriers to applicability and efficacy?

- How does a case study of a multi-institutional project in Puerto Rico, following hurricanes Irma and María, critically assess the applicability and limitations of team science in a post-disaster setting?

The findings presented here offer a guiding framework for evaluating team science practices in post-disaster contexts, while challenging teams to consider how justice and equity are defined, operationalized, and integrated—both in their internal structures (e.g., team composition, power dynamics, and decision-making) and in their external engagements with communities and delineation of research outcomes.

5.2 Methods

The systematic literature review unfolded in four phases: (1) literature sourcing through term searches and a snowballing approach; (2) synthesis using meta-aggregation; (3) categorization and sub-categorization of findings to define a set of best practices and implementation challenges; and (4) application of those best practices to a post-disaster case study (Figure 5-1). To source literature, I first began with a structured term search followed by a snowball approach, in which initial results were reviewed for cited sources and reference lists to identify frequently cited or foundational works (Lecy & Beatty, 2012) (Table 5-1, Phase I). The search terms and Boolean phrases used in the two sub-phases of Phase I returned a total of 69 sources spanning a range of disciplines, later categorized as: Computational Science, Disaster Science, Engineering, Medicine, Physical Science/Environmental Science, Social Sciences, and SciTS / General Team Science (Table 5-2)

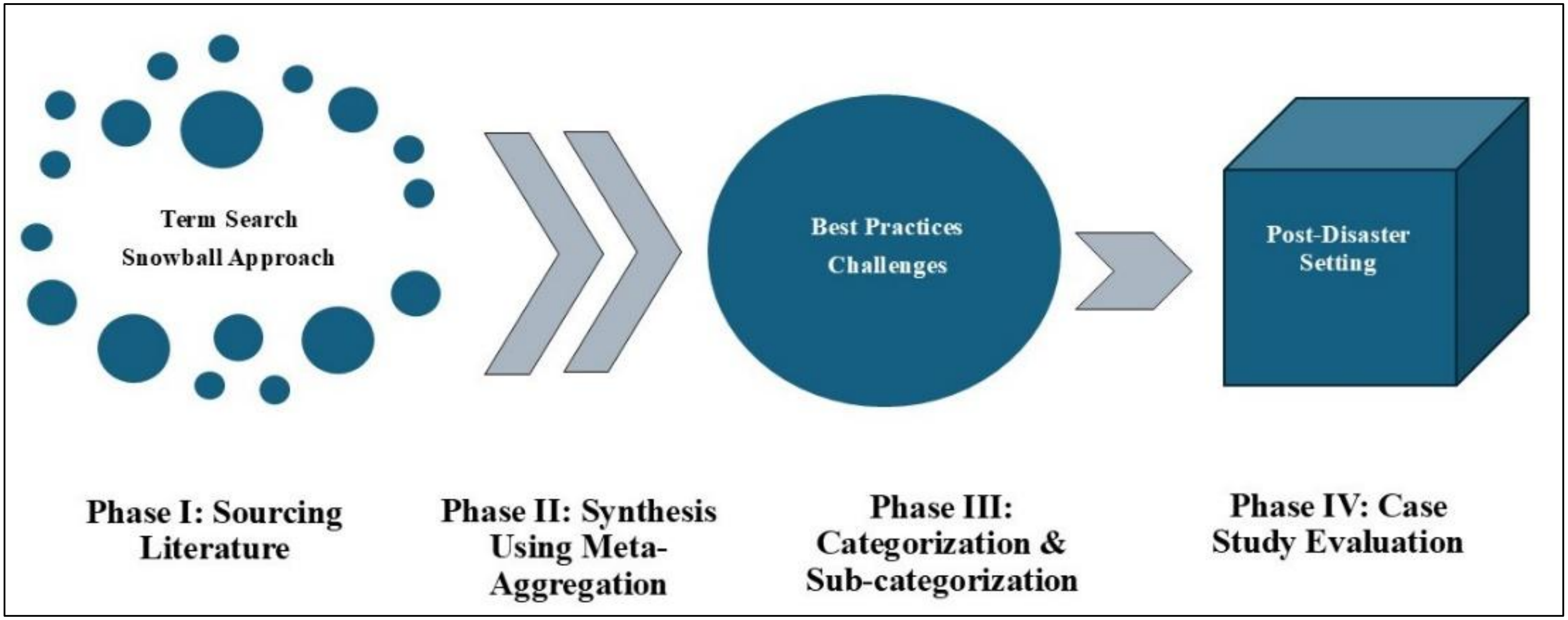


FIGURE 5-1. Conceptual framework for multi-method literature review analysis.

TABLE 5-1. Search terms used in literature review.

Phase 1a - Focus on Team Science / Discipline	Phase 1b - Focus on Disciplinarity / Discipline
team science	Interdisciplinary / interdisciplinarity
team[s] AND [field/discipline]	Multidisciplinary / multidisciplinarity
science of team science	Transdisciplinary / transdisciplinarity
collaborative science	Cross-disciplinary
collaboration AND science	

TABLE 5-2. Citation list by disciplinary category.

Field / Discipline	Citations
Computational Science	Milojevic, 2014.
Disaster Science	Montoya-Rincon et al., 2023; Bui et al., 2022; Johnston & van de Lindt, 2022; Stablein et al., 2022; Frykmer et al., 2021; Ge et al., 2021; Gilligan, 2021; Lahiri et al., 2021; Peek & Guikema, 2021; Thaler et al., 2021; Aguirre & El-Tawil, 2020; Fassnacht & Ma, 2020; Shi et al., 2020; Yonezawa et al., 2020; Matsuura & Razak, 2019; Takara, 2018; Ismail-Zadeh et al., 2017; Rebotier & Pigeon, 2017; Bendito & Barrios, 2016; Machlis & Ludwig, 2014; Trainor & Subbio, 2014; Niekerk, 2012; Riet & Niekerk, 2012; International Council for Science, 2008; McNeil & Quarantelli, 2008; National Research Council, 2006.
Engineering	Yu et al., 2019; Peterson et al., 2014.
Medicine (includes Psychology, Bioscience)	Kozlowski & Bell, 2019; Hall et al., 2018; Tebes, 2018; Baker, 2015; Voegel et al., 2013; Hall et al., 2008; Stokels et al., 2006, 2008a,b; Institute of Medicine, 2005.
Physical Sciences / Environmental Science	Shin et al., 2022; Zabaniotou et al., 2020; Fernández-Giménez et al., 2019; Perz, 2019; Uchida et al., 2019; Sammonds, 2018; Read et al., 2016; Allegretti et al., 2015; Cheruvelil & Soranno, 2015; Ledford, 2015; Lang et al., 2012; Thompson, 2009.
Social Sciences (Includes Communication, Anthropology)	Caughy et al., 2023; Forscher et al., 2023; Carter et al., 2019; Dehart, 2017; McGreavy et al., 2016; Manfredo et al., 2014; Fiore, 2008; Hirsch Hadorn et al., 2008; Pool & Roth, 1989.
SciTS / General Team Science	Love et al., 2022; Yu et al., 2019; Lotrecchiano & Misra, 2018; Bozeman & Boardman, 2014; Börner et al., 2010; Klein, 2021; National Research Council, 2015; Elfner et al., 2011; Wuchty et al., 2007.

To analyze the literature, I applied a meta-aggregation approach supported by conceptual frameworks from lessons learned and best practices research (Figure 5-1, Phase II). Meta-aggregation is a systematic approach that identifies, appraises, and synthesizes qualitative research findings (Lockwood et al., 2015; Munn et al., 2016). It is particularly suited to the process of evaluating research across disciplines that utilize varying conceptual models and methodologies. It accomplishes this through verbatim identification of findings, subsequent categorization, and integration of these results to form comprehensive conclusions (Florczak, 2018; Lamers et al., 2021; Lockwood & Pearson, 2013; Pearson & Hannes, 2012). Furthermore, this approach is supported by the justification for narrative reviews wherein a topically diverse array of quantitative studies synthesized for interconnection with the aim to introduce a new overarching theory (Siddaway et al., 2019). In this case, the review reveals linkages across both quantitative and qualitative studies, diverse conceptual and methodological frameworks, reconcile discipline-specific terminologies as well as inherent bias that might exist across and within fields/disciplines.

Best practices were derived from recurring approaches and strategies that authors described as enabling collaboration, knowledge integration, or problem-solving in team-based research contexts (Figure 5-1, Phase II). Implementation challenges were identified through author-reported barriers, contextual constraints, and critical reflections on limitations and breakdowns in collaborative processes. While meta-aggregation guided synthesis of qualitative findings, the review also drew on the logic of narrative review techniques to incorporate diverse quantitative studies and conceptual frameworks (Siddaway et al., 2019). This hybrid approach enabled the integration of research across disciplinary boundaries, reconciliation of field-specific terminology, and identification of commonalities that inform both effective practices and persistent barriers in team science implementation.

The theoretical underpinnings of the analytical framework used in Phase III—compiling, categorizing, and synthesizing findings into best practices and implementation challenges—are grounded in research on lessons learned and best practices methodology (Bretschneider et al., 2005; Eglene, 2000; Liubchenko, 2017; McDonald, 2015; Mold & Gregory, 2003; Peters & Heron, 1993). As Chirumalla (2013) describes, lessons-learned practices involve knowledge systems that meet "common knowledge" criteria through experience-based learning. Integrating this perspective allows complementarity between field-based insights and literature-derived findings, strengthening the relevance of the synthesized best practices.

This framework also addresses well-documented limitations of traditional lessons-learned approaches, such as lack of contextual specificity, implicit knowledge, and absence of clear application criteria (Buttler et al., 2011; Carillo et al., 2013; Goffin & Koners, 2011; McIntyre et al., 2015; Milton, 2010; Williams, 2008). In this study, those limitations are mitigated by situating lessons learned and best practices within the operational context of team science in post-disaster settings. During analysis, source findings were categorized according to qualities associated with collaborative functioning, internal and external implementation challenges, and dependencies that may constrain team effectiveness. These results were then subcategorized through verbatim compilation of findings across disciplines, with particular attention to identifying shared terminology, concepts, and cross-disciplinary patterns.

To evaluate the relevance and applicability of the best practices identified in the literature, I conducted a case-based reflection grounded in participant observation and field engagement during a post-disaster research collaboration (Figure 5-1, Phase IV). This phase of the study draws on my role as a participant-observer for approximately 15 months on the NSF-funded CRISP Type 2 project, Integrated Socio-Technical Modeling Framework to Evaluate and Enhance Resiliency in Islanded Communities (ERIC)—a multi-institutional collaboration involving Arizona State University, CUNY, NYU, and the University of Puerto Rico–Mayagüez. I served as a Research Associate for 14 months of the 3-year project, based locally in Puerto Rico, the primary research site.

The case study is informed by field notes, informal conversations, internal team communications, and direct observation of team dynamics. A key component of this reflection includes a workshop I co-organized and facilitated in 2019, held at the end of the first project year, which was designed to identify and address barriers to collaboration across disciplines and institutions. While the workshop and team interactions were part of the broader CRISP project, the reflections and lessons presented here are used to critically assess how the best practices derived from the literature align—or fail to align—with the realities of conducting team science in post-disaster contexts.

Because this reflective analysis emerged from my evolving role within the project, formal IRB approval was not obtained for participant observation. However, no personally identifiable information was collected or used, and all data were drawn from publicly available workshop deliverables, anonymized reflections, and non-identifiable field notes. These notes included reflective journaling, informal observations of team meetings and project coordination efforts, and post-engagement reflections based on my direct participation in the research collaboration. Where images or documentation are used, identifying information has been removed or blurred to protect individual privacy. This approach aligns with best practices in reflexive, ethics-informed qualitative research in field-based team science.Rather than serving as a separate source of best practices, the case study serves to evaluate and augment the literature-based findings by identifying context-specific challenges, moments of friction or misalignment, and tacit team dynamics that often go undocumented. These observations were organized thematically and used to reflect on the completeness, utility, and limitations of the identified best practices when applied in real-world disaster research scenarios.

5.3. Results

Findings from the literature demonstrate that the effectiveness of team science depends not only on technical coordination but also on the underlying team dynamics. Factors such as trust, communication, shared decision-making, and equitable power distribution significantly influence a team's ability to conduct integrative and ethical research. I use the term *optimal team functioning* to describe a team's capacity to coordinate effectively, engage inclusively, and adaptively navigate challenges—particularly in high-pressure or justice-centered contexts. While best practices offer valuable guidance, their impact is contingent upon how teams function in practice, especially in post-disaster settings where uncertainty and urgency amplify the need for intentional, values-driven collaboration. In this analysis, I use optimal team functioning as a descriptive framework to assess the attributes commonly associated with what the literature refers to as high-performing teams. The results are organized into three subsections: one synthesizing the characteristics of optimal team functioning, another identifying common challenges and barriers to implementation, and a third presenting a case study-based review of team science in a post-disaster context.

5.3.1 Best Practices for Optimal Team Functioning

The literature identifies several characteristics commonly associated with high-performing teams. These results were sub-categorized into two key areas of best practices: those that support optimal team functioning—such as inclusive communication, adaptability, and shared leadership—and those that strengthen overall team structure and leadership strategies (Table 5-2, Table 5-3). These definitions synthesize discipline-specific language used to characterize team science across levels of interaction (multi/inter/transdisciplinary), providing a framework for interpreting patterns across the literature. The following table presents how frequently each of these best practices appeared in the literature across different disciplinary domains.

TABLE 5-3. Synthesized best practices for optimal team functioning and leadership: Frequency of occurrence across disciplines.

Field / Discipline	Team Dynamics & Functioning								Leadership / Management of Teams					
	Effective Communication	Team Composition	Time	Trusted Relationship Building	Maximizing Integration (Concepts / Methods)	Commitment to Collaborative Process	Connection to External Collaborators	Accountability	Clearly Defined Roles & Responsibilities	Prepared & Experienced Leadership	Conflict Management	High Impact of Research	Cyber-Technological Infrastructure Readiness	Maximizing Institutional Support
Disaster Science	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SciTS / General Team Science	X	X	X	X	X	X	X		X	X		X	X	X
Physical Sciences / Environmental Science	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Social Sciences	X	X	X	X	X	X	X		X	X	X			X
Computational Science												X		
Engineering		X				X			X	X	X		X	X
Medicine	X	X	X	X	X	X		X	X	X	X		X	X

Effective communication, team composition, and commitment to the collaborative process were the most frequently identified best practices across disciplines (Table 5-2, Table 5-4). However, not all disciplines identify, explore, and/or prioritize these characteristics with equal frequency and/or depth. For example, >50% of Physical Science literature identified and explored the value of effective communication, trusted relationship building and the capacity to maximize integration. All other characteristics of team dynamics and functioning were identified in 40% or less of the sources. Accountability was only explicitly evaluated by one source (Allegretti et al., 2015). 90% of all Disaster Science literature prioritized the value of maximizing integration of concepts and methods as a best practice, second only to the value of establishing meaningful connection with external collaborators. These two best practices figured most strongly over any other characteristic within Disaster Science. >60% of sources identified the value of institutional support and infrastructure as essential to optimal leadership and management of teams. Only one source (Bendito & Barrio, 2016) examined the role of high impact. Several of the sources categorized within SciTS presented meta-analysis of team science literature.

The identified best practices (14 in all) highlight practices internal to team functioning that then facilitate external engagement with stakeholders, partners, and institutions, which, in turn, maximizes the impact of team science approaches. By implementing these best practices, teams are held accountable to stated project objectives as well as the necessary processes required to build dynamic, robust, effective teams. Collectively, then, these definitions and distributions provide a foundation for implementing best practices in team science across varied disciplinary and collaborative contexts (Table 5-3, Table 5-4).

TABLE 5-4. Definition and characterization of best practice terms.

Best Practice Term	Definition / Characterization
Effective Communication	Communication competence within the team. Frequency of communication. Understanding / Valuing diverse team composition.
Team Composition	Heterogeneity prioritized/valued (e.g., across (e.g., ages, experience, size, genders, roles, ethnicity). Builds on capacities of individual team members and team as a whole.
Time	Amount of time dedicated to collaborative activities and, in particular, face to face. Prioritization of time for training and integration with the goal of team cohesion.
Trusted Relationship Building	Relates to time spent developing symbiotic, dynamic, trusted relationships. Contributions of all team members valued. Aided by prioritization of value of social cohesion, open sharing of data and ideas. Reduced internal competition between team members.
Maximizing Integration (Concepts / Methods)	Clear mechanism for knowledge integration internally / externally. Sustains benefits to team members, the project, and communities/stakeholders. Can include co-creative production of knowledge. Characterized by flexibility and capacity to recognize opportunities to innovate.
Commitment to Collaborative Process	Supported by development of trusted relationships and clearly defined means of integrating knowledge. Characterized by interdependence, express interest in collaborating, past experience on/with collaborative teams. Requires leadership with understanding of sociology and practice of optimal, ethical, productive collaboration. Agreed upon definition of collaborative experience across roles, type/level of team interaction (multi/inter/trans disciplinary).
Connection to External Collaborators	Prioritized deepened connection characterized by diverse, meaningful interactions (e.g., beyond tokenizing collaborators and/or obtaining commitment on paper only without true coordination and/or interaction). Aids in development of cultural competence. Aids in conflict resolution with partners and encourages healthy competition of ideas.
Accountability	Internal & External. Supports building of trust, valuable integration, positions the research to have greatest impact and application. Aids social learning, particularly for those disciplines less accustomed to navigating diverse communication norms and cross disciplinary integration. Encourages reflexivity and includes assessments of team performance and project effectiveness.

Clearly Defined Roles & Responsibilities	Facilitates trust, collaboration, and capacity to maximize integration of knowledge. Frees researchers to focus on opportunities for teamwork and active learning from across disciplines, less time on social friction (i.e., from diverse personalities, perspectives, and expectations).
Prepared & Experienced Leadership	Fundamental to guiding teams beyond working in silos and toward true integration. Characterized by a capacity to offer a mechanism for evaluating contributions and authorship and capacity to mitigate obstacles from lack/challenges of institutional support (e.g., funding structures, institutional expectations). Incentivizes researchers to invest fully in collaborative process.
Conflict Management	Characterized by team trust and supported by clearly defined roles & responsibilities and prepared/experienced leadership.
High Impact of Research	Benefited by the ability of a team to move toward transdisciplinary team science/level of interaction. Integration beyond frameworks, concepts, ideas of any one discipline, leading to impact multiple disciplines. Mutual benefit with deepened connection with collaborators leading to greater contextualization of applicability of research/knowledge production.
Cyber-Technological Infrastructure Readiness	Supports innovation, optimized/integrated data management, reliable communication. Aids researchers in overcoming limitations in the field (e.g., using remote technology and sensing in post disaster or limited socio-ecological landscapes). Enables communication and collaboration across geographies.
Maximizing Institutional Support	Refers to both material (e.g., technological resources, field equipment, sufficient financial or administrative support) and cultural (e.g., promotion of value of team science, team science curriculum/training) institutional support. Influences individual and collective priorities and biases. Aids teams operating under constraints of time, resources, rapidly changing socio-ecological environments. Supported by prepared and experienced leadership that recognizes and prioritizes time needed for building successful teams.

5.3.2 Barriers to Implementing Team Science

The barriers identified in this section reflect both internal dynamics among team members and broader relational or structural challenges—such as engagement with stakeholders, institutional limitations, or infrastructural gaps—that can affect teams from within or beyond their formal composition. The challenges enumerated in Table 5-5 contextualize the characteristics of best practices identified in Table 5-3 and conversely highlight those best practices that may aid teams in overcoming implantation barriers.

TABLE 5-5. Barriers to optimal team functioning and implementation of team science.

Barriers	Characterization
Internal	
Communicating / Translating across disciplines	Translating terminology (theory, methodology), cultural linguistic framing, academic vs. practitioner teams, different types / definitions of qualified data.
Team composition	Fears of the challenge of operating within a diverse team, conflict, and challenges navigating cross-cultural challenges with external collaborators.
Ineffective leadership	Unable to clearly define team member roles & responsibilities. Poses an obstacle to coordination across disciplines, institutions and ability to accomplish project goals. Lacks good boundary setting, team structure.
Team ethics	Lack of delineation of co-authorship expectations, conflicts of interest. Compounded by lack of team purpose, roles, goals/objectives which create ambiguous understanding of collective team ethics.
Limits mentor / Mentee relationship building	May results from over-prioritization of production of research products, publishing and individual/departmental/institutional expectations. Compressed timelines and/or insufficient allocation of time dedicated to nurturing team dynamics.
Power / Ego	When competition is prioritized over collaboration, integration. Open dialogue and mutual respect are key to reducing this barrier.
Team isolation / Limited geographic proximity	Presents a barrier to face-to-face, in-person interactions, trust building, social relationship building, collaboration across disciplines. Can exist when there is limited use of technology to overcome this barrier.
Lack of mutual respect for disciplines	Team members work in silos and leadership does not encourage valuing of contributions from all team members regardless of discipline.

Level of familiarity with social psychology of team functioning	Occurs when team members/leadership are not well prepared and/or have limited understanding/experience with the value of collaboration/team science.
Moving from concept to practice	Lack of project and team goals/objectives. Lack of understanding/valuing of benefit of diverse disciplines. Ineffective communication/ability to translate across disciplines.
Limited time for collaborations	Lack of planning/understanding by team members/leadership of the value of nurturing team dynamics. Team isolation/limited geographic proximity can contribute to this barrier.
Varying expectations / Needs for professional development	Lack of experienced leadership, institutional support, clarity of roles & responsibilities, team cohesion, effective communication. Can also impact clarity of team ethics, authorship protocols, and recognition of the value of team science.
Method / Ability to determine success	Lack of planning/development of a clear mechanism for assessing success, outcomes, and impacts. This can also evolve from lack of clear roles & responsibilities, poor team cohesion, and ineffective leadership.
External	
Engagement with collaborators / stakeholders	Characterized by a lack of diverse, limited (i.e., time, method of engagement), tokenized engagement with collaborators/stakeholders. Can occur in highly charged, political settings, relationships.
Insufficient technical infrastructure	Presents logistical challenges related to data collection methods and technology, data ownership, metadata management, open data sharing, data availability, data preparation, and data preservation.

Navigating institutional requirements / cultures	May lead to challenges to team identity and functioning including as relates to meeting funding source requirements, a culture of competition over collaboration, departmental/disciplinary silos, policies that don't reward collaboration, limits on institutional resources and uncertainties around stable, long-term funding.
Sustaining projects beyond collaborations	Rely on the capacity of a team to prioritize translation of outcomes and benefits across disciplines and recognize systemic contexts of problems inherent to research goals, objectives, and application of appropriate methods.

Internal barriers to team functioning center largely around ineffective communication, insufficient delineation of roles and responsibilities, and inability of the team and/or leadership to prioritize ethical, unified, coordinated engagement. These dynamics may be shaped by power and gender inequities, ego-based conflict, or lack of inclusive practices. Additionally, internal and external barriers can result from practicalities of teams functioning across distance and/or without sufficient institutional and technological resources. External barriers can stem from poorly designed objectives and low-quality engagement with stakeholders or partners—whether these are external to the team or embedded within it. This includes failure to examine the relevance and potential benefit of the research to communities, cultures, and those directly involved in or impacted by the work.

This literature review also identified a research gap in the field of SciTS. The role of justice and equity in collaborative research practices is noticeably missing from the literature. These concepts were absent from the identification or exploration of best practices and challenges, even in fields where ethics or inclusivity might be expected to feature more prominently. While discussions of general ethics and the ethical responsibilities of teams were identified by Stokels et al. (2008b) and Caughy et al. (2023), no single discipline identified justice or equity as essential components. The following case study examines how many of these barriers manifested—and, in some cases, were intensified—within a post-disaster research setting, offering insight into the lived complexity of implementing team science under conditions of urgency, uncertainty, and structural vulnerability.

5.3.3 Team Science Through a Post-Disaster Lens

This section applies a retrospective lens to team collaboration in a post-disaster context, using a framework of best practices synthesized from an interdisciplinary literature review. The case study presented here illustrates the value and challenges of implementing team science in the aftermath of a disaster, based on reflections from the NSF funded project, CRISP (Critical Resilient Interdependent Infrastructure Systems and Processes) Type 2: Integrated Socio-Technical Modeling Framework to Evaluate and Enhance Resiliency in Islanded Communities (ERIC). Drawing on participant observation and team documentation, this analysis examines the interactions, dynamics, and challenges experienced by the multi-institutional CRISP research team. While the framework was developed after the CRISP project through subsequent review, it provides a useful lens for analyzing team processes, collaborative constraints, and structural barriers encountered during the project.

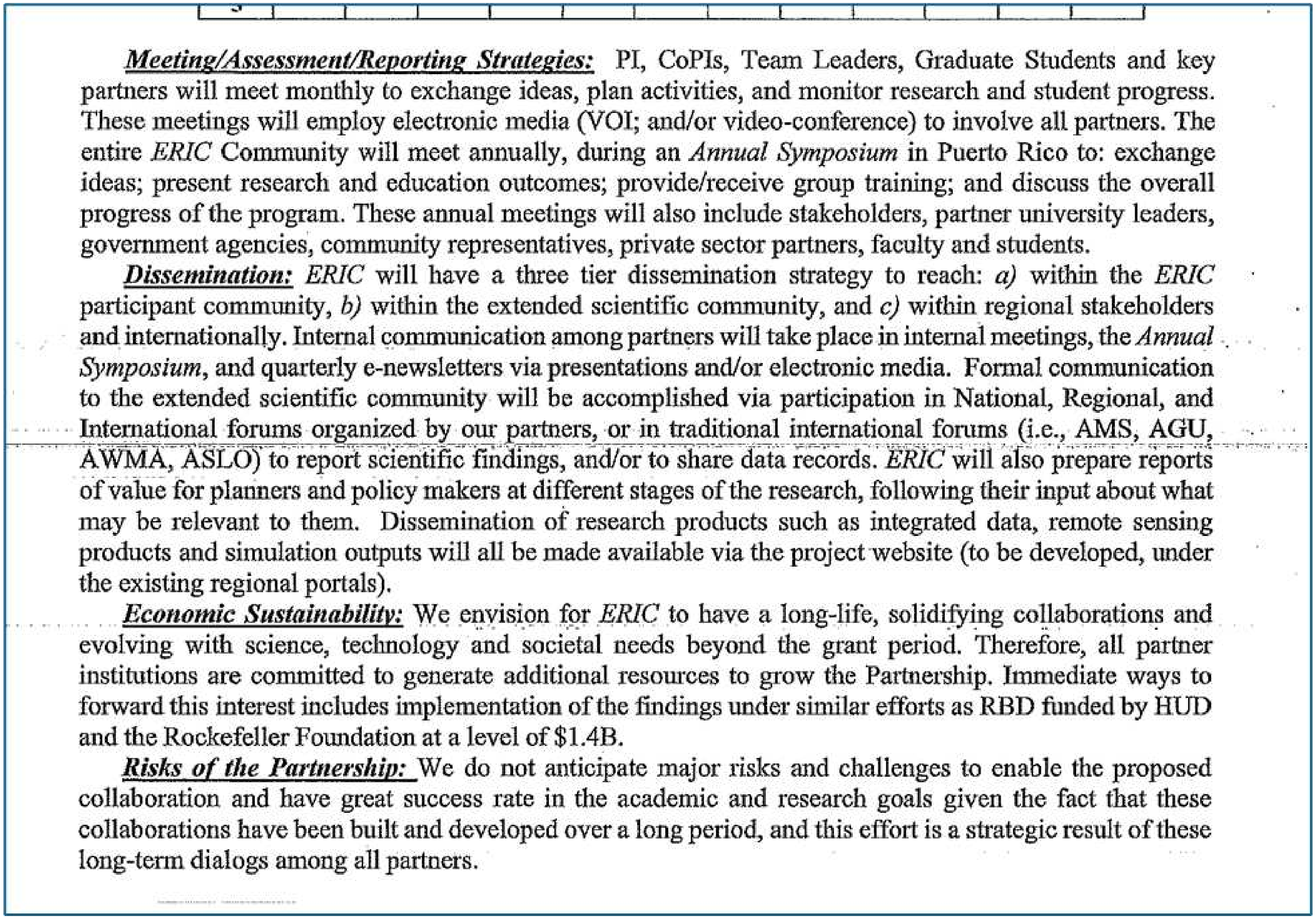
The CRISP project sought to address questions of socio-economic stability given extreme weather events, strategies for resilience unique to the challenges island communities face, and effective engagement with stakeholders with the goal of supporting and enhancing resilience and mitigation effort within the context of the impacts of the 2017 hurricanes, Maria and Irma, on the island of Puerto Rico. The research focused on building models that replicated the systemic networks of failures across infrastructure on the island with the goal of not only understanding the systems to date, but also their potential for rehabilitation and correction, and to reduce risk of future failure, as well as enhance resilience at multiple scales. The post disaster setting characterizing the project offers a unique opportunity to evaluate the confluence of an assessment of the application of a team science approach, its efficacy and the timing of such an approach relative to two significant disasters. This setting presented additional challenges to team functioning (e.g., time constraints, communication hurdles, geographic dispersion, accountability issues, power/ego dynamics, leadership complexities), the ability to sustain projects beyond initial internal and external collaborations, and determining metrics for success, outcomes, and impact. With the growing application of team science in disaster and climate adaptation science, these challenges require examination (National Academies of Sciences, Engineering, and Medicine, 2015; UNDRR, n.d.; USGS, n.d.).

5.3.3a Team Composition and Management

To accomplish CRISP research goals, teams of researchers from CCNY-CUNY (City College of New York – City University of New York), NYU (New York University), ASU (Arizona State University), UPRM (University of Puerto Rico – Mayaguez), and partners from across private, non-profit and governmental agencies collaborated to develop a transdisciplinary approach (Appendix E). The project included development and application of system network models, processing of geophysical data, and gathering and processing of social data. In short, research aims required at least interdisciplinary levels of engagement. There were also ethical considerations related to how the research goals, particularly those involving community engagement and data collection, would affect disaster-impacted populations.

Over the 3-year life of the project and during my tenure on the project (13 months), the composition of the research team included individuals from more than five different countries, ages ranging from 22-42 years, and multiple gender identities. The teams comprised graduate students (master's and PhD), early career scientists, mid-career scientists, and mid-career professionals. Students from several University of Puerto Rico (UPR) campuses were employed to assist the Social Informatics and Rebuilding team research activities. Many of these students had experienced personal loss (e.g., of homes, family members, and community infrastructure) as a result of Hurricanes Irma and María. This reality shaped both the emotional context of the research and the ethical responsibilities of the team. In settings like this characterized by systemic vulnerabilities and recent trauma, research protocols must account for local context through appropriate IRB oversight, trauma-informed practices and training, and inclusive, respectful engagement. These dynamics reinforces the importance of culturally responsive training and ethical frameworks that center the well-being of participants and collaborators, particularly when those collaborators are themselves embedded in affected communities.

Associated tasks, sub tasks and initial expected outcomes were presented to the team at the kickoff meeting in September 2018. The management approach outlined at this meeting identified the need for regular meetings (every two months), strategic involvement with stakeholders, and the nurturing of an "open, collaborative, shared, and engaged" environment within which the research was to take place. Given the remote and geographic dispersal of the teams and stakeholders, periodic all-hands meetings and a shared Google Drive were established to facilitate engagement, communication, and knowledge sharing. During the first year, three of the five all-hands meetings were in person. Only two of the 5 meetings involved cross-team knowledge exchange that moved beyond siloed reporting of sub-team research objectives. The On-Site Kickoff meeting (Jan 2019) and the Integration Workshop (June 2019), at which no PIs attended, were the only meetings that featured team building activities (Appendix F). The planning document (Figure 5-2) illustrates project level intention to implement team science as outlined in the strategies and approaches detailed in the goals and objectives of the project. These included diverse, deepened "stakeholder” engagement, accountability, prioritization of high impact of research fundings/results, and sustained impact of the research. However, of note is the lack of identification of risks and/or challenges associated with this project taking place following two significant disasters.



Meeting/Assessment/Reporting Strategies: PI, CoPIs, Team Leaders, Graduate Students and key partners will meet monthly to exchange ideas, plan activities, and monitor research and student progress. These meetings will employ electronic media (VOI; and/or video-conference) to involve all partners. The entire *ERIC* Community will meet annually, during an *Annual Symposium* in Puerto Rico to: exchange ideas; present research and education outcomes; provide/receive group training; and discuss the overall progress of the program. These annual meetings will also include stakeholders, partner university leaders, government agencies, community representatives, private sector partners, faculty and students.

Dissemination: *ERIC* will have a three tier dissemination strategy to reach: *a)* within the *ERIC* participant community, *b)* within the extended scientific community, and *c)* within regional stakeholders and internationally. Internal communication among partners will take place in internal meetings, the *Annual Symposium*, and quarterly e-newsletters via presentations and/or electronic media. Formal communication to the extended scientific community will be accomplished via participation in National, Regional, and International forums organized by our partners, or in traditional international forums (i.e., AMS, AGU, AWMA, ASLO) to report scientific findings, and/or to share data records. *ERIC* will also prepare reports of value for planners and policy makers at different stages of the research, following their input about what may be relevant to them. Dissemination of research products such as integrated data, remote sensing products and simulation outputs will all be made available via the project website (to be developed, under the existing regional portals).

Economic Sustainability: We envision for *ERIC* to have a long-life, solidifying collaborations and evolving with science, technology and societal needs beyond the grant period. Therefore, all partner institutions are committed to generate additional resources to grow the Partnership. Immediate ways to forward this interest includes implementation of the findings under similar efforts as RBD funded by HUD and the Rockefeller Foundation at a level of $1.4B.

Risks of the Partnership: We do not anticipate major risks and challenges to enable the proposed collaboration and have great success rate in the academic and research goals given the fact that these collaborations have been built and developed over a long period, and this effort is a strategic result of these long-term dialogs among all partners.

FIGURE 5-2. Excerpt from project planning document identifying the intent for frequent communication as a means of encouraging collaboration.

5.3.3b Time, Geography and Communication

For teams to engage meaningfully, time is essential - for coordination, reflection, and sustained relationship-building, both within the team and with external partners. However, many disaster response grants prioritize rapid, short-term implementation, making it difficult to establish the continuity required for optimal team functioning. NSF Type 2 projects emphasize ambitious scientific outcomes -encouraging teams to explore "bold, new perspectives," bring "new lines of critique," and produce innovative models that address risk and resilience in complex systems (U.S. National Science Foundation N.D.). However, they do not necessarily prescribe or delineate the exact mechanisms for collaborative processes needed to achieve these outcomes, particularly in post-disaster settings where continuity and coordination are difficult to sustain.

The CRISP project Social & Informatics Rebuilding team implemented field work more than a year after hurricanes Irma and Maria. However, due to pre-existing economic and political stressors, the overall impact of the hurricanes on livelihoods continued to be acutely felt by the time the social assessment field work (focus groups, outreach) began. Notably, some of the local students tasked with social assessments and supporting the primary team leads with this work continued to experience daily interruptions to both basic livelihood tasks and university activities on campus and off. On almost a weekly basis, disruptions in power and water led to the closing of campuses for a minimum of a day, frequently longer. Time was lost due to school closures immediately following the hurricane impact due to road closures, complete absence of water and electricity, and unavailability of staff and professors. This added to the stress and burden already felt by these students. When establishing local relationships and integrating participation from communities and local researchers, it is vital to consider the multi-scale and multi-temporal impact from events. Local stakeholders and researchers themselves may be members of vulnerable, if not also marginalized communities (Aguilar et al., 2025; Castañeda & Smith, 2022; Chu et al., 2023; Lutze & Liddell, 2024; Valdez-Ward et al., 2024). Research design and implementation should reflect this awareness and provide a means for reducing burden and facilitating mental and physical health support.

Although the NSF Type 2 CRISP project offered a longer 3-4 year timeline and emphasized systemic, interdependent research, the project still encountered significant challenges related to turnover and continuity. Sustained membership fosters team cohesion and functioning – a best practice emphasized across the literature. Researchers entered and exited the project due to graduation, reassignment, or shifting institutional roles, disrupting cohesion and slowing progress toward shared goals. These disruptions limited opportunities for deeper collaborations and collective progress. Compounding this, the research team navigated asynchronous timelines between the research team and external partners (e.g., emergency response agencies) whose operational priorities and decision-making cycles demanded continual adaptation. These factors collectively strained team cohesion, integration, and motivation to collaborate. These challenges are common in large, multi-institutional teams, particularly those composed of researchers at varying stages of their academic careers.

The geographic scale and complexity of the study area can add significant challenges to managing a project in a post-disaster setting. A disturbed landscape may remain highly susceptible to additional and compounded disturbances, even under conditions that would not typically trigger a disturbance (Guariguata, 1990; Kleinman et al., 2019; Knelman et al., 2019; Miller et al., 2017; Sturtevant & Fortin, 2021; Vorster et al., 2023). For example, rain-induced slope failures can disrupt road access to communities and field sites, complicating both data collection and community engagement. The number of affected communities and diversity of terrain can shape how researchers prioritize field activities, structure team logistics, and select modeling approaches for analyzing impacts and resilience. Whether a researcher or a team has firsthand knowledge of an area, particularly if it is a large geographic area, can affect perspectives and assumptions guiding the training of models, context for analysis, and choice of methods.

In post-disaster landscapes, particularly in mountainous or ecologically unstable zones, ecosystems are often in flux, increasing the time sensitivity of field observations and remote assessments. These efforts can be disrupted by damaged infrastructure, difficult terrain, and constraints imposed by the timing of post-disaster funding or relief efforts (Abeysinghe et al., 2025; Ge et al., 2019; Packenham et al., 2021). Practical barriers, such as washed-out roads, reduced access to study sites, and reliance on compromised critical systems, may further limit data collection and analysis timelines (Fogarty International Center, 2021). Basic needs may not be met daily for both researchers and the affected population (including partner organizations and individuals) in the post disaster study area. Additionally, research conducted in a post disaster setting benefits uniquely from cyber-technological infrastructure readiness. Local entities may be limited in access to technology following a disaster resulting in a feedback loop between geography, damaged infrastructure, and institutional resource limitations. Teams, and particularly leadership, must account for these variables in both study design and management of implementation supporting a flexible, committed, experienced team (Bennet & Gadlin, 2012).

Beyond physical and logistical barriers, researchers must also navigate ethical and relational complexities when engaging with communities affected by disaster. The socio-ecological landscape may be marked not only by environmental susceptibility but also by deep social vulnerability. Engaging with these communities requires trauma-informed, ethically sound practices that avoid exacerbating harm or retraumatizing populations (Ferreira et al., 2015; O’Mathúna, 2020; Packenham et al., 2017). Researchers must be especially sensitive to timing, consent, and cultural dynamics in these contexts and their own positionality within collaborative efforts.

This also reflexively speaks to the awareness needed when accessing and working in a stressed network, particularly if co-production of knowledge is a part of the study design. While co-production is often essential for producing contextually relevant, actionable research in post-disaster settings, it can also be emotionally and logistically challenging. These settings frequently involve overlapping vulnerabilities which place additional demands on researchers and community partners alike (O'Mathúna, 2020). As previously explored, collaborative approaches require time, trust, and sustained engagement, but resources to support this may be strained during emergency response or recovery efforts. The ability and willingness to engage in team science, in or out of a disaster setting, is often more developed in mir to late career researchers (Bennett and Gadlin, 2012). Early-career scholars (e.g., graduate students, postdoctoral researchers, and junior investigators) may find themselves less prepared or supported for this kind of engagement (Bennett & Gadlin, 2012). These team members are often under pressure to meet individual benchmarks such as dissertation completion, publication, job placement, or other tasks that may compete with the time-intensive demands of co-production and interdisciplinary work (National Academies of Sciences, Engineering, and Medicine, 2015). Yet, a growing body of literature demonstrates that work produced by geography spanning teams has the potential to have an even greater impact (Hall et al., 2018).

This project involved a geographically dispersed set of researchers, most of whom had limited prior experience or time in the study area. While keen awareness of the value and concept of integrated resources (including data inputs and outputs), shared objectives, and coordinated field efforts were expressed with noticeable frequency at all-hands meetings, the practical implementation reflected the diversity of expectations, individual lab goals, and knowledge across leadership and subgroups on translating differing experiences and approaches. The need to explore these challenges led to the initiative, by two researchers from the geophysical and social teams, to design and facilitate a day long workshop (see Section 5.5.5).

My own experiences interacting with local and regional agencies, community groups, and farmers underscored the depth of post-traumatic stress affecting the capacity of communities to surmount the impact of the collective social system stressors. Of note is that the impact, by any measure, was not felt equally across all communities, municipalities, and geographies. Consequently, the capacity of communities to adapt and restore livelihoods was not equitably distributed. This formed the backdrop to the process of accessing networks and building trusted relationships, an essential step in conducting qualitative data collection. This also had an impact on those teams within the project more focused on quantitative assessments, model building, and mapping. Availability of data, coordination with agencies, ground truthing, as well as any integration with the groups invested in the social impact analysis affected, to a lesser degree, these efforts.

5.3.3c Sample Approach for Facilitating Post-Disaster Team Science

In response to persistent challenges integrating efforts across disciplinary and institutional lines, despite a full year of project activity, I collaborated with a colleague from

CCNY to design and facilitate an interdisciplinary workshop during the CRISP ERIC Integration Meeting in New York (June 20-21, 2019). The workshop featured a series of participatory exercises designed to identify interdisciplinary connections (e.g. between data inputs/outputs, methods, and conceptual frameworks), clarify project-wide data flows, and encourage teams to map how their sub-research objectives aligned with overall project goals (Appendix G).

Workshop objectives drawn directly from the CRISP ERIC Integration Workshop guide included the following:

- Identify sub-research questions, conceptual framings, methods, and data inputs and outputs (sources and sinks), including independent and dependent variables. This information was provided by groups identified as primarily belonging to one of four domain groups (social, geophysical, energy, and built).
- Provide a visual exploration of the density and diversity of analysis and processes currently underway.
- Provide an opportunity for researchers to self-evaluate how sub-research questions support the CRISP ERIC project research questions.
- Creatively identify connections between and within domain workgroups, primarily through integration of conceptual framings and data inputs/outputs. Participants use colored yarn, representing their domain workgroup, to physically connect data and concepts.
- Contribute to a unified understanding of activities and progress by sub-domain workgroups.

Additionally, while the project PIs bore the responsibility of identifying many of the stakeholders, members of various subgroups, such as the social impact team, were also tasked with nurturing relationships with community leaders and organizations. My own work led to relationship building activities with stakeholders. Secondarily, the workshop scope included an examination of these activities and what we, as a collective large research team, mean by "stakeholder", distinguishing between stakeholder, collaborator, and consulting subject matter experts.

The workshop consisted of two primary activities aligned with the objectives outlined above. The first activity involved a breakout session wherein each of the topical subgroups (Energy Domain, Geophysical Domain (Climate, Hydrology), Social Domain) would first internally identify subgroup research questions, conceptual/theoretical framings and methodologies that supported the overarching research question for the project (Appendix H). These subgroups would then visually map out relationships between the questions and theories and the root research question. The results of the breakout group activity are then combined to produce a meta-map for the project.

The results of this first activity form the basis for the second activity. All the subgroup teams combine for this activity in which cross team points of connection, integration and opportunity for collaboration are identified. With the large adhesive notes resulting from the first activity placed on the wall as visuals, team members identified "lines of connection" using string/cord pinned from one post its to another (Appendix I). During this activity, participants physically connected lines of connection between research questions, conceptual frameworks, methods, and data sources and sinks (inputs and outputs). Each color string represented a different team within the project. Figure 5-3 illustrates the density of connections previously unrealized and undocumented.

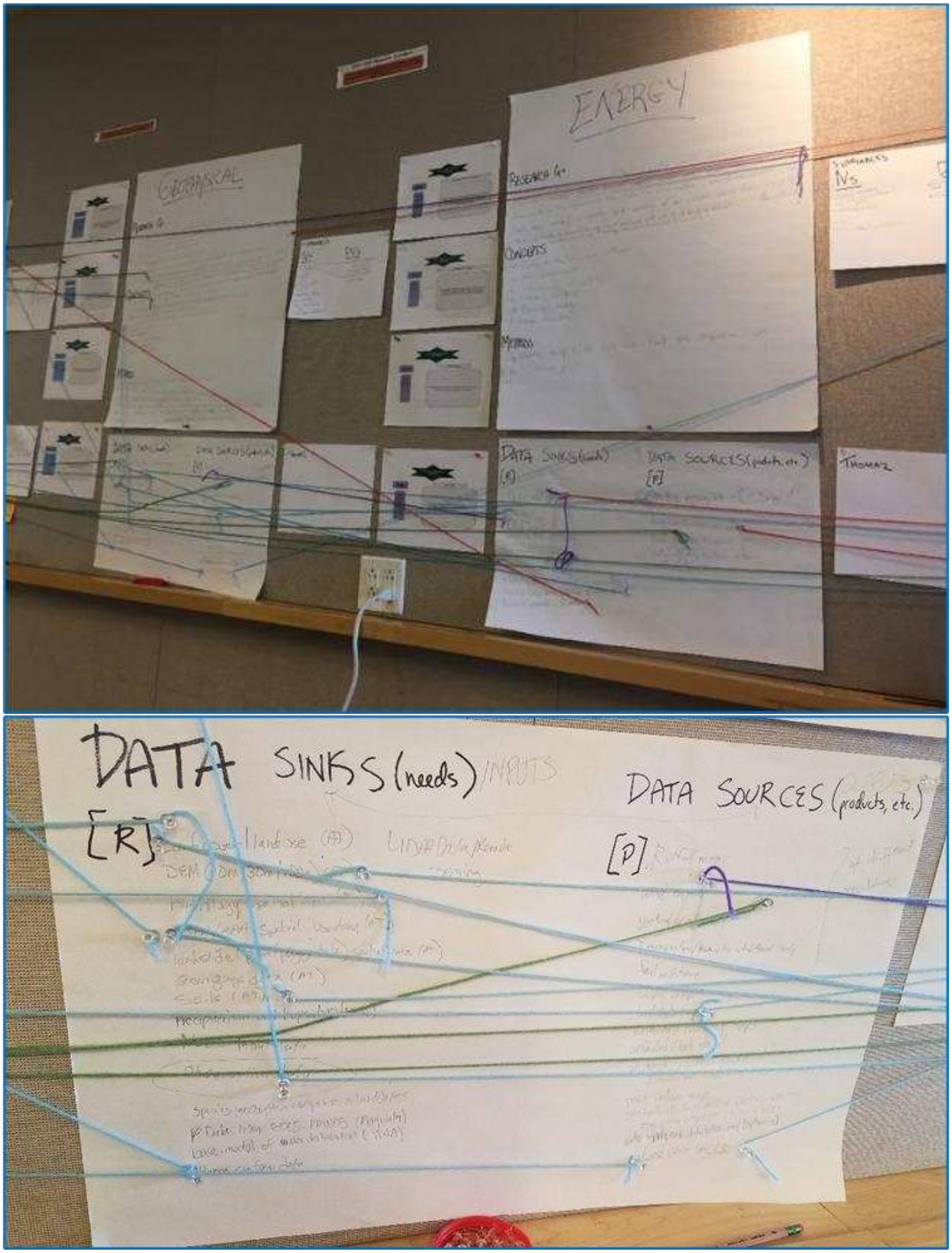


FIGURE 5-3. Photos showing results of the second workshop activity.

As a result of this workshop, multiple teams identified new points of integration, launched additional working groups, and initiated development of a shared data inventory. The physical mapping clarified duplication of efforts, surfaced misaligned spatial and temporal scales of analysis, and allowed for real-time negotiation of conceptual framings. For example, a new area of cross-disciplinary focus could include an examination of the impact of landslides as relates to the analysis of the energy and built infrastructures and climate modeling frameworks. It also fostered discussion and visualization of points of agreement and differences in perception around the greater research question, subgroup priorities, scale, and needs. A range of salient outcomes illustrates the effectiveness of this exercise to deepen implementation of team science.

The workshop also served to identify data being generated across teams that had not been previously shared in full, prompting focused development of a more robust, interdisciplinary data inventory. Data management for research of this size with as many disciplinary teams and institutions involved requires significant planning and management (Laituri et al., 2015). Multiple researchers expressed a desire and commitment to continue developing the data and workflow integration activity remotely. The approach is supported by similar approaches such as those outlined by Banner (2013). In short, this workshop sought to overcome any institutional boundaries or limits in resources or technology between one team or institution versus another.

5.4 Discussion

5.4.1 Foundations of Optimal Team Functioning

Understanding how team dynamics shape a team's capacity to conduct integrative, collaborative research is foundational to identifying best practices for team science (Table 5-2). Across disciplines, the literature emphasizes the value cultivating both individual and collective competencies, effective logistical management structures, and prioritizing leadership practices that support integration through research design, implementation and evaluation (Table 5-3). Despite disciplinary variation, there is broad agreement that team and self-awareness are critical attributes of high-performing teams. In other words, the collective is as strong as the capacity of the individuals to apply learning, build skills, and engage across disciplinary boundaries. While transdisciplinary collaboration is often idealized, its practical implementation often proves far more complex. These dynamics take on heightened significance in post-disaster settings where the ability of individuals and teams to function adaptively (e.g., to communicate clearly, share leadership roles, and integrate data and perspectives across domains), is not just an indicator of optimal team functioning, but a practical necessity when responding to rapidly changing conditions on the ground.

Team structure, defined, in part, by whether collaboration is multi/inter/transdisciplinary, shapes communication patterns, cohesion, and integration (Asencio et al., 2019; Börner et al., 2010; Caughy et al., 2023; Dehart, 2017; McGreavy et al., 2016; National Research Council, 2015; Shin et al., 2022; Uchida et al., 2019; Zabaniotou et al., 2020). Terminology also matters. Mauser et al. (2013) notes, multidisciplinary teams often work in parallel with limited integration while interdisciplinary teams coordinate more closely across frameworks and methods. Transdisciplinary teams aim for full integration, often involving non-academic collaborators to co-produce knowledge. Achieving clarity about the nature of collaboration is essential. This framing should inform team composition, processes, and shared expectations. Without early consensus, misalignment can undermine integration efforts and limit the practical application of best practices.

5.4.2 Communication and Cohesion in Dispersed Teams

Geographic distribution significantly shapes communication practices and team cohesion. The frequency, mode (e.g., virtual digital video meeting and messaging tools, mobile device messaging apps, web-based collaborative spaces, phone, and email), and quality of communication can facilitate or hinder collaboration, depending on how these tools are used (Asencio et al., 2019; Dehart, 2017; Gilligan, 2021; Institute of Medicine, 2005; Johnston & van de Lindt, 2022; Kozlowski & Bell, 2019; McGreavy et al., 2016; Peek & Guikema 2021; Shin et al., 2022; Stokels et al., 2006, 2008a,b; Uchida et al., 2019). The use of different tools and communication resources (e.g., Teams, Zoom, GoogleMeet, Slack, WhatsApp, Signal, WeChat, Miro, etc.) impact the manner and level of connection experienced. They can enhance or detract from the quality of the communication depending on how they are utilized (Akinwande et al., 2023; Karl et al., 2022). Ethical considerations also emerge when communication tools are used for handling sensitive data, particularly when some platforms may not meet required security standards for confidential information (Samarin et al., 2024).

While virtual tools offer expanded access and flexibility, they often limit the nonverbal and socio-emotional cues that help build relationships and mutual understanding across disciplinary and even cultural differences (Bennett & Gadlin, 2012; Stokels et al., 2008b). Communication also involves the capacity to translate ideas and assumptions from one discipline, illuminating the benefits of understanding the value of other disciplines. These challenges can be compounded in large, dispersed teams where disciplinary and geographic distance constrain cohesion. As discussed further in Sections 5.4.4 and 5.4.5, these limitations can exacerbate challenges in post-disaster contexts, where community engagement requires relationship-building and cultural sensitivity that may be difficult to cultivate remotely.

Bennett and Gadlin (2012) note that intermediate levels of interaction, where team members engage across disciplines but without deep integration, are common to distributed teams. They also advocate for an intentional vetting process for the selection of team members to support optimal team composition (Bennet & Gadlin, 2012). This vetting process includes reference checks and interview questions to assess possession of personal attributes such as commitment to the team, collective goals, and integrative process, as well as self-awareness. Even so, it cannot be assumed that a team of individuals, even those with prior team science experience, will automatically be able to collectively overcome challenges to team cohesion. To move beyond this, teams must navigate differing communication styles, expectations around leadership and feedback, and variations in disciplinary language. To aid teams in aligning the research with disasters and needs of communities, disaster science literature offers the practice of running scenarios as a pragmatic mechanism for exploring diverse methods and approaches for collaboration and illuminating pragmatic considerations (Table 5-2, Disaster Science section).

5.4.3 Structure, Scope, and Leadership Dynamics

Establishing team norms, values and expectations takes time, even with frequent in person interactions across different disciplines (Table 5-3). This is a reality often limited in post-disaster contexts where timelines and fluid conditions can delay or destabilize the early formation stages of a team. Furthermore, communication is influenced by time constraints, power dynamics, gender/identity, and stage of career (Table 5-2, Social Science, SciTS sub sections). More experienced team members and leaders, particularly in interdisciplinary or transdisciplinary team science, are often better equipped to contribute to and model an integrative, collaborative, conflict reduced communication norm. Additionally, team continuity is a critical challenge in large, interdisciplinary teams (Stokels et al., 2008b). Leadership that fosters reflexive accountability enables balanced team dynamics, capacity to be responsive to compressed timelines, and increases the relevance of research outcomes (Derrick et al., 2023; Schippers et al., 2015; West & Hirst, 2003). This is especially important in post-disaster settings where team structure may need to adapt rapidly to disruptions in personnel, such as occurred and explored in the case study, Section 5.3.3., shifting institutional priorities, or evolving community needs.

Time and experience also shape internal power dynamics. A researcher's sense of inclusion and perceived social integration within the team can be reinforced or negatively augmented by leadership behaviors and capacity to nurture a space for diverse voices. Gender and career stage often intersect with power dynamics that can affect team cohesion. Fassnacht and Ma (2020) identified the value of individual and collective contributions for strengthening team commitment and reinforcing shared goals. An essential component supporting all of these variables is the intentional cultivation of trust.

Gender, discipline, and experience diversity within the leadership often dictates the mode and tenor of communication as well. Additionally, proficient, robust leadership guides teams through the forming, storming, norming and performing stages (Tuckman, 1965). One best practice involves the inclusion of professionals in place to assist teams with transitions through these stages. Misalignment in the early stages of team formation (e.g., lack of clarity of roles and responsibilities, disparate goals, mixed messaging from leadership) can derail collaboration before it has time to become firmly established (Table 5-3). The storming phase can be especially challenging in a transdisciplinary setting where the epistemological and methodological differences may vary widely across disciplines. For example, teams that include both social scientists and quantitative atmospheric modelers may navigate differing expectations around data, methods, and what constitutes valid evidence. To reduce these challenges team members are called upon to step outside comfort zones and disciplinary bias to think about data, questions, process, methods, and results through a different lens.

5.4.4 Power, Equity, and Positionality Within Teams

Diverse team composition (e.g. across career stages, levels of collaborative experience, disciplines, gender, identity, lived experience) enriches collaborations, creativity, problem-solving strategies, and promotes equitable outcomes (Zabaniotou et al., 2020). Stokels et al. (2008b) highlight the challenge of power differentials resulting from disparities in institutional resources (e.g., funding, decision-making power, technological resources), disciplinary hierarchies, and decision-making authority. Reflexivity is key, especially for researchers working outside their home contexts or institutions, is crucial for recognizing and addressing these imbalances.

These dynamics are often magnified in post-disaster settings. Researchers must navigate pressurized timelines, coordination with response agencies, ongoing trauma, recovering socio-ecological systems, and complicated external engagements. In these conditions, communities may be hesitant or even unable to engage with research teams. It is even more imperative, then, that the team is characterized by the capacity for timely and productive coordination with external partners through effective communication, a sense of unity of purpose, and a clear understanding of roles and responsibilities.

5.4.5 Justice and Equity

Despite growing attention to collaboration and integration in team science, the literature reviewed in this study did not explicitly identify justice or equity as best practices or barriers (see Table 5-2, Table 5-4). This absence is especially noteworthy given the documented ethical, logistical, and epistemological complexities of conducting research in post-disaster settings. Post-disaster research often occurs in communities experiencing overlapping vulnerabilities, such as trauma, displacement, infrastructural breakdown, and political marginalization (Garcia et al., 2021; Pescaroli & Alexander, 2016; Stablein et al., 2022). This requires deliberate prioritization of ethical approaches to data collection and community engagement (Allegretti et al., 2015; Louis-Charles et al., 2020; O'Mathúna, 2020). This is particularly important for those teams composed of non-local researchers, where issues of access to privileged spaces, trust, and positionality must be carefully navigated (Liu & Burnett, 2022; Miyazawa, 2018; Scott et al., 2023; Uekusa, 2024). Local researchers and community members may be managing their own recovery while being asked to contribute to data or serve as cultural and logistical intermediaries (Aguilar et al., 2025; Chu et al., 2023). Trust built between the researcher and the community may result in special or “privileged” access to information, particularly as relates to the sacred, culturally significant spaces, or interactions with vulnerable populations (Carlson 2024).

This challenge is further complicated by the historic negative impact of "parachute projects" (Louis-Charles et al., 2020). These types of projects are characterized by teams of researchers entering a space to conduct research, often qualitative research activities and in spaces where trust building is essential, in a compressed timeline, without involvement of the local community in project design or implementation. Data collection is conducted and then research teams leave, often without feedback or long-term engagement with the community of focus (Louis-Charles et al., 2020). To address this, teams must reduce burden on already stressed systems and design projects for sustainability beyond grant funding timeline limitations. One potential solution may lie in the prioritization of co-creative engagements with communities that grants local agency to communities to manage the maintenance of the project and/or data collection beyond the life of the funded project and presence of the researchers (Fernández-Giménez et al., 2019).

Francis and Hendrickson's (2021) reflection on post-disaster research at the University of the Virgin Islands underscores the importance of culturally grounded, human-centered approaches in academic institutions directly impacted by disaster. Their emphasis on authentic academic care—rooted in empathy, relational support, and institutional attentiveness—resonates with calls for trauma-informed and justice-oriented research practices. By highlighting the lived realities of historically underrepresented institutions and communities, their work affirms the value of embedded knowledge systems and institutional responsiveness as core dimensions of equity in post-disaster research settings.

Another central consideration is the distinction between explicit and tacit knowledge. Tacit knowledge acquisition often requires face to face interaction, thereby potentially putting both the researcher(s) and community representative, knowledge holder(s) at risk. This experiential knowledge requires time in person and relationship building. If a project is relying primarily on explicit knowledge, some local knowledge may be missed. These realities support sensitivity and risk-informed awareness and account for the influence of time after an event. Tacit knowledge may be more difficult to communicate since it is indirect and could get buried by the immediacy of the trauma from the disaster or related/compound event (e.g., social/political unrest, disease outbreak, failure of critical infrastructure). Because such data are often perishable and relational, projects must be designed to allow sufficient time for relationship-building and iteration, especially when team members are not based in the affected region. The time-compressed nature of post-disaster research can also create pressure that compromises ethical engagement, particularly if timelines or funder expectations do not align with community needs or recovery processes. As a result, the knowledge generated, observed, or shared during the project may be omitted from post-project evaluation. Additionally, teams relying solely on extractive, technology-driven, expert-led approaches may inadvertently reproduce inequities, particularly when derived outside of long-term relationship-building or co-created agendas.

Team composition (e.g., disciplinary diversity, positionality, prior collaborative experience), shapes not only internal dynamics, but also ethical dimensions of data collection in post-disaster contexts. Qualitative methods such as interviews, focus groups, and participatory research are often necessary where secondary data is limited (Louis-Charles et al., 2020). These methods require sensitivity to local conditions, as communities may still be recovering from trauma or instability. While IRB protocols offer baseline protections for vulnerable populations, they are not sufficient in isolation. Teams must also engage with cultural and place-based norms, avoid overreliance on community “gatekeepers”, and ensure that all researchers, including those from disciplines not typically involved in fieldwork, receive cross-disciplinary training in ethical engagement (Potnis & Gala, 2020). Assumptions of neutrality or objectivity can obscure the subtle ways researchers, particularly those unfamiliar with the social and cultural landscape, may reproduce asymmetrical power dynamics in community engagement. These biases can influence not only data collection but also project design and team conduct. Reflexivity, trauma-informed training, and adaptable research designs that center the needs and agency of affected communities.

5.6 Conclusions

Team science not only expands and diversifies the scientific ecosystem or community within which the work is occurring geographically and topically, it creates opportunities for professional development and new thought that may have not been possible when operating in isolation (Forscher et al., 2023). This study identifies and examines a significant gap by synthesizing and contextualizing best practices for these challenging settings, highlighting barriers such as disciplinary silos, insufficient institutional incentives, and unacknowledged justice and equity concerns. As the field evolves, there may be a shift toward stricter frameworks aimed at fostering cross-disciplinary consensus, which would challenge teams to achieve deeper, truly transdisciplinary integration. This study also summarizes and evaluates the primary best practices observed in the field utilizing a case study evaluation. Thus, it reflects both where real-world application diverges from theory and where nuances exist that underscore the complexity of fieldwork.

This research contributes to the SciTS field by advancing both theoretical understanding and practical methodologies for conducting science in extreme and often unpredictable conditions. Drawing from a case study of the NSF CRISP Type 2 project in Puerto Rico, following hurricanes Irma and María, this research illustrates how best practices must be adapted for contexts characterized by trauma, instability, and infrastructural fragility. Conducting transdisciplinary team science in post disasters settings, especially in regions like the Caribbean that experience compound and high frequency events, may provide unique advantages in supporting highly stressed systems. The best practices and approaches presented offer potential to build capacity for under-resourced island communities by generating dynamic, systemic, technologically innovative, action-oriented solutions benefiting short and long-term recovery efforts (Bui et al., 2022).

To accomplish this team science must account for the role of time, the effects of trauma on populations and landscapes, and the high degree of uncertainty, each of which demands heightened flexibility and adaptive strategies. These practices span domains such as team formation and leadership, communication across geographic and disciplinary boundaries, and building trust and cohesion in uncertain conditions. Future efforts in team science must integrate justice-centered, trauma-informed, and context-responsive strategies, especially in climate-vulnerable regions where the stakes of scientific collaboration are both urgent and enduring.

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CHAPTER 6 – DISCUSSIONS AND CONCLUSIONS

This chapter synthesizes key findings from Chapters 3, 4, and 5 and revisits the three interconnected research goals introduced in Chapter 1. These goals were:

- To develop and apply a socio-ecological framework for watershed health assessment that prioritizes risk-informed, equitable watershed governance.
- To assess socio-ecological vulnerability to landslides and extreme erosion within the Río Grande de Añasco (RGA) watershed.
- To synthesize and critically assess team science best practices across disciplines, using a post-disaster case study to examine unique implementation barriers and highlight justice and equity as vital considerations.

Each of these goals is revisited in the sections that follow. The discussion moves from the empirical analysis of landscape change and socio-ecological vulnerability to broader implications for governance, knowledge integration, and equitable, risk-informed approaches essential for climate-adaptive watershed health. Together, these discussions show how physical, social, and institutional dimensions of governance interact to shape the health of the RGA watershed and inform more just and sustainable management strategies for comparable socio-ecological systems. Section 6.1 synthesizes findings from an assessment of the impacts of Hurricanes Irma and María on the RGA watershed. It explores how compounding hazards (e.g., landslides, critical infrastructure failures, unplanned urban expansion) interact with social vulnerability to heighten risk. Section 6.2 moves from community to institutional and global scales, integrating insights of risk-informed governance, cultural and participatory dynamics, and justice-centered approaches for adaptive and team science research practice. Section 6.3 outlines research opportunities that build on this work through hydrologic modeling, field-based ecological assessments, and participatory analyses of risk perception. Together, these sections trace a clear progression from empirical analysis to conceptual synthesis, linking socio-ecological vulnerability, risk-informed governance, and equity-driven strategies to strengthen watershed health and resilience across scales.

6.1 Landscape Change, Infrastructure, and Socio-Ecological Vulnerability

Regional studies show escalating storm intensity, rising temperatures, and more frequent drought, with localized ecological consequences across Puerto Rico (Batista et al., 2024; Drought.gov, 2023; IPCC, 2014; IPCC, 2022a, 2022b; Jury, 2020; Muñoz et al., 2022; Puerto Rico Climate Change Council, 2015; Roy, 2024; Taylor et al., 2012; US Department of Energy, 2023). For example, temperatures in Mayagüez rose 1.17ºC over 40 years (e.g., 1961 – 2000), almost double the global average (Harmsen et al., 2009). These shifts reinforce the urgency of adaptive strategies that address ecosystem degradation and uneven socio-economic impacts, as seen in the variable effects of forest fragmentation and landslides across the watershed (Van Beusekom et al., 2018).

Reducing vulnerability across socio-ecological systems (SES) depends on a shared commitment to environmental protection (Folke et al., 2010). This aligns with the SES Watershed Health Assessment (WHA) Framework (Chapter 3, Figure 3-1) which integrated ecological and social indicators to evaluate resilience. Biodiversity loss, poor land and water management, and ecological degradation compromise the carrying capacity of ecosystems, threaten food systems, water availability, and public health. Disaster risk reduction requires policies that value ecosystem services, both economically and culturally, to sustain ecological function alongside community well-being (Anderies et al., 2006; Millennium Ecosystem Assessment, 2005; Munang et al., 2013). As discussed in Chapter 3 (Table 3-2), ecosystem services are central indicators of watershed health, connecting ecological processes with human well-being.

Resilience research increasingly recognizes the inseparability of human activity and ecosystem processes (Folke et al., 2002; Walker et al., 2006). As explored in Chapter 4, climate-related hazards in Puerto Rico, including increased landslide risk, must be understood through the interactive dimensions of vulnerability, risk, and adaptive capacity. Spatial analyses of the impact of landslides throughout the RGA watershed revealed high landslide density in forested and agricultural zones, especially within valley and mountain farming communities (Larsen & Torres-Sánchez, 1998; Larsen & Simon, 1993) (Chapter 4, Table 4-1). Specific municipalities, including Maricao, Las Marías, and Lares, were identified as landslide hotspots, with Maricao characterized by the highest density of landslides (Chapter 4, Figure 4-5).

Additionally, infrastructure development, particularly under pressures of rapid urbanization, can strain SES functioning when sustainability principles and risk reduction are ignored. The RGA watershed experienced significant land-use change from agriculture to urban development, particularly around Mayagüez, creating ongoing challenges to sustainable watershed management and hazard mitigation. Informal road construction threatens slope stability and undermines erosion and sedimentation controls (Montgomery, 1994; Ramos-Scharrón, 2010; Ramos-Scharrón & Figueroa-Sánchez, 2017; Ramos-Scharrón & Thomaz, 2016) (Chapter 2, Figure 2-7; Chapter 4, Figure 4-8). Although new technologies and networks can aid adaptation, poorly planned growth reduces recovery capacity following successive hazards. The resilience of ecological and social systems unfolds at different spatial and temporal scales, further complicating planning. Transportation networks, for example, may function as either enablers of recovery or sources of fragility depending on how they are maintained and governed. Additionally, the expansion of urban areas into steep, erosion-prone regions increase landscape vulnerability, emphasizing the need for integrated land-use and infrastructure planning that links ecological and social resilience (Chapter 4, Figure 4-9).

Adaptive governance must integrate local communities in designing responses that address both social and ecological needs (O'Brien & O'Keefe, 2014). Nature-based disaster risk reduction strategies align with international guidance emphasizing equity and environmental justice, supporting the assessment and protection of SES health, even when immediate social benefits are not apparent after large-scale disturbances (O'Brien & O'Keefe, 2014; UNISDR, 2004). Such approaches call for multi-scalar, systemic assessments of risk, resilience, and adaptive capacity grounded in social diversity and inclusivity, forming the basis for adaptive, equity-centered watershed governance.

6.2 Governance, Knowledge Systems, and Justice-Centered Adaptive Governance

6.2.1 Local and Institutional Dimensions of Risk-Informed Governance

Institutions have increasingly recognized the value of participatory approaches that emphasize interdisciplinary, and, often, transdisciplinary, collaboration, as demonstrated by the establishment of a cross-municipality and multi-institutional watershed governance council and the promotion of NbS and EbA to mitigate disaster risks (Pahl-Wostl, 2009; Pahl-Wostl, 2015) (Chapter 3, Table 3-7, 3-9). Such adaptive strategies and governance depend on integrating local communities in designing responses that address both social and ecological needs (O'Brien & O'Keefe, 2014). Effective watershed governance also relies on cultural acceptance of institutions, trust in regulatory processes, and a value-based relationship to the environment. As detailed in Chapter 3 (Table 3-3), the SES WHA Framework distinguishes between LEK and LIK to emphasize culturally grounded, participatory governance approaches. This differentiation highlights how integrating community-based epistemologies can enhance institutional trust and adaptive capacity without abstracting Indigenous knowledge systems. The findings in this section directly address Research Goal 1 by illustrating how governance practices influence resilience within the RGA watershed. The emphasis on culturally grounded risk communication supports an equitable, risk-informed SES WHA Framework.

Building on this institutional perspective, nature-based disaster risk reduction strategies align with international guidance emphasizing equity and environmental justice, supporting the assessment and protection of SES watershed health, even when immediate social benefits are not apparent following large-scale disturbances (O’Brien & O’Keefe, 2014; UNISDR, 2004). Effective implementation of these approaches also requires economic capacity and institutional legitimacy, even if engagement is limited to regulatory compliance rather than active participation (Dietz et al., 2003). This reflects the institutional and governance challenges identified through the SES WHA Framework (Chapter 3, Table 3-9), which highlight resource constraints and coordination gaps as critical barriers. For example, households and institutions must often demonstrate willingness to pay for ecosystem services. As described in Chapter 3 (Table 3-6), valuation of ecosystem services is a factor linking social equity with ecological sustainability. The ability to diversify hazard mitigation strategies through socio-ecological approaches, including willingness to invest in ecosystem services, strengthens both short- and long-term planning and narrows the gap between assessment and implementation. Socio-cultural structures shape resilience over longer time scales, influencing access to resources, community cohesion, and leadership (Adger, 2000). Cultural dynamics (e.g., class systems, migration, belief systems) shape how communities prioritize, interpret, and respond to hazards. Disasters can destabilize or reconfigure these structures, demanding new shared understandings to guide recovery and adaptive governance (O'Brien et al., 2008).

NbS are interventions to protect, sustainably manage and restore natural and modified ecosystems in ways that address societal challenges, such as climate change, food security land degradation and biodiversity loss (United Nations World Water Assessment Programme)/UN-Water, 2018; Roopnarine et al., 2021). Research shows that these solutions contribute to a reduction of vulnerabilities to climate change impacts and can provide up to 37% of the mitigation needed between now and 2030 to meet the 2°C Paris Agreement climate change goal: "actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (IUCN, 2016). NBSs also prioritizes inclusive governance, incorporation of local knowledge systems, and adaptive, risk informed, low-cost approaches (United Nations World Water Assessment Programme)/UN-Water, 2018). For example, NbS solutions promote transitioning from hard, grey infrastructure and engineering, where possible, to natural vegetation for flood and stormwater management. Opting for natural vegetation over impervious surfaces reduces soil erosion and increases infiltration (Ramos-Scharrón, 2010; Ramos-Scharrón & MacDonald, 2007). This can also support an uptake in nutrients in the soil and for surrounding vegetation (e.g., honeycomb "pavement" for parking lots). An overall reduction of impervious surfaces minimizes on-site disturbances in valley farmland through the establishment of a riparian buffer. Rainwater harvesting is a NbS particularly useful in high hazard zones like the Caribbean. In the RGA watershed, this would have been a particularly useful socio-ecological solution when drinking water conveyance infrastructure failed and drinking water was unavailable post Hurricane María. Additionally, the development of green corridors reduces risks of infectious disease and contributes to habitat density and reduction of biodiversity loss.

There is a growing awareness within the literature that adaptive, cooperative, trust-building management in an inclusive atmosphere of social learning is needed as opposed to development of approaches and methods in relative isolation from social systems (Andersson & Ostrom, 2008; Armitage et al., 2009; Bajracharya et al., 2005; Bodin & Crona, 2009; Ison et al., 2007; Leahy & Anderson, 2008). These studies excluding the social system interactions focus on specific components of the natural system such as issues of water quality and availability or biodiversity or land degradation in critically threatened landscapes as relates to food security and energy (Ison et al., 2007; Zimmerer, 2006). While providing valuable examination of the natural system story, such examinations lack critical social system contextualization necessary for implementation. Disaster risk reduction literature and conceptual framing highlight the value of the inclusion of all sources of knowledge across multiple social networks, along with the elevation of users to the position of stakeholders in sustainable, implementable natural resource management (Mercer et al., 2009; Thomalla et al., 2006). The study conducted by Thiele et al. (2001) and others provides a key example of the use of participatory methods to evaluate land use with reference to crop distribution and farming techniques (Brush et al., 1992; Zimmerer & Bassett, 2003).

In addition, incorporating local, traditional, and Indigenous knowledge pieces into watershed management approaches connects multiple informal and formal knowledge holders and aids in the incorporation of bottom up as well as top down, integrated, multi scale approach (Gaillard & Mercer, 2013; Wisner et al., 2012). Participatory social assessments also assist in the empowerment of marginalized populations, thereby creating opportunities for enhanced, transformed social resilience to disasters (Alexander, 2013; Diržytė et al., 2017; Mercer et al., 2009; O'Brien & O'Keefe, 2014). Including multiple institutions from different scales of governance greatly benefits the process of establishing successful CBNRM. The conflict inherent within the polycentric attempts at governance of natural resources throughout the watershed and indeed, the island, may hinder future processes if the value of the social networks inherent within both institutionalized efforts and the local/community population are not bridged (Andersson & Ostrom, 2008). It is not possible to separate one issue from the other given the way these complex, interrelated components of the social system play out in the landscape. For example, focusing on the right to food and water security from a nature-based perspective that also supports conservation and successful management of diverse ecosystems we will find achievable common goals, particularly with consideration for the impact of climate change and associated shifts in disturbance regimes. Central to this process is untangling the inherent complexity of the impact of the ecosystem response to hurricane and landslide disturbances. As evidenced in the RGA watershed assessment, Puerto Rico faces an urgent need as well as a multitude of opportunities to advance sustainable management practices through nature-based solutions and community-based resource management.

A risk-informed approach requires not only technical knowledge but an understanding of stakeholder perceptions and communication norms at all levels, including down to the household scale (Paton, 2008). Since Hurricane María, there has been a noticeable rise in community-led risk communication and environmental management, particularly in the RGA watershed where community-based approaches emerged as critical for addressing infrastructure vulnerabilities and promoting resilience (Chapter 3, Table 3-10). As Velado et al. (2015) observed, risk communication strategies often fail to engage communities effectively. Clear, culturally grounded information is essential to foster proactive risk reduction and empower community-based governance. Cultural identity, vocabulary, and methods and modes of communication shape how people interpret environmental risks. Communities mobilize through trusted venues such as parks, churches, and community centers, a dynamic especially visible in post-María recovery efforts (Kelman et al., 2015). In a highly dissected a watershed such as the RGA, community level norms for exchanging communication and building connection (e.g., community gathering places such as "canchas", parks, churches) as well as means for communication may become significant variables key to assessing vulnerability (Chapter 3, Table 3-10).

From 2018 to 2020, I participated in the watershed management working group (la iniciativa de Cuencas del Oeste) for the RGA and Yaguez watersheds, which included representation from local governments, UPRM (e.g., Dept of Civil & Environmental Engineering, SEA, Sea Grant), NRCS, USGS, FEMA, and community organizations. The group examined a range of challenges and opportunities affecting watershed-scale hazard mitigation planning. Key issues included the need to foster a watershed-based perspective within local hazard mitigation strategies and to enhance institutional support through data, resources, and coordination mechanisms. However, efforts were often hindered by differing municipal priorities and the fact that activities were unfolding at different stages across jurisdictions, complicating efforts to synchronize planning at the watershed level. Participants also identified a lack of awareness among federal agencies, research institutions, and municipalities about available resources and technical expertise, contributing to fragmented efforts and missed opportunities for collaboration. Moreover, many municipalities faced significant constraints due to limited financial and human resources, which limited their capacity to engage meaningfully in watershed-scale initiatives. These challenges were compounded by the fact that critical ecological and physical data for the watershed was often incomplete, outdated, or entirely unavailable, making evidence-based planning difficult. These experiences illustrate both the promise and persistent fragmentation of watershed governance in Puerto Rico.

Furthermore, Stablein et al. (2022) emphasized the value of knowledge co-production as a foundation for community engagement and institutional trust. Local knowledge provides critical insight into community resilience, behavioral norms, and responses to environmental change (Schipper, 2008). The inclusion of LEK and LIK in the SES WHA Framework operationalizes this principle and attempts to decolonize their inclusion by recognizing local and Indigenous knowledge holders as co-producers of data and decision-making rather than as external informants. Table 5-3 (Chapter 5) outlines best practices for team science, emphasizing community engagement and knowledge co-production as essential for building stakeholder trust and integrating diverse practices. The CRISP project illustrated that integrating local knowledge (LIK/LEK) into resilience planning can enhance stakeholder and community buy-in and improve data accuracy, but they also revealed challenges in balancing scientific models with community-driven perspectives (Chapter 5, Sections 5.3.3c and 5.4.5). Local knowledge influences how communities take action on the landscape, perceive environmental degradation, and make decisions related to livelihoods, public health, and economy. This demonstrates the value of integrating community epistemologies into resilience planning. The integration workshop (Figure 5-3) demonstrated how collaborative mapping exercises facilitated integration of local insights with scientific data, highlighting the importance of co-creative approaches to research in post-disaster settings. Table 5-5 details the barriers to conducting team science and thus research that may contribute to sound policy and management, including the difficulty of aligning academic models with community priorities, emphasizing the need for reflexive practices. Despite international guidance promoting such approaches, integration into policy and management remains uneven, highlighting the gap between collaborative ideals and the realities of post-disaster implementation.

6.2.2 Scaling Local Insights Toward Adaptive, Justice-Centered Governance

At broader scales, globalization functions as both a stressor and a constraint on local resilience, depending on the existing vulnerabilities (e.g., extremes of wealth and poverty) of socio-ecological systems. While it may introduce economic opportunities, it also facilitates unregulated resource extraction (Wisner et al., 2004). In doing so, it deepens inequalities, reinforcing cycles of poverty and institutional instability (Levy & Spicer, 2010). These dynamics are intensified where governance capacity is weak or fragmented. Demographic pressures (e.g., population growth, density, and uneven distribution) further strain infrastructure and natural resources (Wisner et al., 2004). Without risk-informed policies, these factors exacerbate exposure to hazards and undermine social learning from past events, limiting the potential for adaptive governance. Social memory, if integrated into governance, can serve as a critical adaptive resource (Caniglia et al., 2014; Dale et a., 2016; Folke et al., 2005). If ignored, it reinforces systemic vulnerability (Walker et al., 2004; Levy & Spicer, 2010).

Resilience in both ecological and social systems is shaped by their capacity to absorb disturbance and reorganize without losing function. Ecosystem resilience is measured by spatial-temporal rates of recovery and system persistence (e.g., the ability to absorb change and disturbance) (Holling, 1974; Millar et al., 2007). Severe disturbances can lead to regime shifts (e.g., transformation from forest to grassland) that fundamentally alter ecosystem services and adaptive potential (Folke et al., 2004; Holling, 1973; Scheffer et al., 2001). These dynamics are clearly visible in the upper RGA watershed, where remote communities experienced up to six months without power or communication (e.g., ~80% of island's electrical network damaged) following Hurricane María due to damaged critical infrastructure. Ham radio networks emerged as a key tool for emergency response, reflecting local adaptive capacity. Yet the persistence of an aging energy grid and uneven access to communication technologies continues to shape social vulnerability and future risk exposure (Montoya-Rincón et al., 2023). Although international guidance such as the SDGs and UNDRR guidance promote equitable, nature-based approaches to disaster risk reduction, their local implementation remains inconsistent (UNDRR, 2015). These translation gaps reveal enduring challenges in aligning global policy with grounded, context-specific governance systems, echoing the justice and equity considerations explored in Chapter 5 which emphasize ethical engagement, inclusivity, and the recognition of local epistemologies in post-disaster research. It also underscores the need for nested governance structures, as reflected in the SES WHA Framework's integrated indicator organization and the inclusion of LEK / LIK (Chapter 3, Table 3-2, Table 3-5, Table 3-9).

Addressing Research Goal 3, this section highlights the intersection of team science and community-driven resilience planning. While the CRISP project highlighted the importance of integrating local knowledge into research activities (Chapter 5, Figure 5-3), it also underscores the complexities of reconciling community-driven insights with formal scientific models, issues further analyzed through the barriers summarized in Table 5-5. This tension reflects a broader challenge within adaptive governance. Namely, balancing local epistemologies with standardized assessment approaches without compromising stakeholder engagement or data precision Cash et al., 2003). From an academic standpoint, addressing these gaps requires not only methodological innovation but also sustained commitment to community involvement, ensuring that scientific practices remain relevant and responsive to local contexts. The SES WHA Framework presented in Chapter 3 (Table 3-9) helps to bridge the gap between academic study and applied practice, providing a model for scaling local knowledge into adaptive, justice-centered governance.

6.3 Future Work

6.3.1 Modeling Sediment Yield for Post-Disaster Watershed Resilience

Building on the watershed health assessment indicators identified in Chapter 3 and the landslide and erosion hotspot analysis presented in Chapter 4, future modeling will refine sediment-yield estimates post-Hurricane María. This work would also build on prior hydrologic modeling in the RGA Watershed, including work by Rojas González (2012) and Ramos-Scharrón et al. (2014), which used SWAT (Soil and Water Assessment Tool) and remote sensing to trace sediment transport from upland sources to the coastal outlet (Arnold et al., 1998). These studies identified land use practices as primary drivers of sediment release. Additional storm prediction models developed by Torres-Molina (2014) and conceptual hydrologic frameworks from Prieto et al. (2018) provide useful reference points for model calibration and comparison.

The SWAT model evaluates the hydrologic and geomorphic impacts of Hurricane María as well as continued impact from extreme storms (e.g., Hurricane Fiona), focusing on flow regimes, sediment loading, and changes in channel morphology. SWAT's ability to delineate sub-basins and Hydrologic Response Units (HRUs) allows for site-specific assessments of land use, soil type, and vegetation dynamics, offering a way to simplify and simulate complex system interactions. Inclusion of post-María hydrologic data, in combination with an ecological landslide assessment, will allow refinement of previously identified “erosion hotspots” and support resilience strategies developed under NRCS’s National Water Quality Initiative. Outputs will be compared with FEMA flood and landslide maps to improve hazard prediction and planning.

These modeling efforts also support predictive scenario development aligned with IPCC projections, aiding climate adaptation across the food–energy–water nexus in Puerto Rico (Bowden et al., 2020; Harmsen et al., 2009; Nurse et al., 2014; PRCCC, 2022). To enhance long-term adaptation planning, integrating climate models, such as the Coupled Model Intercomparison Project (CMIP6) and dynamically downscaled regional projections can provide critical insights into future hydrologic patterns under different emission scenarios (Eyring et al., 2016; Taylor et al., 2020). These integrated approaches would not only improve the precision of SWAT outputs, but also enable scenario-planning for changes in rainfall intensity, storm frequency, and subsequent geomorphic responses. For instance, projects suggest that by mid-century, Puerto Rico may experience an annual temperature increase between 1˚C and 1.3˚C. coupled with up to 25% annual rainfall reduction in certain areas, increased drought, and increased frequency and magnitude of extreme weather events (e.g., hurricanes, tropical storms) (IPCC, 2022a, 2022b; North Carolina Institute for Climate Studies, 2022; Southeast Climate Adaptation Science Center, 2025; Taylor et al., 2020; USGS, 2023; US Global Change Research Program, 2018). Notably, initiatives like the Caribbean Climate Hub and the Caribbean Climate Adaptation Network (CCAN) are actively working to bolster climate resilience in the region by providing region-specific data and fostering collaborative research efforts.

6.3.2 Evaluating Ecosystem Response: Landslide Field Assessments

Future work could focus on understanding the ecosystem's response to landslide disturbance and its implications for resilience and geomorphic change throughout the RGA. Building on previous findings in the Luquillo Experimental Forest, this research will examine how abiotic factors (e.g., slope, soil moisture, landslide size and type, proximity to roads or channels) interact with biotic responses (e.g., vegetation cover, species composition, canopy recovery) (Guariguata, 1990; Shiels et al., 2014; van Beusekom et al., 2020). Specific attention will be given to the role of topography, land use history, and micro-site conditions in shaping post-disturbance successional dynamics.

Climate-driven shifts in the Caribbean (e.g., warming seas, changes in rainfall intensity, and inland moisture disruption) are altering the frequency and spatial distribution of landslide-inducing storms (Comarazamy & González, 2011; Van Beusekom et al., 2018). These changes intensify the disturbance regimes ecosystems must absorb and recover from. Hurricanes trigger over half of all landslides in Puerto Rico, and increased storm intensity, compounded by land use impacts, may push ecosystems beyond recovery thresholds (Larsen & Simon, 1993; Larsen & Torres-Sánchez, 1998; Myster & Walker, 1997). Field assessments will analyze soil structure, texture, and drainage capacity as key controls on slope stability and vegetation regrowth. Differences in soil catenae influence susceptibility to slope failure and also dictate water availability and seedbed conditions post-landslide (Scatena & Lugo, 1995; Guariguata, 1990). Topographic position (ridge vs valley) and wind exposure during storms further shape spatial heterogeneity in regeneration patterns.

Building on previous long-term studies in Luquillo (Myster et al., 1997; Zimmerman et al., 1994), the field-based work presented in this section as future work would explore whether similar successional trajectories exist in understudied western watersheds, like in the RGA Watershed. By establishing new post-landslide plots, this work will test species convergence/divergence patterns and assess the influence of disturbance history on vegetation dynamics. Special focus will be given to litterfall, canopy gap formation, and the role of pioneer versus non-pioneer species in driving early recovery. Many advocate that it is challenging, if not impossible, to fully separate anthropogenic influences, either historic (i.e. logging, agriculture) or current (i.e. roads, increases in agriculture production) on plant species distribution, age, and density or landslide susceptibility (Boose et al., 2004; Denslow, 1995; Foster et al., 1999; Larsen & Torres-Sánchez, 1998; Myster & Fernandez, 1995; Myster et al., 1997; Scatena & Larsen, 1991; Zimmerman et al., 1994). Ultimately, these analyses will inform vulnerability assessments and management practices by identifying where landslides generate persistent ecosystem fragmentation or contribute to sediment transport. The findings will also support integration of ecological data into watershed-scale resilience strategies and help evaluate how vegetation recovery may shift under future climate scenarios.

6.3.3 Assessing Risk Perception

Future work will explore how risk perception intersects with modeled and mapped ecosystem responses to inform stakeholder-driven watershed planning. Stakeholders previously identified include UPR-Mayagüez, NRCS, IITF, PR Department of Natural Resources, and local community members and farmers across the RGA. A relational geodatabase of interview responses will support spatial queries that contextualize stakeholder perceptions, conservation practices, and landscape change. By mapping perception data alongside biophysical model outputs, this approach enables geospatial analysis of how local knowledge and institutional classifications align or diverge (Cutter & Finch, 2008; Slovic, 2000). It also offers a tool for use beyond this study, as agencies seek community-based and cross-sector strategies for land and water management.

Leveraging these results in focus groups aids in the identification of spatially explicit and relevant perceptions and local knowledge for targeted design of resource management and slope stabilization conservation efforts. In addition to assisting in an assessment of watershed health, this approach reveals vital information about social norms, class structures, and gaps in the local knowledge base which may or may not be in consonance with governmental or scientific terminology, classification systems, or priorities (Paton, 2008). Integrating the results of this work with SWAT model outputs enables a multi-dimensional assessment of watershed health. It reveals spatial and temporal mismatches between ecosystem response and social understanding of change. The work addresses knowledge gaps about landslide-driven sediment release and supports targeted conservation strategies through statistically significant links between physical predictors and biotic responses. These findings are especially useful to agencies like NRCS and Aqueducto as they evaluate the effectiveness of slope stabilization and land management efforts.

Importantly, this work underscores the role of perception in advancing socially responsive disaster risk reduction and ecosystem-based management (UNDRR, 2015; Wisner et al., 2004). The novel incorporation of perception data benefits risk communication and evaluations of natural and social system resiliency to both change and hazards. It equips resource managers with tools for predictive planning and fosters community ownership of adaptive responses to climate and hazard-driven landscape change. Together, the discussions in this chapter emphasize the deeply interconnected roles of governance, environmental thresholds, global drivers, and community engagement in shaping resilience within socio-ecological systems. As this research evolves, continued adherence to team science principles (e.g., sustained stakeholder engagement, transparent data sharing, and co-designed research processes) will be essential for ensuring that modeling outputs and hazard mitigation strategies reflect both scientific rigor and community relevance (Lang et a., 2012; Stokels et al., 2008). In post-disaster contexts, where urgency, trauma, and unequal access to resources complicate collaboration, embedding justice and equity within team science approaches is vital (Schlosberg, 2013). This includes recognizing power asymmetries, honoring local knowledge systems, and ensuring that research processes are inclusive, culturally responsive, and grounded in community-defined priorities. The proposed future work builds on these foundations by advancing integrative, applied research that links ecological processes, landscape change, and local knowledge. In doing so, it reinforces the value of transdisciplinary approaches and participatory planning for adaptive watershed management in a changing climate.

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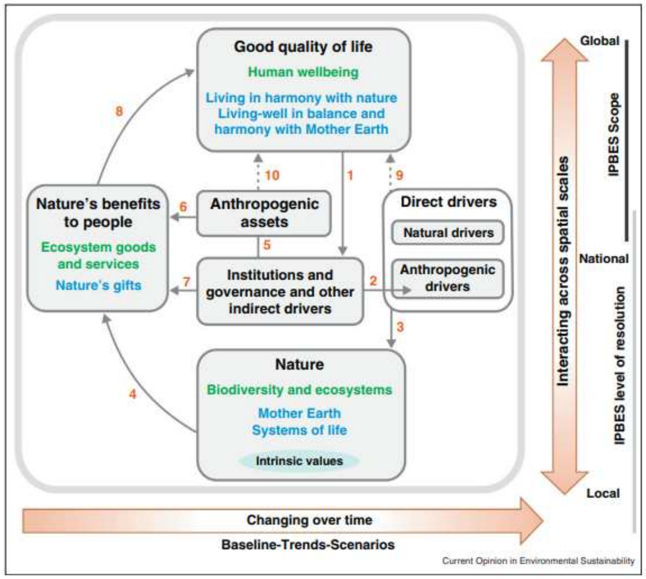
APPENDIX A

A.1 Conceptual diagrams associated with international frameworks referenced in CHAPTER 3.

International Framework	Relevant Conceptual Diagrams / Descriptions*
Global Commission on Adaptation Global Commission on Adaptation (GCA). (2019a). *Adapt now: A global call for leadership on climate resilience*. World Resources Institute. https://gca.org/wp-content/uploads/2019/09/GlobalCommission_Report_FINAL.pdf. GCA. (2019b). *Water: Infrastructure for climate adaptation – Unlocking the potential of nature*. World Resources Institute. https://gca.org/reports/.	 * In the following paragraphs we use the pronoun "we" to refer to individual or groups of Commissioners, Action Track partners, and Managing Partners as the ones carrying forward commitments to action—not all members of the Commission or the Commission as whole. **FIGURE 3.1** Relationships between the Natural Environment and Climate Change Adaptation by Sector 

Sustainable Development Goals United Nations. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development* (A/RES/70/1). United Nations Department of Economic and Social Affairs. https://sdgs.un.org/goals.	 THE 17 GOALS 169 Targets 4033 Events 1357 Publications 8036 Actions 1 NO POVERTY 2 ZERO HUNGER 3 GOOD HEALTH AND WELL-BEING 4 QUALITY EDUCATION 5 GENDER EQUALITY 6 CLEAN WATER AND SANITATION 7 AFFORDABLE AND CLEAN ENERGY 8 DECENT WORK AND ECONOMIC GROWTH 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE 10 REDUCED INEQUALITIES 11 SUSTAINABLE CITIES AND COMMUNITIES 12 RESPONSIBLE CONSUMPTION AND PRODUCTION 13 CLIMATE ACTION 14 LIFE BELOW WATER 15 LIFE ON LAND 16 PEACE, JUSTICE AND STRONG INSTITUTIONS 17 PARTNERSHIPS FOR THE GOALS SUSTAINABLE DEVELOPMENT GOALS See all
Sendai Framework United Nations Office for Disaster Risk Reduction. (2015). *Sendai Framework for Disaster Risk Reduction 2015–2030*. United Nations. https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030.	 **Sendai Framework at a Glance** The Sendai Framework outlines seven global targets to be achieved between 2015 and 2030. SUBSTANTIALLY REDUCE A. Global disaster mortality B. Number of affected people C. Economic loss in relation to GDP D. Damage to critical infrastructure and services disruption E. Number of countries with national and local DRR strategies by 2020 F. International cooperation to developing countries G. Availability and access to early warning systems and DRR information SUBSTANTIALLY INCREASE SEVEN TARGETS TO ACHIEVE BY 2030 SENDAI FRAMEWORK FOR DISASTER RISK REDUCTION 2015-2030

Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. (2019). *Summary for policymakers of the global assessment report on biodiversity and ecosystem services* (S. Díaz, J. Settele, E.S. Brondízio, & H.T. Ngo, Eds.). IPBES secretariat. https://doi.org/10.5281/zenodo.3553579.	**Figure 1**  Current Opinion in Environmental Sustainability
Brisbane Declaration* Arthington, A.H., Bhaduri, A., Bunn, S.E., Jackson, S.E., Tharme, R.E., Tickner, D., Young, B., Acreman, M., Baker, N., Capon, S., Horne, A.C., Kendy, E., McClain, M.E., Poff, N.L., Richter, B.D., & Ward, S. (2018). The Brisbane Declaration and Global Action Agenda on environmental flows. *Frontiers in Environmental Science, 6*, Article 45. https://doi.org/10.3389/fenvs.2018.00045.	Emphasizes the central importance of maintaining environmental flows to support ecosystem health, biodiversity, and human well-being. Calls for inclusive, adaptive, and participatory governance of river basins and freshwater ecosystems, recognizing the interconnectedness between water management, socio-economic resilience, and ecological integrity. Key components include protecting flow regimes to sustain ecosystems, balancing competing water uses, and prioritizing nature-based solutions.
Paris Agreement* United Nations Framework Convention on Climate Change. (2015). *Paris Agreement*. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.	Legally binding international treaty on climate change aimed at limiting global warming to well below 2°C above pre-industrial levels. It promotes adaptive capacity, climate resilience, and low greenhouse gas emissions development, linking climate action with sustainable development and poverty eradication. Emphasizes nationally determined contributions (NDCs), encourages ecosystem-based adaptation, and supports climate-resilient infrastructure and land use planning as key strategies for local and regional governance.

**Note: Direct visual representations of the guidance presented as part of the Brisbane Declaration and the Paris Agreement are not available. Descriptive summaries are provided instead.*

APPENDIX B

B.1 Overview table relating data source to metadata information and the associated phase of analysis, referenced in CHAPTER 4.

Data	Type	Scale/Resolution	Source	Analysis Phase
Landslide point data	Point/Polygon Feature Datasets	1:600; 1:1000; 1m resolution	Hughes; Bessette-Kirton et al., 2017, 2019; Original data USGS 1-m LIDAR imagery	All phases
Field Site Data	Point Datasets	Ground	Lead author site data collection	Phase 1
DEM	Tiled GEOTIFF Raster	10m Resolution	USGS; Bare Earth Lidar	Phase 1
Municipality / Barrio Boundaries & Built Infrastructure	Polygon Feature Dataset	Unknown	Pr.gov (la División del Sistema de Información Geográfica del Departamento de la Vivienda de Puerto Rico)	All Phases
Barrio Boundary	Polygon Feature Dataset	Census Tracts	Pr.gov (Puerto Rico Planning Board)	All Phases
Municipality Boundaries	Polygon Feature Dataset	15 m	TigerLine Shapefile (2017); US Census Bureau	All phases
Soils	Polygon Tabular Dataset	Scales range from 1:12,000 to 1:63,360	NRCS National Cooperative Soil Survey; Derived from SSURGO database	Phase III
Hydrography	Line/Polygon Feature Datasets	1:24,000	NOAA National Hydrography Dataset	Phase III
Hydrography	Line/Polygon Feature Datasets	Varies	PR DNR, Acueducto (AAA-Provider of water and sewage services)	Phase III

Roads	Line Feature Dataset	Accuracy typically 5-25 m; Can vary	ESRI Tele Atlas North America	Phase III
Land Use/Land Cover	Raster Dataset from Landsat TM satellite imagery	15 m	USDA Forest Service, International Institute of Tropical Forestry	Phase IV
Social Vulnerability Index	Polygon Feature Dataset	Census Tracts	CDC ATSDR	Social Assessment

**Note: A clip or mask function was applied to datasets to restrict data to the watershed boundary for analysis. The watershed boundary layer was derived from hydrography data.*

APPENDIX C

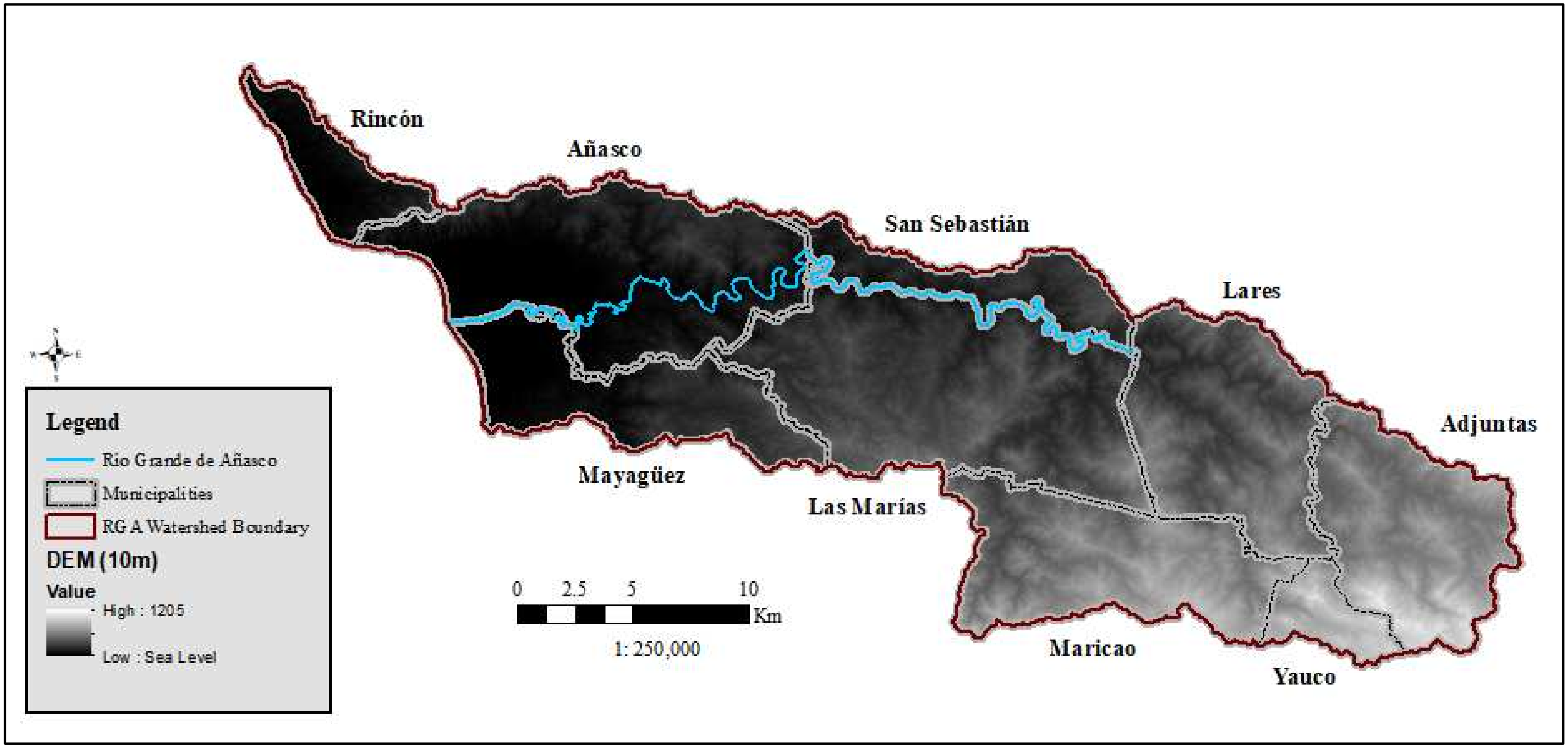
C.1 Land use / cover data for the RGA Watershed and associated class names used for final reclassification, referenced in CHAPTER 4.

NOAA Class name	**MS-GAP Reclass**	
	Primary	***Secondary***
background		
bare land	bare	
cultivated crops	agriculture	
developed, open space	urban grassy/pasture	
estuarine aquatic bed	estuarine water	
estuarine emergent wetland	estuarine emergent	
estuarine forested wetland	estuarine woody	
estuarine scrub/shrub wetland	estuarine woody	
grassland	grassy/pasture/range	low herbaceous veg
impervious surface	--	
open water	--	
palustrine aquatic bed	wetland	
palustrine emergent wetland	palustrine emergent	
palustrine forested wetland	wetland	
palustrine scrub/shrub wetland	wetland	
pasture/hay	grassy/pasture/range	urban grassy/pasture
scrub/shrub	freshwater shrub/scrub	urban low herbaceous
unclassified	--	
unconsolidated shore	estuarine water	
upland forest	mixed forest	med/high density hardwood

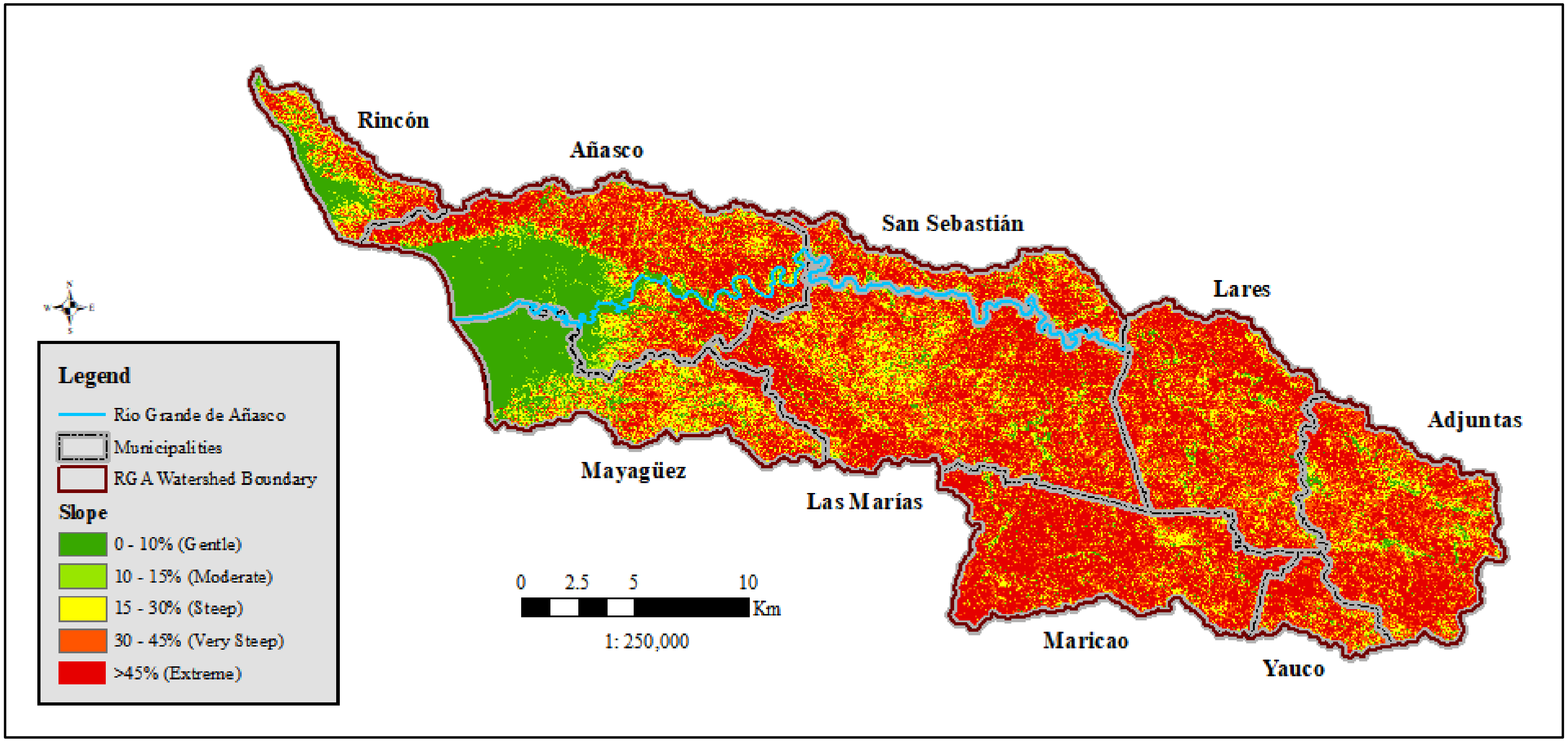
APPENDIX D

D.1 Supplementary maps providing additional background information about the study site, the RGA Watershed.

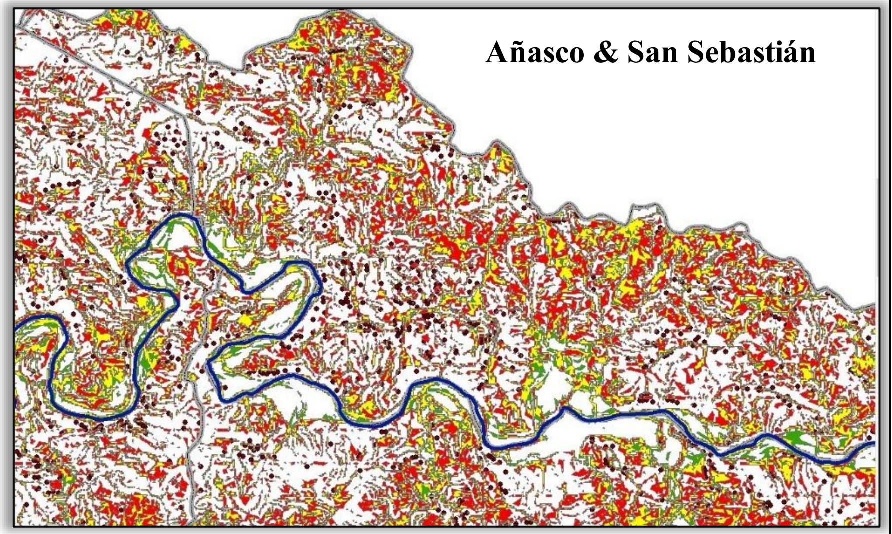
D.1.1 DEM map of the RGA Watershed.

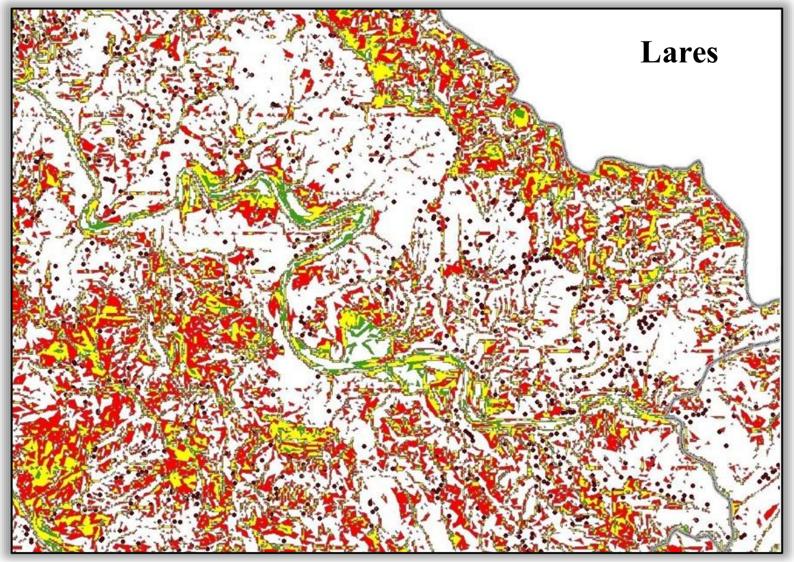


D.1.2 Slope map of the RGA Watershed.

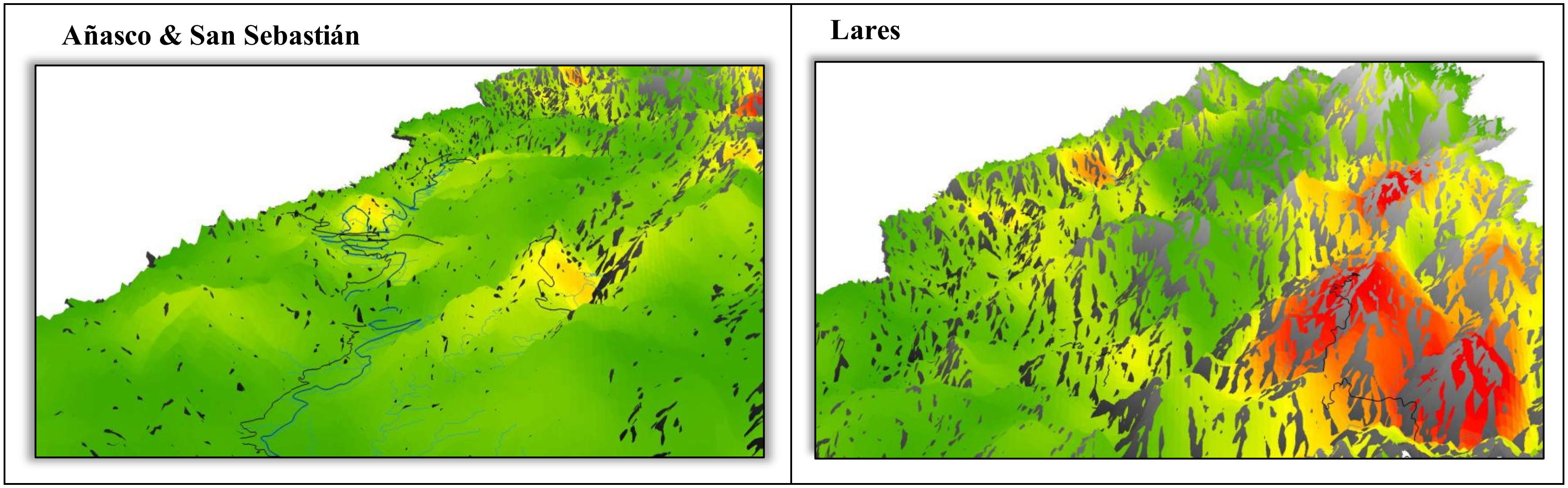


D1.3 Targeted visualizations of slope distribution in relation to mapped landslide occurrences were generated by overlaying landslide point data onto the Phase 1 slope raster map and extracting zoomed-in views of selected areas within the municipalities of Añasco, San Sebastián, and Lares.





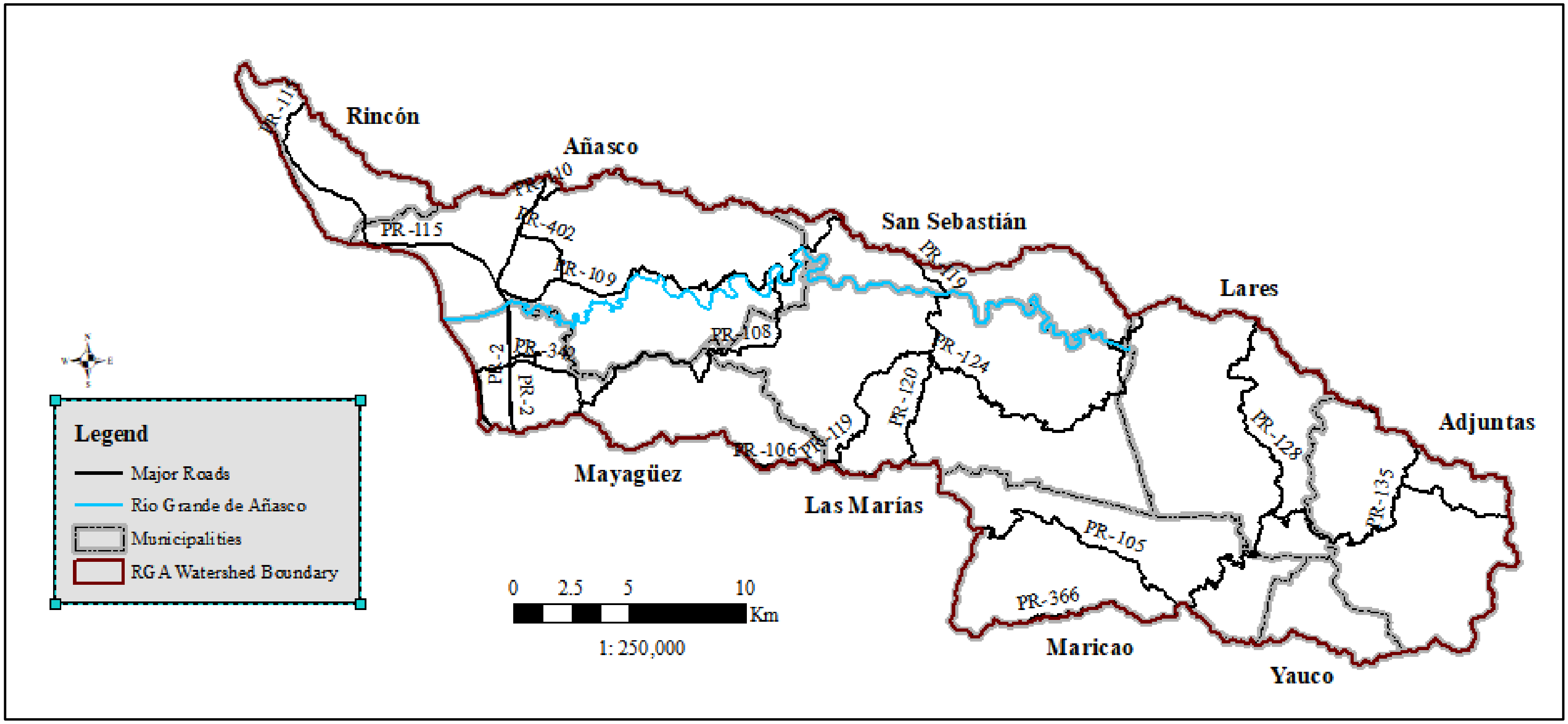
D1.4 Screenshots from the 3D terrain fly-through highlighting landslide density patterns from a dynamic perspective across key regions in Añasco, San Sebastián, and Lares. The visualizations were generated by integrating landslide point data with the Phase 1 slope raster in a GIS environment, enabling enhanced spatial interpretation of landslide clustering in steep terrain.



Añasco & San Sebastián

Lares

D.1.3 Map of primary roads in the RGA Watershed.



APPENDIX E

E.1 Distribution of CRISP project team members and associated institutions and disciplines, referenced in CHAPTER 4.

Team	Team Member Affiliation	Research / Disciplinary Focus
Geophysical Modeling	CCNY; UPRM; BNL	Climate and atmospheric data analysis and modeling; Watershed modeling
Water Infrastructure	UPRM; CCNY; Autoridad de Acueductos y Alcantarillados (AAA) de Puerto Rico	Water infrastructure; Data analysis & modeling
Power Infrastructure	ASU; CCNY; UPRM	Energy infrastructure; Data analysis & modeling
Social Informatics / Rebuilding	NYU; UPRM; BU; ASU	Social data gathering & analysis; Stakeholder engagement
Resiliency Analysis	ASU; NYU; SNL	Network modeling for integrated and interconnected infrastructure; model development, validation, and scenario analysis.

APPENDIX F

F.1 Record of CRISP project meetings with locations and scope of meeting, referenced in CHAPTER 4.

Date(s) of Meetings	Meeting Type	Scope / Agenda	Location
Jan. 14 – 18, 2019	On Site Kickoff	All-Hands; Review project scope, strategy, and stakeholder/community engagement	Rincon, Puerto Rico
May 7, 2019	Status Check	All-Hands; Team members reported on progress of work	Remote / Virtual
June 20-21, 2019	Integration Workshop	Team members /Researchers only; No PIs in attendance; Various activities aimed at identifying opportunities to transform team tasks from interdisciplinary to transdisciplinary	In Person; CUNY, NY
Sept. 2019	Status Check	All-Hands; Team members reported on progress of work	Remote/Virtual
Oct. 24 - 25, 2019	Mini Conference Sponsored by Project, “Enhancing the Resiliency of Critical Infrastructure in Island Communities: An Integrated Approach”	All-Hands; Researchers and PIs gave oral presentations and/or presented posters	In Person; NY

APPENDIX G

G.1 Integration Workshop guiding document provided to participants, June 21, 2019, referenced in CHAPTER 5.

EVOLVING BEST PRACTICES FOR TEAM SCIENCE IN POST-DISASTER RESEARCH SETTINGS

Facilitators: Alicia Tyson (UPRM), Katie Bryson (CUNY)
Duration: TBD (Estimate of 1hr 15 min)

Data Integration Session

Introduction: **(10 minutes)**

In order to truly identify fundamental connections between all the subgroups and the development of the network model and as discussed previously in our Feb meeting and several subsequent research team meetings, we should continually touch point with the research questions and purpose of the project as outlined in the proposal.

Secondarily, we suggest that the identification of stakeholders is really the role of the PIs and that fundamentally we have been tasked with figuring out how to integrate the workflows, the different analysis and related work products, and how we might conceptually and methodologically integrate toward the common goal. Essential to this process of integration we propose is identifying and coordinating a unified understanding of how we are each accomplishing our subgroup priorities.

Stakeholder engagement is important, but we would suggest that that is a primary function of the PIs and in fact, we should perhaps be asking ourselves how we are incorporating the prime "stakeholder" - communities. If you look at recent documents from NSF and from the United Nations, it is now greatly encouraged if not required that research seek to develop bottom-up solutions and include communities as stakeholders. This is not just a priority for a social study or assessment. We can explore this as a secondary element to the activities of this session.

Furthermore, as we have seen, there are times when different terms have varying levels of significance across disciplines. "Stakeholders", for example, can mean different things and much like "resilience", we suggest we should first focus on the work and how we actually accomplish the integration and secondarily how we are addressing the needs of stakeholders (note: there is a difference between a stakeholder, a collaborator, and a consulting expert and especially with a large grant, there is a difference at a financial and even political level) at ALL levels.

Activity 1: Rooting the Branches of our Research with NSF (30 minutes)
Activity Objectives:

1. Show how subgroups' research questions connect to main research questions.
2. Build mind maps that help visualize intra-group connections.

Facilitation Notes:

- Main research questions/objectives will be projected overhead for reference.
- Have different break out groups individually brainstorm *their research sub-questions that address some or all of the primary research questions* and visually map how they connect to the root, the project's main research questions. This is done thinking about primary conceptual/theoretical framings and methodologies. Data types and formats will be addressed in Activity 2.
- Project the main research questions on the board with a map of each sub-group underneath, in a format that allows space to draw in all the connecting branches from different subgroups to the main research questions in a meta-map.
    - Network model will be displayed as the first level in the hierarchy of workgroups.

Subgroups: Energy Domain, Geophysical Domain (Climate, Hydrology), Social Domain (Sense Maker, Capitals), Others?

Product(s):

- Integration map of all subgroup research questions and methodologies and their relationship to the larger research questions presented in the approved NSF proposal.

Activity 2: Developing the Diagramming of Data Sinks, Sources, and Flows (20 minutes)
Activity Objectives:

1. Show how conceptual framings connect to methodology connect to results by mapping data inputs/outputs.
2. Illustrate role of spatial scale in that process.
3. Show how data generated or needed relates to the capacity to respond to research questions.

This activity builds on the research question integration activity by tying these connections to actual data (inputs, outputs), looking at the types of data we are working with and thinking about the format of that data. This activity will be springboarded off of collaboration from February 6th meeting where those present brainstormed using big paper pages to record data needs, outputs, etc.

While activity 1 highlights connections between subgroup questions and larger research questions, this activity focuses on connections between subgroup and subgroup directly through analysis of data inputs and outputs.

Facilitation Notes:

- Have each subgroup create a list of their data inputs and their data outputs from their research on big sheets of paper. Subgroups will need to work together to record all of their data inputs and outputs for this activity.
- After gathering lists of data inputs and data outputs from each subgroup and posting them to board, have a competition between two large groups to see which can find the most connections. Larger groups come up to **circle and connect all inputs and outputs that are the same** and **star all inputs and inputs or outputs and outputs that are the same**.
- Give prizes to the winning group.
- Discuss and visualize areas of agreement and areas where we need to resolve differing perceptions.
- After looking over the results created, participants tie data outputs back to research questions that were created in Activity 1.

Projected Product(s):

- Integration diagrams at the data level.
- An organizational chart showing how everyone is connected.
- Questions to PIs may also be a useful product of this activity.

Data Inventory Discussion

Goal of Discussion: Get everyone up to speed about what is meant by data inventory, metadata, and source tracking. Some might think this only applies to geophysical data, but, in reality, this can apply across all disciplines.

Goal of Data Inventory: Efficient tracking of data acquired, manipulated/analyzed, and produced to increase data sharing and unified, integrated efforts across all workgroups. Reduce duplication of efforts and ensure we are all working from the latest, most appropriate data sources and making the most of the diversity of connections we all have established, particularly from within Puerto Rico.

Facilitation Notes:

- [NameofParticipant] and [NameofParticipant] have done a lot with regards to data storage and so a lot of geophysical data has a storage option already. It would be useful to discuss this and see if they could help teach the group how we could use a shared cloud-based storage system.

- Future group decision on data storage method with basic training could be useful after this discussion.

Activity 3: Stakeholdership Discussion (15 minutes)

Discussion Goals:

1. Tease out distinctions between collaborative partners and stakeholders.
2. Define stakeholders and whose message we want to be heard/ agreed that we would have heard with NSF.

Facilitation Notes:

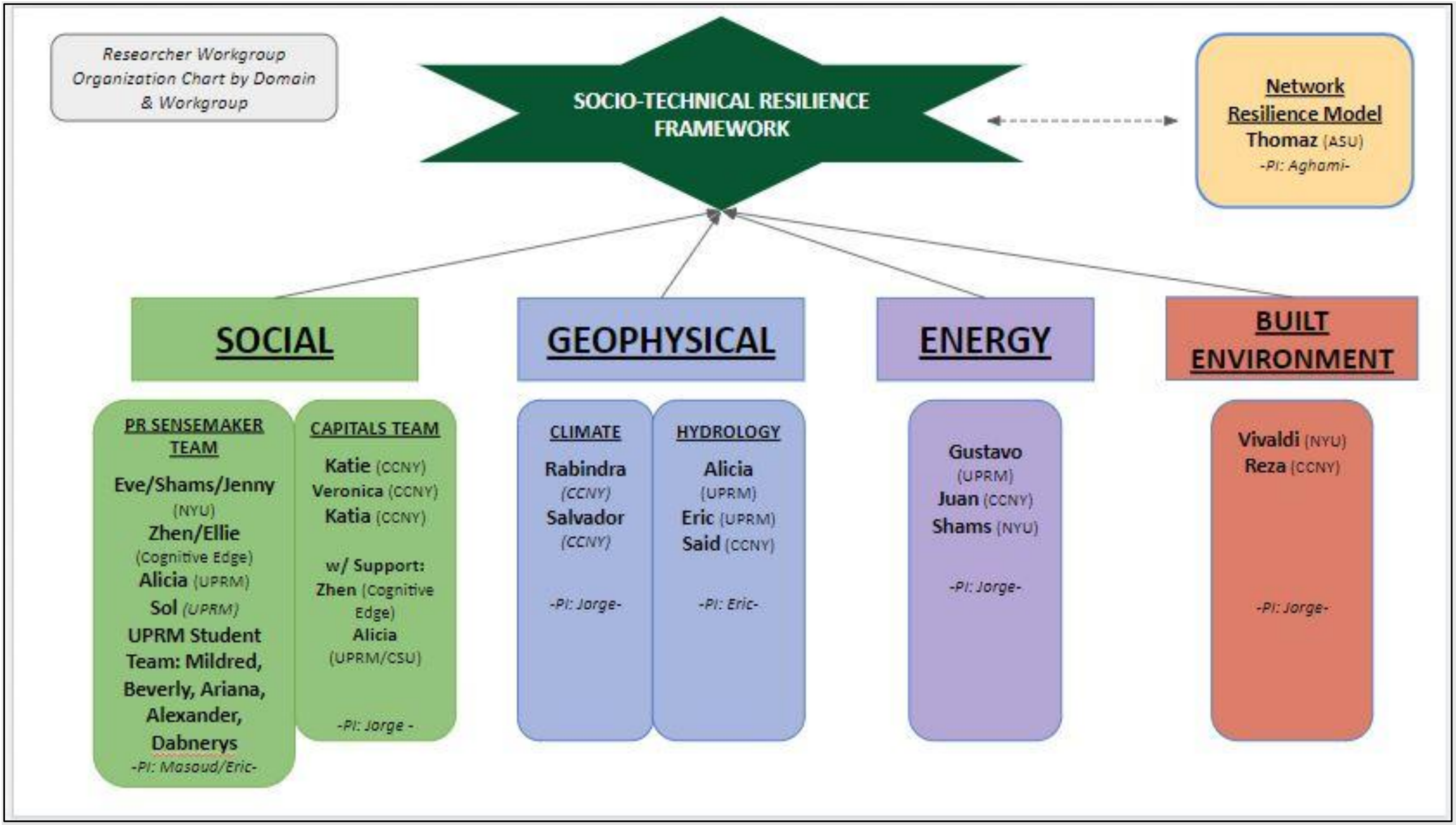
- Open discussion up by asking about who are considered our stakeholders. Ask for list of stakeholders from each person that have been part of their sub group's portion that can be recorded later in a shared space.
- Suggestion that we maintain a Google Sheet with a bank of stakeholders, collaborative partners, and subject matter experts we've consulted to help with maintaining a more transparent flow of information.

Stakeholder Bank Goals:

- Make a list of stakeholders vs. collaborative partners vs. key subject matter experts.
- Sort stakeholders by labeling them as community, municipal, or private.

APPENDIX H

H.1 PowerPoint slides collaboratively reviewed and completed during the Integration Workshop, referenced CHAPTER 5.



Researcher Workgroup Organization Chart by Domain & Workgroup

SOCIO-TECHNICAL RESILIENCE FRAMEWORK

Network Resilience Model
Thomaz (ASU)
-PI: Aghami-

SOCIAL

PR SENSEMAKER TEAM
Eve/Shams/Jenny (NYU)
Zhen/Ellie (Cognitive Edge)
Alicia (UPRM)
Sol *(UPRM)*
UPRM Student Team: Mildred, Beverly, Ariana, Alexander, Dabnerys
-PI: Masoud/Eric-

CAPITALS TEAM
Katie (CCNY)
Veronica (CCNY)
Katia (CCNY)
w/ Support:
Zhen (Cognitive Edge)
Alicia (UPRM/CSU)
-PI: Jorge -

GEOPHYSICAL

CLIMATE
Rabindra *(CCNY)*
Salvador *(CCNY)*
-PI: Jorge-

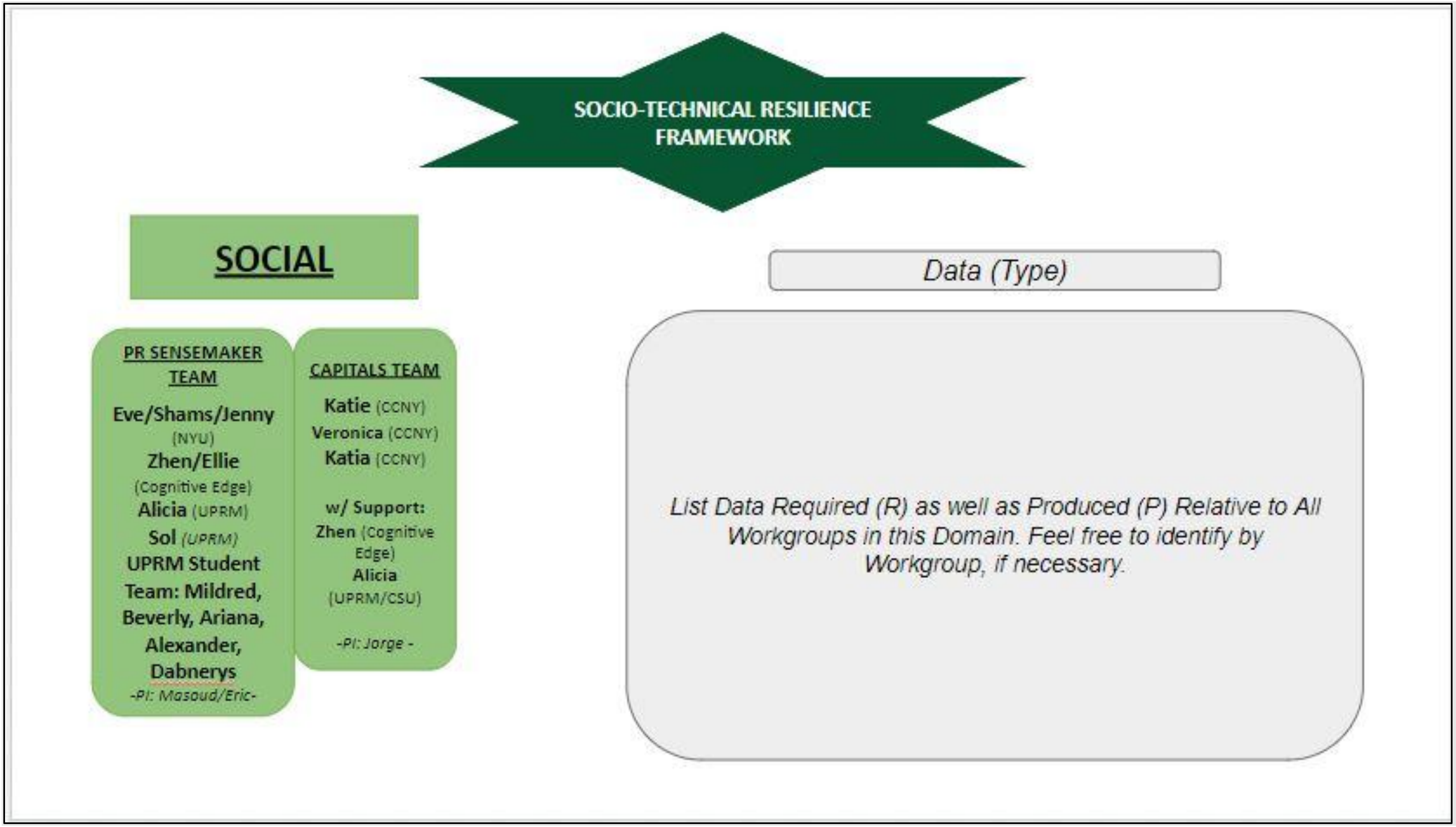
HYDROLOGY
Alicia (UPRM)
Eric (UPRM)
Said (CCNY)
-PI: Eric-

ENERGY

Gustavo (UPRM)
Juan (CCNY)
Shams (NYU)
-PI: Jorge-

BUILT ENVIRONMENT

Vivaldi (NYU)
Reza (CCNY)
-PI: Jorge-



SOCIO-TECHNICAL RESILIENCE FRAMEWORK

SOCIAL

PR SENSEMAKER TEAM

Eve/Shams/Jenny (NYU)
Zhen/Ellie (Cognitive Edge)
Alicia (UPRM)
Sol *(UPRM)*
UPRM Student Team: Mildred, Beverly, Ariana, Alexander, Dabnerys
-PI: Masoud/Eric-

CAPITALS TEAM

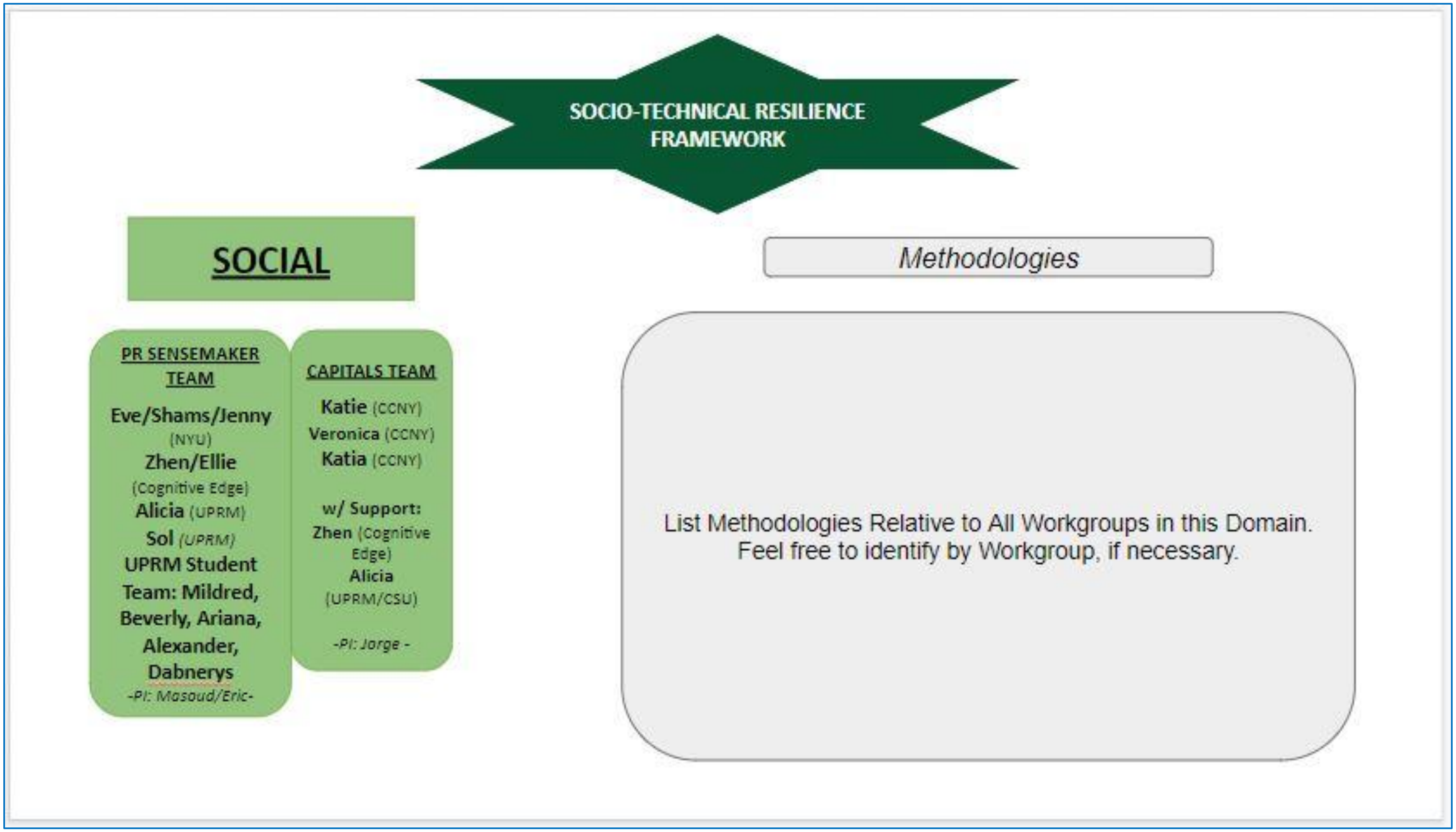
Katie (CCNY)
Veronica (CCNY)
Katia (CCNY)

w/ Support:
Zhen (Cognitive Edge)
Alicia (UPRM/CSU)

-PI: Jorge -

Data (Type)

List Data Required (R) as well as Produced (P) Relative to All Workgroups in this Domain. Feel free to identify by Workgroup, if necessary.



SOCIO-TECHNICAL RESILIENCE FRAMEWORK

SOCIAL

PR SENSEMAKER TEAM

Eve/Shams/Jenny (NYU)
Zhen/Ellie (Cognitive Edge)
Alicia (UPRM)
Sol *(UPRM)*
UPRM Student Team: Mildred, Beverly, Ariana, Alexander, Dabnerys
-PI: Masoud/Eric-

CAPITALS TEAM

Katie (CCNY)
Veronica (CCNY)
Katia (CCNY)

w/ Support:
Zhen (Cognitive Edge)
Alicia (UPRM/CSU)

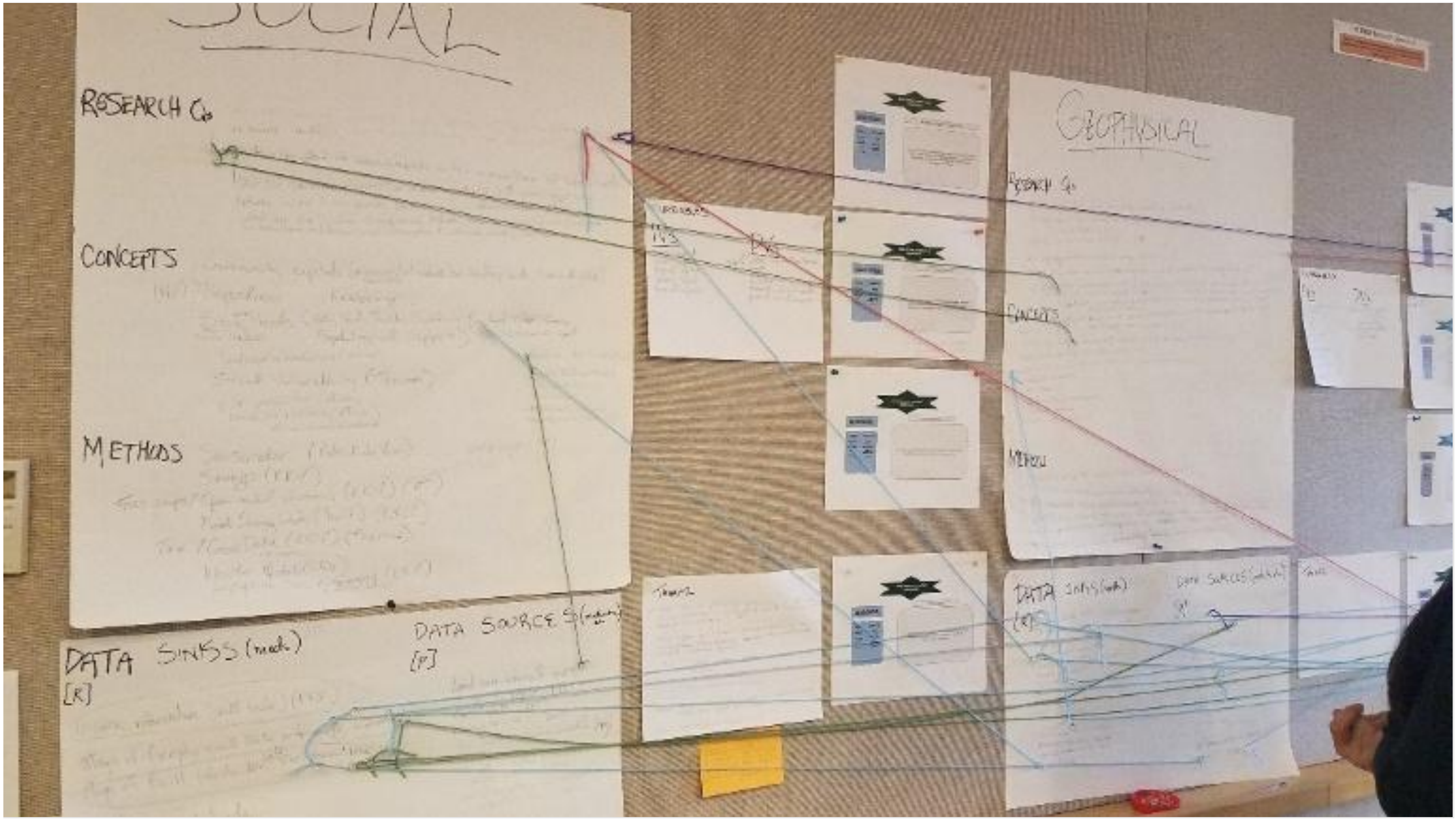
-PI: Jorge -

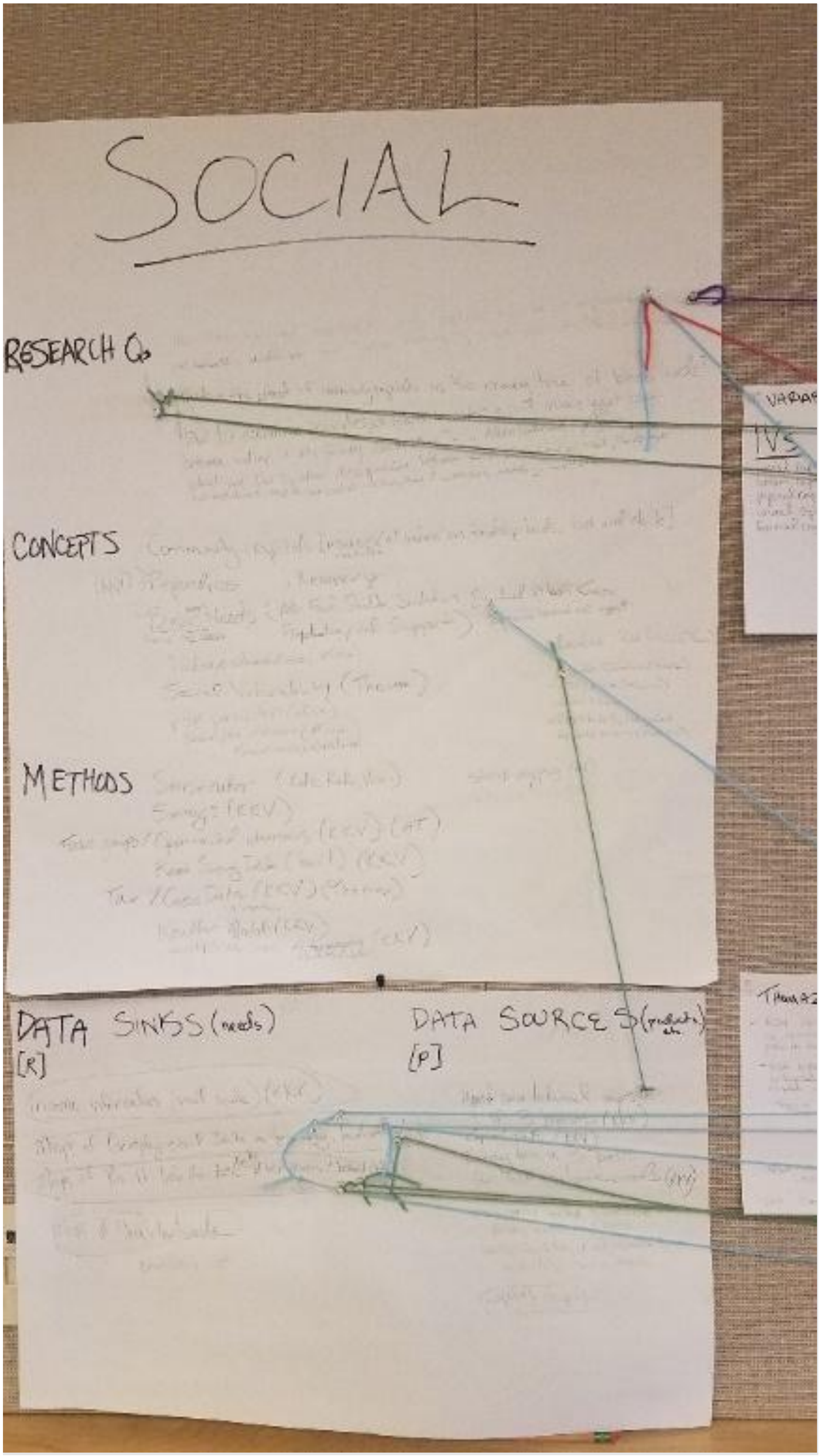
Methodologies

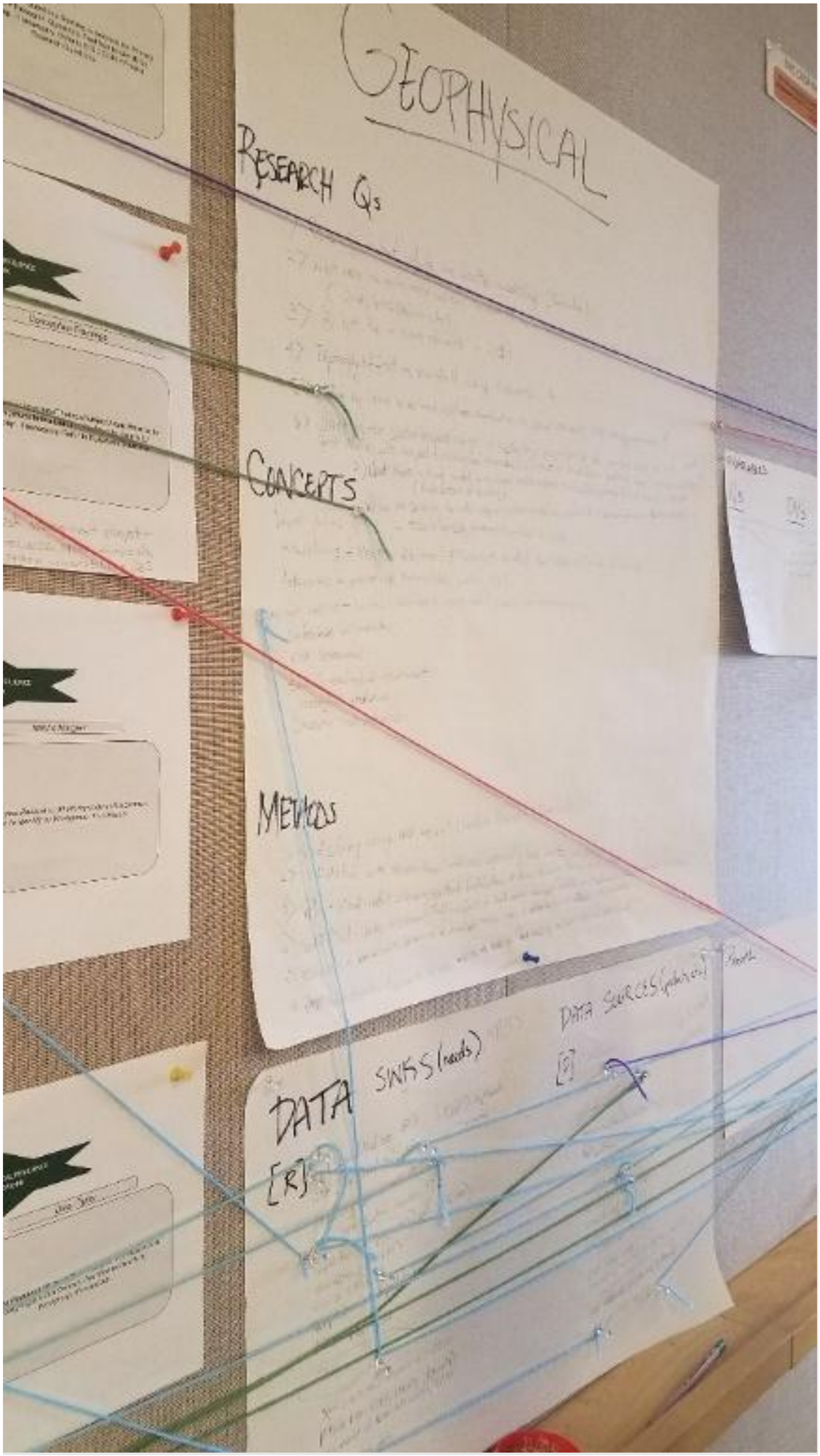
List Methodologies Relative to All Workgroups in this Domain.
Feel free to identify by Workgroup, if necessary.

APPENDIX I

I.1 Supplementary case study photos depicting the results of the Integration Workshop activities, referenced in CHAPTER 5.




SOCIAL
RESEARCH Q.
CONCEPTS
METHODS
DATA SINKS (needs)
[R]
DATA SOURCES (products)
[P]


GEOPHYSICAL
RESEARCH Qs
CONCEPTS
METHODS
DATA
SINKS (needs)
DATA SOURCES
[R]
[?]


SOCIAL
GEOGRAPHICAL
ENERGY

GLOSSARY

1. **Adaptive capacity:** Refers to the ability of a system (whether defined as ecological, social, institutional, or coupled socio-ecological) to anticipate, absorb, respond to, and recover from disturbances while maintaining core functions and identity (Adger, 2006; Pahl-Wostl, 2007). It encompasses not only short-term coping strategies but also longer-term capacities for learning, innovation, and transformation in the face of uncertainty and change. Within socio-ecological systems (SES), adaptive capacity depends on feedback mechanisms, diversity (biological and institutional), social learning, trust, leadership, and the flexibility of governance structures (Folke et al., 2002; Walker et al., 2004).

   In disaster and climate contexts, it determines how well individuals, communities, and institutions can adjust to extreme events (e.g., hurricanes, landslides, droughts) and adapt to longer-term stressors such as climate change or economic shifts. Furthermore, adaptive capacity is not evenly distributed. Environmental justice (EJ) and vulnerability literature show that structural inequities (e.g., poverty, marginalization, and lack of access to resources or decision-making) limit the adaptive capacity of many communities (Cutter et al., 2003; Sultana, 2022). This means that increasing adaptive capacity is not only a technical challenge, but a political and ethical one, as it requires addressing the underlying social determinants of risk and supporting equitable access to knowledge, power, and adaptive resources (Adger, 2006; Eakin et al., 2014; Eriksen et al., 2015; Sultana, 2021; Tschakert et al., 2013). In post-disaster governance and resilience planning, enhancing adaptive capacity involves both material improvements (e.g., infrastructure, communication systems, ecosystem services) and relational capacities (e.g., trust, inclusion, leadership, culturally grounded practices) (; Berke & Campanella, 2006; Cutter et al., 2008; Matin et al., 2018; Norris et al., 2008; Sherrieb et al., 2010). It also requires recognizing and incorporating local and Indigenous knowledge systems (LIK and LEK) that have long histories of responding to disturbance regimes (Berkes, 2018; Kimmerer, 2013; McMillen et al., 2017; Nakashima et al., 2012; Whyte, 2013).

2. **BRIC:** Building Resilient Infrastructure and Communities (FEMA program)

3. **CDC/ATSDR:** Centers for Disease Control / Agency for Toxic Substances and Disease Registry

4. **Climate Change Adaptation (CCA):** Refers to the process of adjusting ecological, social, economic, and governance systems in response to actual or anticipated climate impacts, in order to reduce harm, moderate risk, or take advantage of emerging opportunities (Füssel & Klein, 2006; IPCC, 2022; UNFCCC, 2022). Adaptation can be reactive or anticipatory, incremental or transformative, and may involve changes in behavior, practices, institutions, infrastructure, or ecosystem management (Smit & Wandel, 2006; UNEP, 2025). Effective adaptation requires context-specific planning and prioritizes equity, resilience, and sustainability, particularly for populations most vulnerable to climate-related hazards and structural/institutional inequities (; Eriksen et al., 2011; IPCC, 2022; Schipper et al., 2022; Siders, 2019; Sultana, 2022; UNFCCC, 2022).

5. **Co-production/Collaborative Knowledge Production:** Refers to the collaborative process of generating knowledge through the equitable involvement of multiple actors (e.g., researchers, policymakers, practitioners, and community members) who contribute diverse expertise, values, and lived experiences (Kimmerer, 2013; Latulippe & Klenk, 2020; Mauser et al., 2013; Newig & Fritsch, 2009; Norström et al., 2020; Wyborn et al., 2019). It emphasizes mutual learning, shared decision-making, and context-specific relevance, challenging traditional top-down models of knowledge creation (Jasanoff, 2004; Mauser et al., 2013). In the context of climate adaptation, disaster risk reduction, and environmental governance, co-production is a strategy for bridging scientific, local, and Indigenous knowledge systems, ensuring that solutions are socially robust, actionable, and just (Norström et al., 2020; Wyborn et al., 2019).

6. **Decolonizing methodologies:** Refers to research approaches that critically examine and resist the colonial foundations of dominant knowledge systems, centering Indigenous worldviews, community priorities, and self-determination in the research process (Chilisa, 2012; Smith, 2021; Tuck & Yang, 2014; Tuhiwai Smith, 1999). These methodologies challenge extractive, hierarchical, and Eurocentric practices by emphasizing relational accountability, cultural protocols, knowledge sovereignty, and the ethical responsibilities of researchers (Chilisa, 2012; Smith, 2021). In climate adaptation, disaster risk reduction, and socio-ecological research, decolonizing approaches aim to reposition power, prioritize place-based and lived experience, and support community-led knowledge production (Tuck & Yang, 2014; Whyte, 2017).

7. **DEM:** Digital Elevation Model

8. **Disaster Risk Reduction (DRR):** Refers to the systematic efforts to analyze, reduce, and manage the causes and impacts of disasters by addressing underlying vulnerabilities, strengthening preparedness, and promoting resilience across physical, social, and ecological systems (UNDRR, 2015; Wisner et al., 2004). DRR encompasses policies, strategies, and practices aimed at preventing new risks, reducing existing risks, and managing residual risks, with a focus on minimizing loss of life, damage to infrastructure, and disruption of livelihoods (UNDRR, 2022). Effective DRR integrates climate risk, social vulnerability, and community participation, and is central to sustainable development, equity, and adaptive capacity in the face of increasing climate-related hazards (Bailey et al., 2017; Gaillard, 2010).

9. **Disturbance Regime:** A disturbance regime refers to the characteristic patterns of natural or anthropogenic disturbances (e.g., their frequency, intensity, duration, spatial extent, and type) that shape the structure, composition, and functioning of ecological systems over time (Rogers, 1996; Turner, 2010). These regimes are central to understanding ecological resilience and landscape dynamics, particularly as some ecosystems evolve in response to specific disturbance patterns (e.g., fire-adapted forests, floodplains, or landslide-prone mountain systems) (Pausas & Keeley, 2009; Pickett & White, 1985; Renaud et al., 2013; Turner, 2010). In the context of socio-ecological systems (SES), disturbance regimes also interact with human systems, contributing to cumulative

impacts, threshold effects, and long-term vulnerability when compounded with climate change or land use change (Biggs et al., 2016; Renaud et al., 2013). Effective watershed governance, disaster risk reduction, and climate adaptation depend on understanding both historical and projected disturbance regimes, especially in contexts where disturbances are becoming more frequent, intense, or systemically interconnected (e.g., compound drought–fire–flood cycles) (IPCC, 2022; Turner et al., 2003).

10. **Ecosystem-based Adaptation (EbA):** Refers to the use of biodiversity and ecosystem services to help people adapt to the adverse effects of climate change (CBD, 2009; UNFCCC, 2013). It involves the protection, sustainable management, and restoration of ecosystems to reduce vulnerability and build resilience in social-ecological systems. EbA offers co-benefits for both people and nature, such as buffering climate impacts (e.g., flooding, erosion), enhancing livelihoods, and conserving biodiversity (Colls et al., 2009; Munang et al., 2013). It is increasingly recognized in global climate frameworks as a cost-effective, participatory, and locally appropriate adaptation strategy (IPBES, 2019; UNFCCC, 2013).

11. **Environmental Justice (EJ):** Refers to the rights of all people, regardless of race, ethnicity, income, gender, or geographic location, to equitable treatment, protection, and meaningful participation in environmental decision-making, policy, and law (Bullard, 2000; Schlosberg, 2007). EJ emphasizes the fair distribution of environmental benefits (e.g., clean water, healthy ecosystems) and burdens (e.g., pollution, disaster risk) across communities (Bullard, 2000; Schlosberg, 2007; US EPA, 1998; Walker, 2012). In the context of climate change adaptation, EJ frameworks underscore the uneven exposure, sensitivity, and adaptive capacity of different populations, particularly low-income, historically marginalized communities, and Indigenous communities (IPCC, 2022; Thomas et al., 2019). These communities often face disproportionate socio-ecological vulnerability due to legacies of colonialism, underinvestment, displacement, and environmental degradation (Shi, 2020; Sultana, 2022). EJ also intersects with climate justice, which links environmental outcomes to broader structures of power, systemic inequality, and the demand for just transitions (Sultana, 2022; UNEP, 2021).

    Within climate adaptation science, EJ frameworks push beyond technocratic solutions to incorporate equity-informed planning, procedural inclusion, and the recognition of place-based knowledge systems (including LIK and LEK) (Shi, 2020; Thomas et al., 2019). In socio-ecological systems (SES) and disaster resilience research, EJ serves as a normative foundation for evaluating whether adaptive strategies reinforce or redress existing inequities (IPCC, 2022; UNEP, 2021). This definition is grounded in evolving international norms that recognize environmental justice as central to climate resilience, disaster risk reduction, and human rights, including the Sendai Framework, the SDGs, and IPCC guidance (IPCC, 2022; UN, 2015; UNISDR, 2015). It's important to note that EJ is not a static or singular framework. It is plural, evolving, and politically contested. Scholars increasingly call for Critical Environmental Justice approaches (Pellow, 2018) that examine intersecting injustices and advocate for transformation of dominant systems, not just inclusion within them.

12. **ESRI:** Environmental Systems Research Institute

13. **FEMA:** Federal Emergency Management Agency

14. GAP: The GAP Analysis Project is a U.S. Geological Survey (USGS) program that produces standardized land cover maps and ecological data to support biodiversity conservation and natural resource planning (Gould et al., 2008; Jennings, 2000; USGS, 2020a). Its land cover classification system provides detailed, nationally consistent data on vegetation types and habitat distribution using a hierarchical framework aligned with the National Vegetation Classification Standard (USGS, 2020b). GAP data are widely used for species habitat modeling, conservation prioritization, and landscape-scale ecosystem assessment (Crist et al., 2005; Gould et al., 2008; Jennings, 2000; USGS, 2020b).

15. **GCA:** Global Commission on Adaptation

16. **Governance:** Refers to the processes, institutions, norms, and relationships through which societies make and implement collective decisions, allocate authority, and manage resources (Kooiman, 2003; Pierre & Peters, 2000). In environmental and disaster contexts, governance encompasses both formal institutions (e.g., laws, agencies) and informal arrangements (e.g., community norms, customary practices) that influence how power is exercised and by whom (Ostrom, 2010). Equitable governance prioritizes inclusivity, justice, and the fair distribution of risks, benefits, and decision-making power across different social groups, especially those historically marginalized or disproportionately affected by environmental hazards (Bulkeley et al., 2013; Sultana, 2022). Polycentric governance refers to the existence of multiple, overlapping centers of authority operating at different scales (e.g., local, regional, national) that enable more adaptive, flexible, and context-responsive management (Newig & Fritsch, 2009; Ostrom, 2010; Termeer et al., 2010). In the context of climate adaptation, DRR, and SES management, strong governance structures must support participatory processes, cross-sectoral coordination, and knowledge pluralism, recognizing the importance of diverse worldviews and the legitimacy of local and Indigenous governance systems (Meadow et al., 2015).

17. **HMPs:** Hazard Mitigation Plans

18. **IITF:** International Institute of Tropical Forestry

19. **IPBES:** Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

20. **Integrated Water Resources Management (IWRM):** Defined by the Global Water Partnership as “a process which promotes the coordinated development and management of water, land and related resources, in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems” (GWP, 2000). It emphasizes cross-sectoral coordination, stakeholder participation, and the

integration of water governance across hydrological, administrative, and sectoral boundaries (Medema et al., 2008; Pahl-Wostl et al., 2011). While IWRM has become a dominant framework in global water policy, it has also faced critique for its vague operational guidance, technocratic orientation, and limited integration of justice and social vulnerability (Biswas, 2004; Sultana, 2022; Zeitoun et al., 2016). Scholars have argued that IWRM often overlooks power asymmetries, historical marginalization, and the importance of place-based or Indigenous knowledge systems, particularly in contexts of climate risk and water insecurity (Giordano & Shah, 2014; UN-Water, 2021). As such, while IWRM laid the foundation for more holistic resource governance, it is increasingly recognized as inadequate for addressing the complexity, inequity, and uncertainty that characterize many contemporary water and watershed challenges (Biswas, 2004; Giordano & Shah, 2014; Pahl-Wostl et al., 2011; Sultana, 2022; Zeitoun et al., 2016).

21. **Integrated Watershed Health Framework (IWHF):** A holistic, systems-based approach to assessing and managing watershed conditions by integrating environmental, social, and institutional indicators (Heathcote, 2009; Hooper, 2006; UN-Water, 2008; USEPA, 2016). It emphasizes cross-sectoral coordination, multi-scalar analysis, and the inclusion of both biophysical and human dimensions (e.g., climate risk, land use, governance capacity, and community well-being) to support equitable and sustainable watershed planning and decision-making (Heathcote, 2009; UN-Water, 2008; US EPA, 2016). However, while IWHF represents an important evolution from biophysical-only assessments, it lacks explicit metrics for social vulnerability, justice, and polycentric governance, a critique echoed Engle et al. (2011), Norman et al. (2015), Sultana (2022), and UN-Water (2021). It may also be limited in its treatment of multi-hazard risk, knowledge pluralism, and the role of community-based or Indigenous governance systems (Engle et al., 2011; Natcher et al., 2005; Norman et al., 2015; UN-Water, 2021). As such, it provides a foundational baseline that requires further development to guide equitable, climate-adaptive, and justice-centered watershed management (Armitage et al., 2009; Pahl-Wostl, 2015; Sultana, 2022).

22. **Justice**: In this research, refers to the equitable distribution of risks, resources, and decision-making power within systems of climate adaptation, disaster risk reduction (DRR), and environmental governance (Schlosberg, 2007; Sultana, 2022; Thomas et al., 2019). It includes both procedural justice (e.g., ensuring fair and inclusive processes of participation and governance) and distributive justice (e.g., the equitable allocation of outcomes and resources) (Shi, 2020; Walker, 2012). This framing recognizes that historically marginalized communities often face disproportionate exposure to environmental hazards and have reduced access to decision-making and recovery resources, particularly in post-disaster and climate-stressed contexts (Bullard, 2000; Siders, 2019; UNDRR, 2022). Justice in these domains also entails recognizing and redressing historic and structural drivers of vulnerability, such as colonialism, systemic racism, displacement, and environmental degradation (Shi, 2020; Sultana, 2022). It emphasizes the need for locally defined priorities, knowledge sovereignty, and relational accountability, particularly where historically marginalized communities are concerned (Pellow, 2018; Schlosberg, 2007; Thomas et al., 2019). Within DRR and adaptation frameworks, justice increasingly intersects with concepts of resilience, sovereignty, and

the right to remain, return, or retreat in the face of climate-related displacement (Bronen, 2011; Siders, 2019; Marino, 2018; Thomas et al., 2019; UNDRR, 2022). This framing aligns with calls for transformative adaptation, which foreground equity, repair, and redistribution and not just technical or infrastructural solutions (IPCC, 2022; UNDRR, 2015).

23. **Local Ecological Knowledge (LEK):** LEK refers to the knowledge developed by local (often non-Indigenous) communities through sustained interaction with their environment (Berkes, 2018). It includes practical, place-based insights into species behavior, land use, seasonal cycles, and ecosystem dynamics, often grounded in experience and direct observation (Brook & McLachlan, 2005). While LEK may be cumulative and transmitted across generations, it is frequently experiential, adapting through lived practice rather than through formal institutions or codified systems (Raymond et al., 2010). Key features include:
    a. Rooted in local practice and observation (Brook & McLachlan, 2005)
    b. Often includes non-Indigenous communities (e.g., farmers, fishers, rural residents) (Berkes, 2018)
    c. May incorporate elements of scientific or modern environmental knowledge (Raymond et al., 2010)
    d. Dynamic and adaptable (Raymond et al., 2010)
    e. Often tacit and informal (Berkes, 2018).

24. **Local Indigenous Knowledge (LIK):** LIK is a subset of Indigenous Knowledge (IK) that emerges from long-standing relationships between Indigenous Peoples and specific ecosystems (Berkes, 2018; Kimmerer, 2013; McGregor, 2004; Whyte, 2013). It is rooted in distinct ontologies and epistemologies, shaped by cultural, spiritual, and governance systems that are place-based, relational, and intergenerational (Wilson, 2008; Smith, 2021). LIK differs fundamentally from conventional scientific knowledge in that it is not simply observational or empirical, but holistic — woven through language, ceremony, ethics, responsibilities to land, and more-than-human kin (Kimmerer, 2013; Whyte, 2013). LIK is often transmitted orally, practiced through daily subsistence activities (e.g., agroforestry, fire management, water stewardship), and embedded in protocols for environmental reciprocity and governance (McGregor, 2004). For example, traditional hydrological knowledge held by Indigenous communities has guided seasonal water use, floodplain management, and soil retention strategies that modern infrastructure systems often overlook or erase (Boelens, 2015; McGregor, 2012; UNOCHA & UNU, 2020; Verde et al., 2023). These knowledge systems are governed by community-specific ethics of use, consent, and responsibility, and their inclusion in research must be based on formal agreements, not extraction (Smith, 2021; Whyte, 2013).

    From a systems theory perspective, Local Indigenous Knowledge (LIK) contributes to adaptive capacity, feedback integration, and long-term resilience in socio-ecological systems (Armitage et al., 2009; Berkes, 2018; McGregor, 2004). It enhances understanding of ecological thresholds, non-linear change, and human–environment dynamics that are often invisible to conventional scientific or technocratic models (Folke et al., 2002; Kimmerer, 2013; Whyte, 2013). In climate adaptation science and disaster risk reduction (DRR), LIK offers insight into localized indicators of risk (e.g., species behavior, wind patterns, soil changes), long-standing strategies for hazard mitigation, and early warning systems rooted in collective memory and landscape literacy (Kimmerer, 2013). LIK is crucial for addressing SEV because it centers communities that have historically managed disturbance regimes through adaptive, relational knowledge systems (Berkes, 2018; McMillen et al., 2017; Whyte, 2013; Wildcat, 2009). Integrating LIK into adaptation planning enables equity-informed, culturally appropriate, and systems-aware solutions that challenge dominant technocratic approaches and support Indigenous self-determination (Latulippe & Klenk, 2020; Maldonado et al., 2016; Sultana, 2022). Key features include:

   a. Embedded in Indigenous languages, cosmologies, and laws (Smith, 2021; Wilson, 2008)
   b. Governed by protocols of use, relationality, and responsibility (McGregor, 2004; Wilson, 2008)
   c. Not simply observational or empirical, but relational and sacred (Kimmerer, 2013; Whyte, 2013)
   d. Cannot be fully translated or extracted without harm (Smith, 2021; Whyte, 2013)
   e. Enhances system feedback recognition, adaptive capacity, and long-term resilience in SESs (Kimmerer, 2013; McGregor, 2004)

25. **NWQI:** National Water Quality Initiative is a collaborative program led by the USDA NRCS, in partnership with the EPA and state water quality agencies (USDA NRCS, 2023). It aims to improve water quality in priority watersheds by providing targeted financial and technical assistance to farmers and landowners for implementing voluntary conservation practices that reduce nutrient, sediment, and pathogen runoff (USDA NRCS, 2023). NWQI supports locally led watershed planning, promotes the adoption of conservation systems, and aligns with Clean Water Act goals, contributing to measurable improvements in impaired water bodies (US EPA, 2020).

26. **Nature-based Solutions (NbS):** Defined by the International Union for Conservation of Nature (IUCN) as "actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (IUCN, 2016). Building on this foundation, the United Nations Environment Assembly (UNEA-5.2) adopted in 2022 the first multilaterally agreed definition of NbS, recognizing them as: "Actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits" (UNEP, 2022). These definitions emphasize several shared core principles:
    a. Ecosystem-based action (protection, restoration, conservation, or sustainable management)
    b. Systemic problem-solving addressing societal challenges such as climate change, disaster risk, and food/water security
    c. Co-benefits for human well-being, biodiversity, and ecosystem service provision
    d. NbS can include green and hybrid grey-green approaches such as:

   e. Green:
      i. Wetland and mangrove restoration to reduce flood risk and coastal erosion
      ii. Reforestation and agroforestry to stabilize slopes, increase carbon sequestration, and enhance watershed health
      iii. Coral reef restoration to support biodiversity and buffer storm surges
   f. Hybrid grey–green:
      i. Rain gardens and bioswales for stormwater retention in urban areas
      ii. Vegetated levees and green roofs that combine structural protection with ecological function
      iii. Permeable pavements with natural filtration systems to reduce runoff and mimic natural hydrology

Incorporating LEK and LIK strengthens NbS by ensuring solutions are place-based, culturally grounded, and ethically co-produced (Kimmerer, 2013; McGregor, 2004; Raymond et al., 2017). These knowledge systems contribute not only technical insight but also relational, spiritual, and governance dimensions that are essential for building just, adaptive, and system-aligned responses to socio-ecological challenges (Smith, 2021; Whyte, 2013). For example:

   g. In Pacific Island nations, LIK embedded in traditional agroforestry and water harvesting systems reflects intergenerational stewardship rooted in Indigenous worldviews and land-based responsibilities. These systems address both food sovereignty and climate resilience through practices such as multistrata cropping and culturally governed water sharing (McMillen et al., 2017; Raynor & Fownes, 1991).
   h. In mountainous regions such as Nepal and the Andes, LEK has shaped terracing, rainwater harvesting, and soil retention strategies that increase slope stability and reduce erosion. These practices are maintained by local farming communities through experiential adaptation, communal labor, and observation-based decision-making (Altieri & Nicholls, 2017; Tiwari et al., 2008).
   i. In Puerto Rico, community-led watershed stewardship initiatives draw on LEK to guide reforestation efforts, selecting native vegetation for slope stabilization and soil health in landslide-prone areas. While often rooted in campesino knowledge systems, these efforts increasingly engage with Indigenous Taíno resurgence movements, opening space for LIK to inform long-term ecological restoration and cultural renewal (Heartsill-Scalley & López-Marrero, 2014; López-Marrero & Hermansen-Báez, 2011).

27. **NOAA:** National Oceanic and Atmospheric Administration

28. **NRCS:** Natural Resource Conservation Service

29. **NSF:** National Science Foundation

30. **PRASA:** Puerto Rico Aqueduct and Sewers Authority

31. **PROMESA:** Puerto Rico Oversight, Management, and Economic Stability Act

32. **Q99 – Quantile 99 Low-Flow Standard**: A hydrological benchmark indicating the streamflow value exceeded 99% of the time, used to define low-flow conditions in water management (Connecticut DEEP, 2022; Ledford et al., 2020; Sarigil et al., 2024; Smakhtin, 2001; USGS, 2010).

33. **Resilience:** Refers to the capacity of a system, whether ecological, social, or socio-ecological, to absorb shocks, adapt to change, and persist while maintaining essential functions, structures, feedbacks, and identity (Biggs et al., 2016; Holling, 1973;). Originally introduced by Holling (1973) in the context of ecosystems, resilience was defined as the ability of a system to absorb disturbances and reorganize without shifting into an alternative regime or degraded state. In ecological systems, resilience includes the ability to recover from events like fire, drought, or storms while maintaining species diversity, productivity, and ecosystem services. In social systems, resilience refers to the capacity of communities, institutions, or networks to anticipate, respond to, and recover from external shocks (e.g., disasters, pandemics, or economic collapse) while retaining coherence, agency, and function (Munang et al., 2013). In socio-ecological systems (SES), resilience is not only about returning to a prior state, but also about learning, adapting, and potentially transforming in the face of long-term change or systemic risk (Folke, 2006; Walker et al., 2004).

    Communities may be resilient in the sense that they persist under stress, but still remain vulnerable or marginalized due to systemic injustices (Cote & Nightingale, 2012). Justice-centered frameworks highlight that true resilience must involve not only coping but also redressing root causes of vulnerability, redistributing power, and incorporating local and Indigenous knowledge systems (Munang et al., 2013; Whyte, 2013). Resilience is often differentiated into three capacities:
    a. Absorptive capacity: the ability to buffer shocks and maintain system structure.
    b. Adaptive capacity: the ability to make incremental changes to continue functioning.
    c. Transformative capacity: the ability to fundamentally shift or reorganize the system when conditions make the old system untenable.

34. **RGA: Río Grande de Añasco (watershed)**

35. **Risk-Informed Management:** As referred to as "risk-informed decision-making", "risk planning", and "risk-aware governance". It refers to a systematic approach to planning, decision-making, and governance that:
    a. Integrates risk assessments (hazards, exposure, vulnerability) into policies and practices.
    b. Prioritizes prevention, preparedness, and resilience over reactive responses.
    c. Emphasizes data-driven, context-sensitive, and multi-sectoral coordination.
    d. Supports decisions that reduce future harm and promote adaptive capacity.

    (IPCC, 2022; UNDP, 2020; UNDRR, 2015; World Bank, 2017)

36. **Science of Team Science (SciTS):** An interdisciplinary field that examines the processes, structures, and strategies that enable effective collaboration across disciplinary, institutional, and sectoral boundaries (Börner et al., 2010; Hall et al., 2012; Stokols et al., 2008a). SciTS investigates how teams form, function, and achieve scientific goals, focusing on factors such as communication, leadership, knowledge integration, power dynamics, and the evaluation of collaborative outcomes (Bennett & Gadlin, 2012; Falk-Krzesinski et al., 2010; Fiore, 2008).It also provides evidence-based guidance for designing, supporting, and sustaining cross-sector research partnerships that are responsive to complex societal challenges (Bennett & Gadlin, 2012; Hall et al., 2012; Stokols et al., 2008a).

37. **SDGs (Sustainable Development Goals): A** universal set of 17 interconnected goals adopted by the United Nations in 2015 as part of the *2030 Agenda for Sustainable Development*. They aim to end poverty, protect the planet, and ensure peace and prosperity for all by promoting social inclusion, environmental sustainability, and economic development. The SDGs apply to all countries and emphasize integrated, cross-sectoral approaches to addressing global challenges such as climate change, inequality, and ecosystem degradation (United Nations, 2015).

38. **SIDS: Small Island Developing States** are a group of low-lying coastal and island nations that face unique sustainable development challenges due to their small size, geographic isolation, limited resources, high exposure to natural disasters, and vulnerability to the impacts of climate change (Pelling & Uitto, 2001; UNDESA, 2023). These states often contend with economic dependence on a narrow range of sectors (e.g., tourism, fisheries), limited institutional capacity, and heightened risk from sea level rise, hurricanes, drought, and coastal erosion (Kelman & West, 2009; UNDESA, 2023). SIDS are politically and geographically diverse, spanning the Caribbean, Pacific, and Atlantic/Indian Ocean/Mediterranean/South China Sea (AIMS) regions (UNDESA, 2023; United Nations General Assembly, 2014). Despite these differences, they share common structural challenges that have been internationally recognized since the 1992 Earth Summit and further supported through dedicated global frameworks such as the Barbados Programme of Action (1994), the Mauritius Strategy (2005), and the SAMOA Pathway (2014). In the context of climate adaptation, disaster risk reduction (DRR), and sustainable development, SIDS are often referenced as frontline nations—those facing disproportionate environmental, economic, and social vulnerability despite contributing minimally to global emissions (Kelman & West, 2009; Pelling & Uitto, 2001).

39. **Social Vulnerability:** Reflects how entrenched social, economic, and infrastructural inequities shape differential exposure, sensitivity, and adaptive capacity to environmental hazards and disaster events (Cutter et al., 2003; Flanagan et al., 2011). These factors include poverty, age, gender, disability, housing conditions, health status, education, access to transportation, and availability of social networks and services (UNDRR, 2015). Social vulnerability is context-specific and often intersects with historical patterns of marginalization, such as racialized discrimination, colonization, and systemic underinvestment (Adger, 2006). For example, individuals with limited access to resources or social support may be less able to evacuate during a flood or recover after a landslide.

The IPCC underscores that vulnerability is multi-dimensional, socially constructed, and unequally distributed, reinforcing that adaptive capacity and resilience must address not only environmental exposure but also governance, justice, and participation (IPCC, 2022). Structural factors (e.g., unsafe housing, reliance on failing infrastructure, lack of insurance) compound this vulnerability and increase the likelihood of long-term displacement or loss (Cutter et al., 2003; Flanagan et al., 2011; Peacock et al., 2014; Thomas et al., 2019).

40. **Social Vulnerability Index (SVI):** A tool developed by the CDC ATSDR to help identify communities that may need support before, during, or after hazardous events such as natural disasters, disease outbreaks, or environmental crises. The SVI uses U.S. Census data to assess social vulnerability at the census tract or county level across four key themes:
    a. Socioeconomic Status – Factors such as poverty, unemployment, income level, and educational attainment.
    b. Household Composition & Disability – Includes age (e.g., children under 17, elders over 65), disability status, and single-parent households.
    c. Minority Status & Language – Captures race, ethnicity, and English proficiency, recognizing structural and linguistic barriers.
    d. Housing Type & Transportation – Reflects vulnerability based on housing density, mobile homes, crowding, access to vehicles, and group quarters residency.

    Each tract or region receives a percentile ranking (0.0–1.0) for each theme and a composite SVI score, with higher values indicating greater vulnerability. The SVI is widely used in emergency preparedness, environmental justice analysis, public health planning, and climate adaptation policy, helping to direct resources to communities at greatest risk. (ATSDR, 2021; CDC/ATSDR, 2018; Flanagan et al., 2011)

41. **Socio-Ecological System (SES):** SES is a complex, integrated system composed of social and ecological components that interact dynamically and co-evolve over time through feedback, cross-scale linkages, and adaptive responses (Berkes et al., 2003; Folke, 2006; Ostrom, 2009). SES frameworks emphasize that human and natural systems are not separate but interdependent and co-constituted, forming a single system in which changes in one domain affect the other. These frameworks are grounded in systems theory and complex adaptive systems thinking, recognizing the nonlinear, emergent, and often unpredictable behavior of SESs (Gunderson & Holling, 2002; Walker et al., 2004). Key concepts include resilience (the capacity to absorb disturbances while maintaining core functions), adaptive capacity, transformability, and thresholds beyond which systems may reorganize into fundamentally different configurations (Walker et al., 2004; Folke, 2016).

    SES theory considers institutions, governance, power dynamics, and knowledge systems as essential drivers of system outcomes, aligning with justice-centered and transdisciplinary approaches (Chapin et al., 2009; Cote & Nightingale, 2012). In the context of climate adaptation, disaster risk reduction (DRR), and vulnerability research, SES frameworks help illuminate how exposure to hazards, sensitivity to disruption, and capacity to respond are distributed across social-ecological gradients. For example, a mountainous watershed prone to landslides must be assessed not only for its biophysical risk but also for land tenure policies, historical patterns of land use, community capacity, and local knowledge systems (Adger, 2006; Turner et al., 2003).

42. **Socio-Ecological Vulnerability (SEV):** Refers to the degree to which coupled social–ecological systems (SESs) are likely to experience harm from external disturbances, such as natural hazards, climate change, or human-induced degradation (Adger, 2006; Turner et al., 2003). SEV integrates multiple dimensions of vulnerability including exposure, sensitivity, and adaptive capacity across both human and ecological subsystems. In an SES context, exposure refers to the presence of people, infrastructure, or ecosystems in locations prone to hazards (e.g., floodplains, landslide-prone slopes), while sensitivity denotes how strongly those systems are affected when exposed (e.g., poor soils, fragile housing, dependence on climate-sensitive livelihoods). Adaptive capacity is the system's ability to adjust to changing conditions and recover from disturbances (Adger, 2006; Folke et al., 2002).

    What distinguishes SEV from traditional vulnerability frameworks is its attention to feedbacks, interdependencies, and co-evolving risks between ecological and social systems (Adger, 2006; Eakin & Luers, 2006; Turner et al., 2003). For example, deforestation or urbanization may increase ecological sensitivity to landslides, while institutional weaknesses or poverty heighten the social consequences of such events (Cutter et al., 2008; IPCC, 2022). In this way, SEV is critical to understanding compound risks, nonlinear impacts, and the systemic nature of vulnerability in dynamic environments (Cote & Nightingale, 2012; Renaud et al., 2013). SEV has become increasingly central to disaster risk reduction (DRR) and climate change adaptation frameworks, including those developed by the IPCC and the UNDRR, which emphasize the need for multi-scalar, cross-sectoral analyses of vulnerability (IPCC, 2012; IPCC, 2022; UNDRR, 2015). Moreover, SEV provides a lens through which to assess how inequities, governance failures, and socio-political marginalization can amplify ecological degradation and disaster risk, particularly for historically excluded populations (Cote & Nightingale, 2012; Cutter et al., 2003).

43. **SSURGO:** The Soil Survey Geographic Database is a detailed, publicly available geospatial dataset maintained by the US Department of Agriculture's Natural Resources Conservation Service (USDA NRCS), providing fine-resolution soil mapping and attribute data developed from field surveys, aerial imagery, and laboratory analyses. It includes information on soil composition, texture, drainage, slope, depth, and suitability for land use, agriculture, engineering, and ecological applications. (USDA NRCS, 2019; 2023; Wieczorek & Snyder, 2009)

44. **Tacit vs. Explicit Knowledge:** Explicit knowledge can be articulated, documented, and shared formally. Tacit knowledge is experience-based and often difficult to codify or transfer. (Nonaka & Takeuchi, 1995; Polanyi, 1966).

45. **Team Science:** Refers to a collaborative mode of research in which knowledge, theory, and methodology from multiple disciplines and collaborators beyond academia (e.g.,

institutions, stakeholder groups, communities) are integrated to address complex scientific and societal challenges (Love et al., 2022; Stokols et al., 2008a). Unlike traditional single-investigator models, team science emphasizes shared goals, collective problem-solving, and coordination across epistemological boundaries, often in response to "wicked" problems such as climate change, disaster resilience, health equity, or environmental justice (National Research Council, 2015). Team science occurs along a continuum of disciplinary integration:
   a. In multidisciplinary teams, members contribute from their disciplinary silos with minimal integration.
   b. Interdisciplinary teams synthesize concepts and methods to form a more integrated framework.
   c. Transdisciplinary teams go further by co-producing knowledge with non-academic partners (e.g., communities, agencies), often addressing real-world problems through participatory and justice-centered approaches (Mauser et al., 2013; Hall et al., 2012).

46. **Trauma-Informed Management / Governance:** Trauma-informed governance and management refers to an approach to organizational decision-making, planning, or research collaboration that recognizes the prevalence and impact of trauma, both individual and collective (Bowen et al., 2022; Canadian Mental Health Commission, 2024; Longman et al., 2025; Office of Management and Budget, 2023; Rosenberg et al., 2022; Watson, 2020). Enacting this approach includes the intentional design of processes, policies, and interactions to avoid re-traumatization, foster safety, and support healing, particularly for communities historically exposed to displacement, violence, and environmental injustice (Berke & Campanella, 2006; Krieger, 2020; Shultz & Neria, 2013). In the context of post-disaster governance and climate resilience, trauma-informed approaches seek to build trust, promote equity, acknowledge historical harm (e.g., colonialism, displacement, underinvestment), and support meaningful participation from affected communities (Berke & Campanella, 2006; Office of Management and Budget, 2023; Shultz & Neria, 2013; Watson, 2020). This approach involves:
   a. Recognizing the presence of trauma and its social-ecological dimensions
   b. Prioritizing emotional, cultural, and physical safety in all interactions
   c. Fostering transparency, collaboration, and mutual trust
   d. Empowering community leadership and valuing lived experience
   e. Addressing power imbalances and structural violence in governance systems

   Trauma-informed governance is especially important when working with historically marginalized groups, disaster-affected communities, or in contexts where institutional trust is low. It intersects with principles of Environmental Justice, community care, and healing-centered engagement (Ginwright, 2018).

47. **UNDP:** United Nations Development Programme

48. **UNDRR:** United Nations Office for Disaster Risk Reduction

49. **UNEP:** United Nations Environment Programme

50. **EPA:** U.S. Environmental Protection Agency

51. **USGS:** United States Geological Survey

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