Advance the Estuarine System's Adaptation to Extreme Weather Events and Protect Communities

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Risk and Its Vulnerability Analysis

Baseline

The San Juan Bay Estuary (SJBE) is increasingly vulnerable to a variety of weather-related hazards and anthropogenic influences, which present significant risks to both natural and human systems. The landfall of hurricane Maria in 2017 starkly illustrated the estuary's exposure to extreme weather events, producing the largest recorded rainfall in over six decades and triggering widespread flooding and landslides across the island (Keellings and Hernández Ayala, 2019). This event not only caused immense physical damage but also revealed the social vulnerabilities embedded within the affected populations, as indicated by excess mortality and population displacement (Keellings and Hernández Ayala, 2019). Observations indicate that recent hurricanes impacting the SJBE exhibit greater intensity than historical climatological averages. To address this, additional hurricane scenarios with elevated intensities have been developed, highlighting the potential for Category 4 and 5 wind speeds within a 1% annual chance event (Estuario, 2025). These risks are exacerbated by ongoing trends in weather events and sea level data, which have increased the probability of extreme rainfall events by nearly five times in the most affected regions (Keellings and Hernández Ayala, 2019).

As extreme weather events and unprecedented shifts in nutrients, ocean temperature, pH, and other factors persist, understanding and predicting trends and events are further compounded by new unprecedented events. One example is the increase in sargassum weed, which in large quantities can smother coral reefs and seagrass and further contribute to eutrophication of the SJBE. There remains no consensus on why the sargassum weed has increased so dramatically.

Recent advancements in vulnerability assessments for the SJBE have formalized the selection of key parameters that drive risk across social, ecological, and infrastructural sectors. For this action plan, specific events will be discussed in detail, and generalized terms will be used to describe groups of events. Extreme weather events will be used as a term to describe increased storms that result in more frequent and intense rainfall, flooding, and mud slides. Environmental stressors will be used to describe other hazards, risks, and environmental drivers that are not individual events, but lasting or secondary effects. Estuario developed a plan for adapting to the foreseen effects of changes due to six environmental stressors: warmer summer months, warmer water temperatures, more frequent droughts, more intense rainfall, sea level rise, and carbon dioxide effects including ocean acidification (Bauzá-Ortega, 2015).

Flooding, one of the primary hazards facing the estuary and the critical infrastructure and communities adjacent to the estuary. Floods arise from multiple sources including riverine overflow, flash floods, and coastal storm surges. The estuary's geographic and hydrological characteristics make it particularly susceptible to flooding events. Estuario (2025) used the Federal Emergency Management Agency's (FEMA) Advisory Flood layer and Hazus program to model the potential damage from such flooding, highlighting the substantial risk posed by riverine and flash floods. Coastal flooding is driven largely by storm surge events associated with tropical cyclones which can cause significant flooding, even when a hurricane does not make direct landfall (Estuario, 2025). Additionally, coastal erosion exacerbated by storm surges threatens the integrity of estuarine shorelines, with municipalities like Loíza experiencing erosion beyond normal rates (Díaz et al., 2022; Estuario, 2025).

Landslides further compound the estuary's vulnerability, triggered by extreme rainfall and seismic activity. The heavy rains from hurricane Maria and subsequent earthquakes in 2020 led to widespread landslides,

destabilizing slopes and threatening infrastructure and habitats within the watershed (Estuario, 2025). These landslides not only damage ecosystems but also disrupt water quality through increased sedimentation, thereby impacting estuarine health.

Drought imposes chronic stress on the estuarine system. The 2015 drought brought reservoir levels across Puerto Rico, including those feeding into the SJBE, to record lows, affecting water availability for both ecological and human needs (Estuario, 2025). Regular drought cycles, occurring approximately every other year, emphasize the need for adaptive water management to buffer against long-term water scarcity (Estuario, 2025). Periodic fish kill events in the San José Lagoon are due to poor water quality conditions due to excess nutrient inputs from sanitary discharges and lack of circulation during drought conditions. latest significant fish kill event occurred in August 2020 (Almodóvar Santana et al, 2023).

Sea level rise represents a pervasive and escalating threat, contributing to increased coastal flooding and erosion. While some FEMA data suggest natural erosion processes dominate, communities such as Loíza exhibit significant concern for accelerated erosion linked to rising sea levels (Díaz et al., 2022). Rising sea levels will also raise groundwater, reducing drainage capacity of septic systems, stormwater systems, and highway drainage. The interaction of sea level with storm surges and increased precipitation creates compounded risk scenarios that further challenge the estuary's resilience.

The complexity of Puerto Rico's hydroclimate, influenced by tropical storms, easterly waves, and convective systems, introduces significant variability and uncertainty into risk assessments (Keellings and Hernández Ayala, 2019). This variability underscores the need for integrated vulnerability analyses that incorporate physical, ecological, and social data to fully capture the estuary's risk profile (Díaz et al., 2022). Such analyses are critical for identifying hotspots of vulnerability and informing targeted adaptation efforts.

The SJBE system faces multifaceted and intensifying risks from extreme weather and anthropogenic influences. Integrating detailed risk and vulnerability assessments that consider hydrological hazards, ecosystem sensitivities, and socio-economic factors is essential to guide effective adaptation and protect the estuary's ecological functions and surrounding communities.

Objectives

- Determine and monitor the risk to and vulnerabilities of the estuarine system against extreme events.

Actions

HW - 22 Estimate or model the SJBE's vulnerability to the impacts of extreme weather events and sea level rise, and present adaptation measures.

Activities

Activity	Performance Measures	Milestones	Responsible Stakeholder(s) and Partner(s)	Status	Timeframe	Estimated Costs	Potential Funding Sources
1. Expand and implement monitoring.	Measure rainfall, coastal erosion, water temperatures, water elevations, and pH.	Installed devices and created databases.	Lead: U.S. Geological Survey (USGS) Implementing partners: Estuario, Department of Natural and Environmental Resources [DNER], U.S. Fish and Wildlife Service (USFWS), National Oceanic and Atmospheric Administration (NOAA), FEMA, U.S. Army Corps of Engineers (USACE), municipalities, academia	Ongoing	0-2 years	TBD	U.S. Environmental Protection Agency (USEPA), DNER
2. Model impacts to SJBE from more intense rainfall and increased runoff.	Develop a model for multiple rainfall scenarios for the SJBE and watershed.	Developed model(s).	Lead: Estuario Implementing partners: DNER, municipalities	Pending	3-5 years	TBD	USEPA, DNER
3. Evaluate multiple rainfall and sea level rise scenarios for the SJBE and watershed and the effects on septic systems, sewer collection systems, treatment plants, and overflow of combined sewer systems.	Identify and evaluate impacts to septic systems, sewage collection systems, and combined sewer systems based on the elevation, flooding and runoff impacts in the SJBE and basin.	Identified and evaluated septic system and sewage collection systems impacts.	Lead: DNER Implementing partners: Municipalities, Estuario	Pending	3-5 years	TBD	DNER, municipalities
4. Evaluate the effects of more intense rainfall on flooding in urban areas, flood control facilities, retention ponds, and coastal areas.	Develop a model and evaluate effects of more intense rainfall on flooding in urban areas, flood control facilities, retention ponds, and coastal areas in the SJBE and basin.	Developed model(s).	Lead: DNER Implementing partners: Municipalities, Estuario	Pending	3-5 years	TBD	DNER, municipalities

Activity	Performance Measures	Milestones	Responsible Stakeholder(s) and Partner(s)	Status	Timeframe	Estimated Costs	Potential Funding Sources
5. Evaluate the effect of more intense rainfall and droughts on pollutant solubility and distribution through flood waters.	Evaluate pollutant loads, distribution, solubility, and polluted flood waters on the communities, flora, and fauna in the SJBE.	Evaluated consequences of pollutant distribution and effects on communities, flora, and fauna.	Lead: Estuario Implementing partners: DNER, municipalities	Pending	3-5 years	TBD	USEPA, DNER
6. Evaluate the effect of sea level rise on the freshwater layer depth and salinity concentrations in the SJBE.	Develop models on the effects of sea level rise on salinity.	Developed model(s).	Lead: Estuario Implementing partners: DNER, municipalities	Pending	3-5 years	TBD	USEPA, DNER
7. Evaluate the effect of sea level rise on erosion and loss of beaches and wetlands.	Develop models for the effects of sea level rise on loss of beaches and wetlands.	Developed model(s).	Lead: Estuario Implementing partners: DNER, municipalities	Pending	3-5 years	TBD	USEPA, DNER
8. Evaluate the effects of warmer summers on the increase in estuary nutrient levels and low oxygen.	Develop models for the effects of warmer summers on nutrients and low oxygen in the SJBE.	Developed model(s).	Lead: Estuario Implementing partners: DNER, municipalities	3-5 years	0-2 years	TBD	USEPA, DNER

Regulatory and Policy Requirements

New or modified legislation may be needed in response to the data and model results to account for extreme weather events and sea level rise, in planning projects to provide for increased resilience and reduced vulnerability to these changes.

NEW - 1* Develop a vulnerability index to rate the sensitivity and adaptive capacity of species and their habitats to Environmental stressors.

Activities

Activity	Performance Measures	Milestones	Responsible Stakeholder(s) and Partner(s)	Status	Timeframe	Estimated Costs	Potential Funding Sources
1. Identify the potential exposure to environmental stressors for each critical species and habitat in the SJBE system.	Determine the magnitude of predicted stressors for each critical species and habitat (i.e., sea level, temperature, moisture, pH, salinity).	Tabulated magnitude of predicted stressors for each critical species and habitat.	Lead: Estuario Implementing partners: DNER, USFWS, National Marine Fisheries Service (NMFS), NOAA, FEMA, USACE, municipalities, academia	Pending	0-2 years	TBD	USEPA, DNER, NOAA

Activity	Performance Measures	Milestones	Responsible Stakeholder(s) and Partner(s)	Status	Timeframe	Estimated Costs	Potential Funding Sources
2. Identify the sensitivity to change for environmental stressors for each critical species and habitat.	Determine the sensitivity to change across the range of expected values to stressors for each critical species and habitat (i.e., range of temperature, moisture, pH, and salinity).	Summarized relative value for sensitivity to change across the range of expected values to stressors for each critical species and habitat.	Lead: Estuario Implementing partners: DNER, USFWS, NMFS, NOAA, FEMA, USACE, municipalities, academia	Pending	0-2 years	TBD	USEPA, DNER, NOAA
3. Determine the adaptive capacity to withstand environmental stressors for each critical species and habitat.	Determine the adaptive capacity to stressors for each critical species and habitat (i.e., dispersal and movement).	Evaluated the adaptive capacity to change across the range of expected values to stressors for each critical species and habitat.	Lead: Estuario Implementing partners: DNER, USFWS, NMFS, NOAA, FEMA, USACE, municipalities, academia	Pending	0-2 years	TBD	USEPA, DNER, NOAA

Regulatory and Policy Requirements

None to establish the vulnerability index. The results of the index assessment will help inform future regulatory and policy requirements.

***NEW - 2* Establish scenario - based risk modeling to simulate potential extreme Weather Events and their impacts on the SJBE.**

Activities

Activity	Performance Measures	Milestones	Responsible Stakeholder(s) and Partner(s)	Status	Timeframe	Estimated Costs	Potential Funding Sources
1. Model hurricane event-based rainfall-driven floods.	Develop models for rainfall-driven floods for each hurricane category.	Developed models.	Lead: Municipalities Implementing partners: Estuario, Puerto Rico Aqueduct and Sewer Authority (PRASA), NOAA, FEMA	Pending	0-2 years	TBD	DNER, FEMA, NOAA, municipalities
2. Model hurricane event-based wind-driven damage and debris assessments.	Develop models for damage to power infrastructure, buildings, and debris for each hurricane category.	Developed models.	Lead: PRASA Implementing partners: Estuario, municipalities, NOAA, FEMA	Pending	0-2 years	TBD	DNER, FEMA, NOAA, municipalities

Regulatory and Policy Requirements

Model creation and validation will require funding for data collection and modeling, including a robust data collection network to ensure accurate measurements are collected even during hurricane events. Model

outputs can provide valuable data to inform planners and engineers with needs for critical development and retrofits, and emergency managers on targeted warnings and evacuations.

**NEW - 3* Use Existing Risk Assessments and Adaptation Plan information to inform zoning, land use, and infrastructure development plans.*

Activities

Activity	Performance Measures	Milestones	Responsible Stakeholder(s) and Partner(s)	Status	Timeframe	Estimated Costs	Potential Funding Sources
1. Integrate assessment findings into regulatory and planning frameworks.	Incorporate assessment findings into existing frameworks.	Collaborated with applicable stakeholders.	Lead: Estuario Implementing partners: Municipalities, DNER	Pending	3-5 years	TBD	USEPA, DNER
2. Develop guidelines for resilient infrastructure and land use practices.	Formulated guidelines.	Coordinated with stakeholders to develop guidelines.	Lead: Estuario Implementing partners: Municipalities, DNER	Pending	3-5 years	TBD	USEPA, DNER
3. Incentivize the development of practices that support sustainability.	Increased number of developers and builders participating in incentive programs or initiatives.	Developed criteria for sustainable development practices.	Lead: Estuario Implementing partners: Municipalities, DNER, builders and developers	Pending	3-5 years	TBD	USEPA, DNER, developers

Regulatory and Policy Requirements

The outputs from this action will rely on the quality and validity of the vulnerability assessment to inform regulatory and policy requirements.

References

Almodóvar Santana, Y., Santos-Flores, C., and Martínez, G. 2023. Factors Associated with an Algae Bloom In a Tropical Estuarine Lagoon: The Case of the San José Lagoon in Puerto Rico. University of Puerto Rico Mayagüez.

Díaz, E., Terando, A., Gould, W., Bowden, J., Chardón, P., Jury, M., Meléndez, M., and Morell, J. 2022. Working Group 1: Geophysical and Chemical Scientific Knowledge. State of the Climate Report. Puerto Rico Climate Change Council. Díaz, E., Gonzalez, M., and Terando, A. [Eds.]

Estuario. 2025. Multijurisdictional Risk Mitigation Plan. Risk Assessment – Natural Events.

Keellings, D., and Hernández Ayala, J. J. 2019. Extreme rainfall associated with Hurricane Maria over Puerto Rico and its connections to climate variability and change. Geophysical Research Letters, 46, 2964–2973. https://doi.org/10.1029/2019GL082077.

Resilience - Based Estuarine System Adaptation Management

Baseline

Adaptation to extreme weather events and environmental stressors demands a comprehensive, integrated, and resilience-centered management approach. Resilience, defined as the system's capacity to absorb disturbances while maintaining essential functions, is necessary given the estuary's complex ecological and social interactions (Resetar et al., 2020). Effective adaptation strategies require embracing the dynamic and adaptive nature of social-ecological systems, where ecological processes and human activities are deeply interconnected and influence one another (Resetar et al., 2020).

In 2015, Estuario undertook an effort to develop a plan for adapting to the foreseen effects of changes in environmental stressors. This process identified six stressors: warmer summer months, warmer water temperatures, more frequent droughts, more intense rainfall, sea level rise, and carbon dioxide effects including ocean acidification (Bauzá-Ortega, 2015). These stressors affect stormwater and wastewater management in urban areas; increase pollutants and pathogens; erode riverbanks, streambeds, and coastlines; increase flooding; cause more extreme weather events; and impact critical habitats and species (Bauzá-Ortega, 2015).

To effectively implement adaptation strategies, adaptive management is key. Adaptive management forms the foundation of resilience-based estuarine management and integrates ongoing monitoring, assessment, and stakeholder participation to refine management strategies in response to changing conditions and emerging knowledge (Resetar et al., 2020). Given the uncertainties in extreme weather events, environmental stressors, and ecosystem responses, adaptive management offers a flexible framework to navigate complex feedback and nonlinear dynamics characteristic of estuarine systems (Resetar et al., 2020).

Ecological restoration and conservation are critical components of this integrated management. Restoration efforts targeting degraded habitats within the estuary and adjacent areas enhance natural buffers against storms and sea level rise, supporting biodiversity and ecosystem services (Carrubba et al., 2022; Committee of Experts and Advisors on Climate Change [CEACC], 2024).

Community engagement is integral to resilience-based management. Engagement through participatory processes fosters local stewardship, ensures that adaptation strategies are contextually appropriate, and builds social capital necessary for collective action (Centeno-Torres et al., 2022). Inclusive planning empowers communities to develop adaptive capacities, fostering resilience against floods, storms, and rising sea levels (Centeno-Torres et al., 2022). Integrated estuarine management also requires coordination across sectors and jurisdictions to address interconnected threats such as pollution, habitat fragmentation, and unsustainable land use (Díaz et al., 2022; Resetar et al., 2020).

Leveraging innovative technologies such as remote sensing, environmental DNA monitoring, and predictive modeling, provides critical insights for real-time management and anticipatory adaptation (Díaz et al., 2022). These tools support early warning, risk mapping, and evaluation of management effectiveness, contributing to proactive rather than reactive management strategies.

Integrated, resilience-based adaptation management for the SJBE system must bring together ecological restoration, community participation, scientific innovation, and cross-sector collaboration. These combined

efforts will enhance the system's capacity to withstand extreme weather events, recover effectively from disturbances, and ultimately thrive amid increasing pressures.

Objectives

- Develop integrated resilience-based management practices for estuarine system adaptation.
- Support community preparedness and recovery to extreme weather events.
- Optimize infrastructure to effectively manage extreme weather events.

Actions

GI-02 Create a Pilot Project for Reversing the channelization by concrete of a segment of a river, creek, or freshwater tributary within the SJBE.

Activities

Activity	Performance Measures	Milestones	Responsible Stakeholder(s) and Partner(s)	Status	Timeframe	Estimated Costs	Potential Funding Sources
1. Develop an inventory of the channelized rivers, creeks, and tributaries in SJBE.	Inventory created based on the extension and size of the waterbody including the channelizing characteristics such as completely cased in concrete, concrete banks only, and natural shorelines.	Identified, characterized, and mapped rivers, creeks, and tributaries.	Lead: Estuario Implementing partners: USACE, DNER, municipalities, Conservation Trust, private conservation groups	Pending	0-2 years	TBD	USEPA, DNER
2. Categorize channelized rivers, creeks, and tributaries in SJBE and rank based on needs.	Determine needs for inventory, including conservation, maintenance, flood control, mitigation, and other intervention.	Identified and prioritized needs.	Lead: Estuario Implementing partners: USACE, DNER, municipalities, Conservation Trust, private conservation groups	Pending	0-2 years	TBD	USEPA, DNER
3. Develop a project to revert the channelization of the Juan Méndez Creek.	Remove loose parts of the concrete canal walls and replace with innovative use of the natural infrastructure of its watershed.	Completed the project.	Lead: Estuario Implementing partners: USACE, DNER, municipalities, Conservation Trust, private conservation groups	Pending	3-5 years	TBD	USEPA, DNER

Regulatory and Policy Needs

There are no regulatory and policy needs for the pilot project. However, modifications may be needed to local development codes and ordinances to encourage changes for other channelized waterbodies.

**NEW - 1* Assess vulnerabilities and implement adaptation management practices to become resilient .*

Activities

Activity	Performance Measures	Milestones	Responsible Stakeholder(s) and Partner(s)	Status	Timeframe	Estimated Costs	Potential Funding Sources
1. Evaluate regional risk assessment results and prepare a vulnerability analysis to guide estuarine management actions for identified hazards.	Evaluate areas vulnerable to identified hazards.	Completed vulnerability assessment and evaluated specific vulnerability hazards.	Lead: Estuario Implementing partners: Municipalities, DNER, FEMA, NOAA, USACE	Pending	0-2 years	TBD	DNER, FEMA, USACE
2. Recommend adaptation management practices for each identified hazard.	Identify adaptation action(s) for identified hazards	Selected adaptation actions for vulnerable areas.	Lead: Municipalities Implementing partners: Estuario, DNER, FEMA, NOAA, USACE	Pending	3-5 years	TBD	DNER, FEMA, USACE
3. Implement selected adaptation actions in areas vulnerable to identified hazards.	Implement adaptation action(s) in vulnerable areas.	Implemented adaptation actions.	Lead: Municipalities Implementing partners: Estuario, DNER, FEMA, NOAA, USACE	Pending	5+ years	TBD	DNER, FEMA, USACE

Regulatory and Policy Requirements

This action will require cooperation from municipalities to provide the infrastructure data and prepare models to protect public infrastructure and safety of private citizens and first responders and other emergency personnel.

**NEW - 2* Create an Adaptive Management Steering Group to be responsive and forward - looking .*

Activities

Activity	Performance Measures	Milestones	Responsible Stakeholder(s) and Partner(s)	Status	Timeframe	Estimated Costs	Potential Funding Sources
1. Create an Adaptive Management Steering Group.	Review data, reports, and models on a quarterly basis.	Published annual report.	Lead: Estuario Implementing partners: municipalities, PRASA, community leaders and academia.	Pending	0-2 years	TBD	USEPA, FEMA

Activity	Performance Measures	Milestones	Responsible Stakeholder(s) and Partner(s)	Status	Timeframe	Estimated Costs	Potential Funding Sources
2. Provide a repository for weather and sea level data in the SJBE.	Collect and manage estuarine data and data from municipal, state, and federal agencies; researchers; and conservation groups.	Created database and provided communication or direct links for stakeholders to update their data.	Lead: Estuario Implementing partners: DNER, USFWS, NOAA, FEMA, USACE, municipalities, academia	Pending	0-2 years	TBD	USEPA, DNER
3. Organize a multisector workshop for experts to identify adaptation strategies to extreme weather events and environmental stressors for the SJBE.	Identify stakeholders, engineers, policy makers and experts to workshop the adaptation strategies in SJBE, based on the data and models available.	Initiated workshop and set recommendation s.	Lead: Estuario Implementing partners: USACE, NMFS, USFWS, DNER, municipalities, Conservation Trust of Puerto Rico, academia	Pending	0-2 years	TBD	USEPA, DNER
4. Promote considerations for extreme weather events and environmental stressor adaptive strategies into planning for new infrastructure and land use development in the SJBE watershed.	Provide education and adaptive management strategies to local, state, and federal officials to incorporate into planning, policy, and regulatory actions.	Continued outreach and education to officials on adaptive management strategies to extreme weather events and environmental stressors in the SJBE watershed.	Lead: Planning Board of Puerto Rico Implementing partners: Estuario, USACE, NMFS, USFWS, DNER, municipalities, Conservation Trust of Puerto Rico, academia	Pending	3-5 years	TBD	USEPA, DNER

Regulatory and Policy Requirements

New or modified legislation may be needed to change the required level of service to promote more integrated water management.

***NEW-3* Support resilience -based water management systems to help reduce stress on the SJBE during extreme weather events.**

Activities

Activity	Performance Measures	Milestones	Responsible Stakeholder(s) and Partner(s)	Status	Timeframe	Estimated Costs	Potential Funding Sources
1. Review current practices in the SJBE watershed to identify areas for improvement.	Identify gaps or weaknesses in current practices.	Developed recommendations for improving current practices.	Lead: Estuario Implementing partners: DNER, PRASA, municipalities, scientific community	Pending	0-2 years	TBD	USEPA, DNER, PRASA

Activity	Performance Measures	Milestones	Responsible Stakeholder(s) and Partner(s)	Status	Timeframe	Estimated Costs	Potential Funding Sources
2. Model and design stormwater retention/ detention in upstream areas to reduce downstream flooding.	Create design plans for proper implementation.	Compiled existing data in the study area.	Lead: Estuario Implementing partners: DNER, PRASA, municipalities, scientific community	Pending	3-5 years	TBD	USEPA, DNER, PRASA
3. Develop management guidelines for urban rivers, creeks, and freshwater tributaries.	Formulate guidelines.	Coordinated with stakeholders to develop guidelines.	Lead: Estuario Implementing partners: DNER, PRASA, municipalities, scientific community	Pending	3-5 years	TBD	USEPA, DNER, PRASA
4. Promote the adaptation of integrated water management solutions.	Increase participation in dialogue around adaptation of management solutions.	Established a monitoring framework to evaluate impact of promotional efforts.	Lead: Estuario Implementing partners: DNER, PRASA, municipalities, scientific community	Pending	0-2 years	TBD	USEPA, DNER, PRASA
5. Use field data for reconstruction and revitalization projects.	Increase participation in dialogue around data driven decision making in reconstruction and revitalization.	Established a monitoring framework to evaluate impact of promotional efforts.	Lead: Estuario Implementing partners: DNER, PRASA, municipalities, scientific community	Pending	0-2 years	TBD	USEPA, DNER, PRASA

Regulatory and Policy Requirements

New or modified legislation may be needed to change the required level of service to promote more integrated water management.

References

Bauzá-Ortega, J. 2015. San Juan Bay Estuary Climate Change Adaptation Plan. San Juan, PR: San Juan Bay Estuary Program.

Carrubba, L., Burgos Caraballo, S., Engman, A.C., Galindo Estronza, A.M., Gutiérrez-Fonseca, P.E., Llerandi-Román, I., Pérez Reyes, O., Wagner Vega, K.M., Silander, S., Colón, R., Soler-Figueroa, B.M., Grafals, R., Torres-Pérez, J.L., García-Sais, J.R., Meléndez, M., Zayas-Santiago, C., Murry, B., Colón-Merced, R., Lilyestrom, C., Antoun, H. 2022. Working Group 2: Ecology and Biodiversity. State of the Climate Report. Puerto Rico Climate Change Council. Carrubba, L., Díaz, E., Marrero, V., Gonzalez, M., Leinberger, A., Rodríguez, J.L. [Eds.]

CEACC. 2024. Draft Climate Change Mitigation, Adaptation, and Resilience Plan for Puerto Rico. Government of Puerto Rico.

Centeno-Torres, D., Villerrael, S.I., Cintrón, I., Ortiz Colón, A., Bauzá, J., Ramírez-Durand, L., Morales-Muñoz, B., and Gaztambide-Arandes, S. 2022. Working Group 4: Communications and Outreach. State of the Climate Report. Puerto Rico Climate Change Council. Díaz, E., Marrero, V., Gonzalez, M., Falcón, M. [Eds.]

Díaz, E., Terando, A., Gould, W., Bowden, J., Chardón, P., Jury, M., Meléndez, M., and Morell, J. 2022. Working Group 1: Geophysical and Chemical Scientific Knowledge. State of the Climate Report. Puerto Rico Climate Change Council. Díaz, E., Gonzalez, M., and Terando, A. [Eds.]

Resetar, S.A., Tingstad, A., Mendelsohn, J., Marlier, M.E., Lachman, B.E., Anania, K., Garber, C., Adamson, D.M. 2020. Homeland Security Operational Analysis Center (HSOAC). Recovery Planning for Natural Resources and Parks in Puerto Rico. Natural and Cultural Resources Sector Report, Volume I.

Public Policy for Resilience - Based Estuarine System Readiness

Baseline

The aftermath of hurricane Maria revealed the urgent need to embed resilience-based estuarine readiness into planning and policy across all levels of government responsible for the SJBE. The hurricane exposed critical vulnerabilities in infrastructure, emergency response systems, and the estuarine ecosystem itself, uncovering significant gaps in preparedness and adaptive capacity. It is clear that the more resilient the SJBE, its infrastructure, and emergency response capabilities are, the faster, more efficient, and cost-effective the recovery will be for the entire watershed. Achieving such resilience demands transparent, honest policy-making that prioritizes long-term sustainability over short-term convenience.

Puerto Rico's coastal population exceeds 400,000 residents, many living in flood-prone and sea level rise-vulnerable areas, underscoring the imperative for policy frameworks that emphasize community safety and robust infrastructure (Díaz et al., 2022). Effective policies integrate weather and sea level data into urban planning, land use laws, and infrastructure development to reduce vulnerabilities and enhance adaptive capacity (Aponte-González et al., 2022; FEMA, 2018). Moreover, promoting green building standards and sustainable urban design not only strengthens resilience but also increases the continuity of essential services during extreme weather events (Aponte-González et al., 2022).

A landmark legislative effort addressing these challenges is Puerto Rico's Climate Change Mitigation, Adaptation, and Resilience Act—Law No. 33 of 2019. This law establishes a comprehensive framework to guide the island's public policy on mitigation, adaptation, and resilience by sectors, including the creation of a Committee of Experts tasked with developing actionable plans and measurable goals (2019). The law outlines specific courses of action spanning energy transition, ecosystem restoration, infrastructure improvements, and community engagement, with targets such as increasing renewable energy use, reducing greenhouse gas emissions, and enhancing coastal protections.

Despite the ambitious scope and detailed strategies established by Law No. 33, the Puerto Rican legislature has yet to act decisively to implement its provisions fully. The absence of legislative follow-through creates a critical policy gap, delaying the coordinated response necessary to strengthen the SJBE's resilience. Without the law's full activation and enforcement, the island risks continuing vulnerabilities and missed opportunities to safeguard its ecological and social systems against future extreme weather events, environmental stressors, and anthropogenic pressures.

Robust public policy must institutionalize risk management practices by requiring agencies responsible for critical infrastructure and services within the SJBE to adopt risk assessment tools and embed these considerations into their operational frameworks (Aponte-González et al., 2022). Equally important is equipping management and staff with education and training on weather-related risks to strengthen operational readiness and maintain service continuity during emergencies (Aponte-González et al., 2022).

Public engagement remains a cornerstone of effective policy. Law No. 33 emphasizes community consultation and participation, recognizing that inclusive decision-making processes involving local communities, scientists, and civil society organizations lead to more effective, equitable, and sustainable adaptation strategies (Centeno-Torres et al., 2022; Díaz et al., 2022). Transparent communication and inclusive governance help build trust and social license for adaptation initiatives, which are essential for their success.

Given the multijurisdictional nature of the SJBE, policy frameworks must facilitate coordination among municipal, regional, and federal agencies, alongside non-governmental and academic partners (CEACC, 2024). Cross-sector collaboration allows for comprehensive, coherent approaches that address the estuary's complex ecological, infrastructural, and socio-economic vulnerabilities.

Financing mechanisms embedded within policy are vital to incentivize and sustain resilience-building efforts. Innovative funding strategies—such as public-private partnerships, environmental impact bonds, and dedicated resilience funds—must be developed and expanded to support restoration, infrastructure modernization, and community preparedness (Resetar et al., 2020). Stable, long-term financing reduces reliance on costly reactive disaster responses and fosters proactive resilience.

Finally, adaptive governance models are critical for managing evolving and uncertain risks associated with extreme weather events and human influences. Policies must support flexible, iterative frameworks that incorporate continuous monitoring, scientific advancements, and stakeholder feedback to adjust strategies over time (Resetar et al., 2020). This ensures governance remains responsive and effective amid changing conditions.

In sum, hurricane Maria's legacy offers a powerful lesson: only through honest, integrated, and resilience-focused public policy—fully embraced and enacted by Puerto Rico's legislature—can the SJBE and its communities be prepared to meet the mounting challenges of extreme weather events and anthropogenic pressures. Effective policy must institutionalize the use of updated, high-resolution data sources and enhanced hazard models to guide land use planning, infrastructure development, and emergency preparedness. By incorporating records of recent flood events and scenarios of intensified hurricane impacts, such policies ensure alignment with evolving risk realities. A data-driven approach will not only protect lives and livelihoods but also secure the ecological and economic future of the basin.

Objectives

- Strengthen public policy that supports readiness practices and integrated and resilience-based management of the estuarine system.

Actions

***NEW - 1* Develop policy guidelines for extreme weather resilient estuarine management.**

Activities

Activity	Performance Measures	Milestones	Responsible Stakeholder(s) and Partner(s)	Status	Timeframe	Estimated Costs	Potential Funding Sources
1. Identify extreme weather -related impacts affecting the estuary.	Identify vulnerable species, habitats, and communities within the SJBE.	Identified extreme weather -related impacts within the SJBE.	Leads: Estuario, DNER Implementing partners: Municipalities, scientific community	Pending	0-2 years	TBD	USEPA, DNER

Activity	Performance Measures	Milestones	Responsible Stakeholder(s) and Partner(s)	Status	Timeframe	Estimated Costs	Potential Funding Sources
2. Conduct a needs assessment on current policy gaps.	Use existing data and research.	Collaborated with stakeholders to identify policy effectiveness as well as gaps.	Lead: Estuario Implementing partners: DNER, municipalities, scientific community	Pending	0-2 years	TBD	USEPA, DNER
3. Develop guidelines that outline strategies for extreme weather -resilient estuarine management.	Make guidelines accessible to stakeholders, including community partners.	Drafted guidelines that encompass diverse strategies to extreme weather- related risks.	Leads: Estuario, Planning Board of Puerto Rico Implementing partners: DNER, municipalities, scientific community	Pending	3-5 years	TBD	USEPA, DNER
4. Establish a framework for implementing policy guidelines.	Identify necessary resources for successful implementation.	Finalized implementation framework.	Leads: Estuario, Planning Board of Puerto Rico Implementing partners: DNER, municipalities, scientific community	Pending	3-5 years	TBD	USEPA, DNER

Regulatory and Policy Requirements

None.

***NEW-2* Evaluate how proposed and existing policies affect communities in the sjbe vulnerable to extreme weather events.**

Activities

Activity	Performance Measures	Milestones	Responsible Stakeholder(s) and Partner(s)	Status	Timeframe	Estimated Costs	Potential Funding Sources
1. Identify vulnerable communities in the SJBE watershed.	Analyze community data to identify vulnerable communities.	Determined vulnerable communities.	Lead: Estuario Implementing partners: Municipalities, DNER	Pending	0-2 years	TBD	USEPA
2. Review existing and proposed policies and conduct an impact assessment.	Develop a framework to assess impacts.	Completed impact assessment.	Lead: Estuario Implementing partners: Municipalities, DNER	Pending	0-2 years	TBD	USEPA
3. Engage with community stakeholders to gather insight into how policies are perceived and experienced.	Increase communication and engagement with stakeholders.	Collected feedback from community stakeholders.	Lead: Estuario Implementing partners: Municipalities, DNER	Pending	0-2 years	TBD	USEPA

Activity	Performance Measures	Milestones	Responsible Stakeholder(s) and Partner(s)	Status	Timeframe	Estimated Costs	Potential Funding Sources
4. Develop recommendations for policymakers to implement regarding existing and proposed policies.	Establish clear guidelines for implementing recommendations.	Developed recommendations.	Lead: Estuario Implementing partners: Municipalities, DNER	Pending	3-5 years	TBD	USEPA

Regulatory and Policy Requirements

The results of this evaluation will inform the regulatory and policy requirements needed to provide increased resilience for vulnerable communities in the watershed.

References

Aponte-González, F., Rodríguez-Rivera, L.E., Crespo Acevedo, W., Moyano Flores, R., Quiñones, H., Rodríguez, J.L., Leinberger, A., Santos-Corrada, M., Marrero, V., Rivera-Collazo, I., Ezcurra, P., Parés-Ramos, I.K., Avilés, K.R., Gould, W., Álvarez-Berrios, N., Torres, M., and Rodriguez-Morales, H.K. 2022. Working Group 3: Society and Economy. State of the Climate Report. Puerto Rico Climate Change Council. Aponte-González, F., Díaz, E., Rodríguez-Morales, H.K., Rodriguez, J.L., Marrero, V., Leinberger, A., Crespo Acevedo, W.I., and Gonzalez, M. [Eds.]

CEACC. 2024. Draft Climate Change Mitigation, Adaptation, and Resilience Plan for Puerto Rico. Government of Puerto Rico.

Centeno-Torres, D., Villerrael, S.I., Cintrón, I., Ortiz Colón, A., Bauzá, J., Ramírez-Durand, L., Morales-Muñoz, B., and Gaztambide-Arandes, S. 2022. Working Group 4: Communications and Outreach. State of the Climate Report. Puerto Rico Climate Change Council. Díaz, E., Marrero, V., Gonzalez, M., Falcón, M. [Eds.]

Díaz, E., Terando, A., Gould, W., Bowden, J., Chardón, P., Jury, M., Meléndez, M., and Morell, J. 2022. Working Group 1: Geophysical and Chemical Scientific Knowledge. State of the Climate Report. Puerto Rico Climate Change Council. Díaz, E., Gonzalez, M., and Terando, A. [Eds.]

FEMA. 2018. Mitigation Assessment Team Report: Hurricanes Irma and Maria in Puerto Rico. Building Performance, Observations, Recommendations, and Technical Guidance. October 2018.

Puerto Rico Legislature. 2019. *Law No. 33 of May 22, 2019: Puerto Rico Climate Change Mitigation, Adaptation and Resilience Act*. Government of Puerto Rico.

Resetar, S.A., Tingstad, A., Mendelsohn, J., Marlier, M.E., Lachman, B.E., Anania, K., Garber, C., Adamson, D.M. 2020. Homeland Security Operational Analysis Center (HSOAC). Recovery Planning for Natural Resources and Parks in Puerto Rico. Natural and Cultural Resources Sector Report, Volume I.

Resetar, S.A., Tingstad, A., Mendelsohn, J., Marlier, M.E., Lachman, B.E., Anania, K., Garber, C., Adamson, D.M. 2020. Homeland Security Operational Analysis Center (HSOAC). Recovery Planning for Natural Resources and Parks in Puerto Rico. Natural and Cultural Resources Sector Report, Volume II.