Meeting the Water Needs of the People of Puerto Rico While Safeguarding the Freshwater Ecosystems

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Abstract

The interconnected nature of the geography, history, culture and political system of Puerto Rico has created a water management crisis on the island. Addressing this crisis poses a wicked problem that involves multiple stakeholders and regulatory bodies and thus, cannot be easily solved. The water management crisis in Puerto Rico is currently exacerbated by climate change through instances of prolonged drought, variable precipitation, and increased frequency and intensity of storms, and this trend is expected to continue over the next several decades and beyond. Moreover, sea level rise (SLR) threatens to completely displace coastal communities and cause ecosystems to migrate inland or become altogether eliminated. This case study seeks to ascertain the water management crisis in Puerto Rico in a systems thinking perspective with a participatory modeling exercise which examines the problem through the lenses of the invested stakeholders. In this way, the stocks and flows within the human and environmental systems were conceptually mapped, the hazards and vulnerabilities were identified and weighed, and a range of likely futures that utilizes the latest in data science were postulated. After a thorough review of these variables, the participatory approach to interventions was utilized to develop a range of viable options that could move the trajectory of the system toward a desirable future. These interventions were subsequently linked to the Sustainable Development Goals proposed by the United Nations, and recommendations were developed accordingly.

Table of Contents

Figures

Tables

1 Introduction

1.1 Puerto Rico and Water

Water is an invaluable resource across the globe to both humans and ecosystems. In the U.S. territory of Puerto Rico specifically, the management of water resources is necessary for the survival of local populations. The unique combination of climate, topography, and geography on the island translates to high rates of evapotranspiration, rapid run-off, and low residence time of water across the island. The steep mountain regions of Puerto Rico, combined with the shallow karst geology, causes the water to run easily downhill toward the ocean and prevents much of the water from being stored in the soil layer respectively (Heartsill-Scalley, 2012). Additionally, there exists a wide range of climate zones across a small land area leading to drastically different needs across the island. The north and center of the island are more prone to rain due to the mountains at the center of the island and strong prevailing wind (Larsen, 2000). Conversely, the southern portion of the island becomes gradually more arid as one travels south. For humans to thrive in this southern region, water must be transported from the north to the south.

The prevailing methods of water collection on the island are surface water capture, through reservoirs and spring catchments, and groundwater pumping (DNRA, 2016b). The topography of the island results in few natural lakes; therefore, many mountainous valleys were dammed to facilitate water capture and redirection. Water use on the island has already begun to outpace the supply (Larsen, 2000). A large population of roughly 3.6 million humans distributed across the whole of the island equates to a large domestic stake in water management (United Nations, 2019). Water used for domestic purposes other than consumption, such as waste transport and cleaning, is not considered potable and is removed by sewage systems.

There is also a large demand for managed water for agricultural use. As the topography is more suitable to traditional crops, the southern portion of the island is to a large degree used for agriculture, including livestock. To support such use in the more arid sections of the island, water must be transferred for crop irrigation and livestock needs. Water used for cropland, generally returned to the system through evaporation, evapotranspiration and percolation into the groundwater, is a source of contamination for Puerto Rico's freshwater sources. Industry on the island also consumes a significant portion of the freshwater. This water is used for a multitude of purposes, from chemical synthesis to cooling. Irrespective of the use, the water that comes out of the process is generally considered non-potable and is removed through deep-well injection or domestic sewage systems following self-regulated pretreatment (Kanaujiya, Pual, Sinharoy, & Pakshirajan, 2019).

Other stakeholders in the freshwater system of Puerto Rico include freshwater ecosystems, individuals whose livelihoods depend on these ecosystems, government water managers, and recreational users. The freshwater ecosystems in Puerto Rico are highly dependent on the quantity and quality of the freshwater, but they cannot speak at stakeholder meetings or petition for better access, rather, non-governmental organizations must speak on their behalf. In addition to ecosystems, there exist numerous individuals who are reliant on freshwater ecosystems, such as fisheries. Finally, due to their ability to manage freshwater on the island, federal and state agencies are important stakeholders.

1.2 Challenges to Water Management in Puerto Rico

Management of freshwater resources in Puerto Rico faces many challenges. Primarily, the aging infrastructure combined with the impacts of severe storms on infrastructure has gradually created a leakage crisis on the island. In 2015, roughly 60% of all freshwater transfer in Puerto Rico was lost due to leakages (48%), illegal water use (10%), and metering/data errors (PRASA, 2015). This number rose in 2013 to 57.4% by PRASA estimates. Additionally, reports of water management facilities showed 53% of facilities had leaks ranging from minor to severe (Gould et al., 2018). Structural faults also threaten the ability of water managers to effectively control flows. Sedimentation, a process that results from natural stream flows and is increased during storm events, reduced the capacity of reservoirs due to sediments entering and settling in the bottom of reservoirs. Finally, severe storms, which occur more frequently in the tropics, put freshwater and wastewater transfer facilities at risk. Reliance of these systems on electrical services, which are frequently lost during severe storms, can lead to a lapse in water services which can be detrimental to local communities. These water management challenges have already caused suffering for local communities. Many locals lack sufficient clean drinking water, and often resort to walking miles to the nearest stream to fill buckets (Velazquez, 2019). This is especially a burden on the elderly and sick.

1.3 Conflicts with Freshwater Ecosystems

The freshwater ecosystems of Puerto Rico must also be considered when managing freshwater therein. Reservoir constructions along major rivers have led to a marked decrease in many species of river-dwelling fish. An important endemic fish, the goby, has become a marker for this loss due to segmentation of habitats (Cooney et al., 2013). The ability of this fish to traverse small barriers expands the gradient of segmentation caused by reservoirs. Other fish which are unable to cross the barriers put in place by reservoirs have seen up to a 95% decrease in interior areas of Puerto Rico (Collazo et al., 2018). Contamination also has a marked impact on freshwater ecosystems. Wastewater processing, leakage, and deep-well injection can all pollute freshwater resources, removing them from both human and ecosystem usage, while overconsumption can drastically limit the ability of freshwater and diadromous species to function. Personal usage of water is often difficult to quantify. This difficulty augmented given the current lack of reporting on household usage and household size. Additionally, finding an area of water usage that closely matches the climate, topography, and infrastructure challenges of the focus region for comparison becomes a great challenge. Therefore, it is difficult to determine the extent to which overconsumption contributes to the water management challenges in Puerto Rico. In the following sections, this report focuses on the more apparent conflicts between human and ecosystem usage of water.

1.4 Area of Focus

To better understand the impacts of human water usage and water management on freshwater ecosystems, a single watershed was chosen to represent the whole. The Rio Grande de Arecibo Watershed encompasses a wide land area near the middle portion of the island (Figure 1). The headwaters begin in the mountain ranges of Adjuntas and run into the Atlantic in the north. The watershed also includes the southern region of the island including Lajas and other cities. This area was chosen due to its special relationship with the city of San Juan, as well as the half-dozen municipalities that boarder the northern coast of the island. Trans-basin water transfer, from the Arecibo basin to the San Juan basin, accounts for upwards of 300,000 m^3 per day. This transferred water is primarily used for public consumption in San Juan. The transfer of water south for farming and east for public consumption, water usage for industry, and numerous

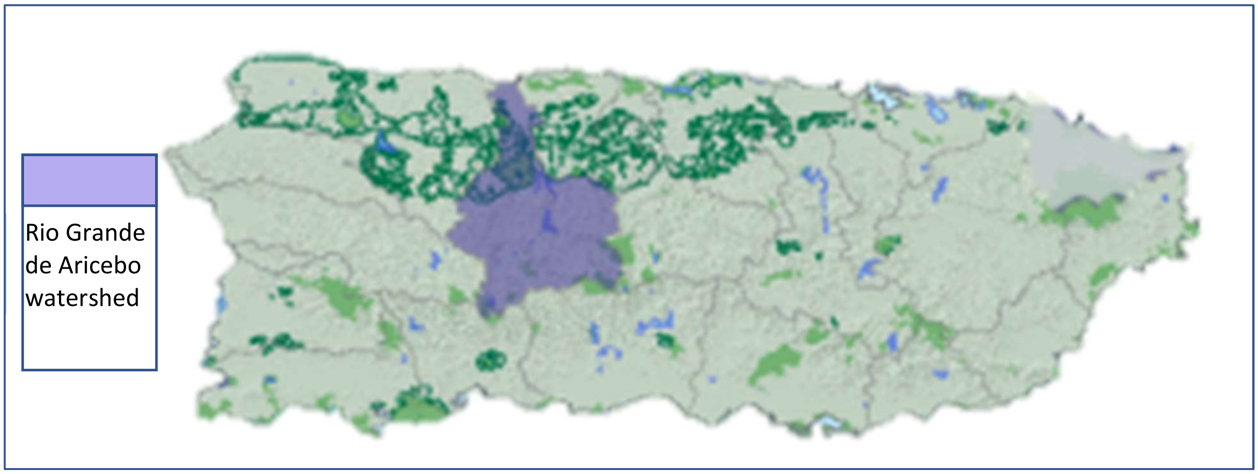


Figure 1. Rio Grande de Aricebo watershed

wetlands and river ecosystems in the region make the Rio Grande de Arecibo Watershed a representative subset of the whole of the island.

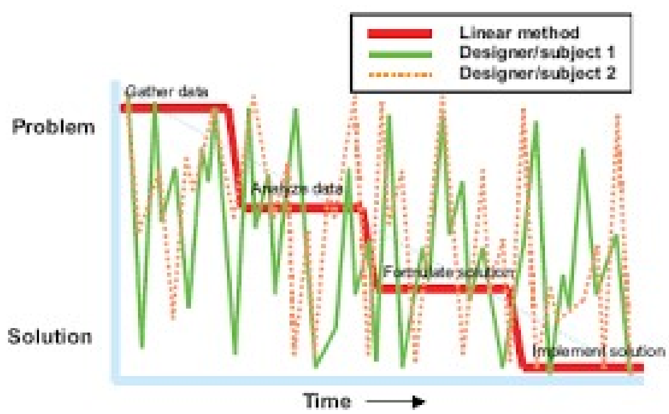
1.5 Wicked Problems

Wicked problems, as opposed to tame or ordinary problems, are fundamental planning issues (Rittel and Webber, 1973). This kind of problem can stem from multiple sources, but very often can be reduced to one specific cause – dynamic resource allocation. Because these societal planning issues have multiple perspectives, there is a broad spectrum of possible solutions. Because of this multiplicity of perspectives, even the formulation of the problem is a challenge. Each stakeholder, an individual with a stake in the outcome of the wicked problem, may see the issue differently. Moreover, those possible solutions might be preferable to one stakeholder or another. Due to their mercurial nature, to seek a possible solution to a wicked problem, one must understand the nature of the system in which the wicked problem exists (Rittel and Weber, 1973). Inherently, wicked problems have these properties: they cannot be solved; there exists no stopping rule that signifies when the job is done; more can always be done to improve the system; and every wicked problem is different from another. Because the number of variables in any given system are indefinite, there will always be one differentiating variable between two wicked problems (Rittel and Weber, 1973). The result of classifying a planning challenge as a wicked problem is that those who seek to deal with wicked problems have no right to be wrong (Rittel and Webber, 1973). As opposed to the scientific approach to problem solving which proposes a hypothesis, which may be refuted at a later date, solutions to wicked problems must improve some characteristic of the system, and planners become liable for the outcomes of their proposed solutions.

1.6 Collaborative Problem Solving

When faced with a wicked problem, planners must decide how to tackle the issue. There are a variety of approaches to interventions in a system, including authoritative, competitive, and collaborative (Roberts, 2000). Authoritative interventions put the responsibility for solving problems in the hands of only a few people. Though this methodology may reduce the decision space, allowing for more timely consideration and implementation of options, one major pitfall of this approach is that not all perspectives are considered. The competitive approach to interventions pits opposing points of view against one another so that the best option can be chosen. However, a major downfall of this approach is that knowledge sharing between invested stakeholders and decision makers is discouraged and even nonexistent in those attempting to achieve a competitive advantage. The collaborative approach to decision making, also called the participatory approach, involves engaging all stakeholders to find the best possible option for interventions. Utilizing this methodology, the perspectives of all stakeholders can be heard, weighed, and incorporated into potential interventions.

Traditional approaches to interventions, including both authoritative and competitive, operate in a "waterfall" fashion, which seeks to reconcile a problem and its solution linearly (Figure 2). Through a series of predetermined steps, stakeholders seek to gather data, analyze data, formulate a solution, and then implement the proposed solution. Unlike traditional approaches to interventions, the participatory approach is constantly evolving and adapting to new hazards and new vulnerabilities that enter into the system (Figure 2). In this way, the dynamic interplay between the problem and solution continues over time, even after interventions have been applied. This framework takes into account the understanding that "solutions" may create more challenges in the system, and as such, there must be continuous monitoring as well as reevaluation of potential hazards and vulnerabilities. After interventions are made, the system is then monitored and reassessed to note whether progress is being adequately made toward the expected desirable future. If new problems arise in the system, new interventions can be put into place that can redirect trajectories toward the desirable future.



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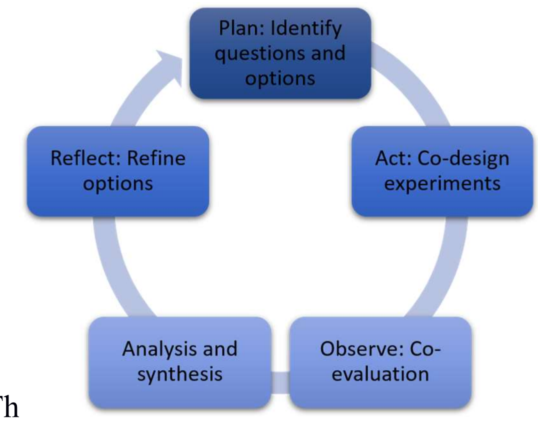

Figure 2. The linear problem-solving process (left) compared to the participatory problem-solving process (right).

This case study was modeled through the lens of systems thinking and utilized the participatory approach to problem solving. In preparation for field research in Puerto Rico, a team of stakeholder representatives was assembled in a role-playing exercise. Each member was tasked with researching a prospective stakeholder on the issue of water management in Puerto Rico. The stakeholders included consumptive users of the freshwater including domestic, industrial, and agricultural sectors, as well as non-consumptive stakeholders including fisheries, wetland ecosystems, and federal and state water managers. A round-table discussion was then held with each member taking the role of the prospective stakeholder researched. Through the collaborative decision-making process outlined above, the stakeholder representatives agreed on a desired future and goal formulation – *meeting the water needs of the people of Puerto Rico while safeguarding the freshwater ecosystems* – which became the unifying framework in which this study was developed.

2 The Wicked Problem

2.1 No Ordinary Challenge

As described in Section 1.5, almost all dynamic resource allocation issues become wicked problems. Using Rittel and Webber's (1973) list of ten properties of wicked problems, the goal of meeting the water needs of the people of Puerto Rico while also safeguarding the freshwater ecosystem meets the criteria for a wicked problem. As with any dynamic system, there is no point at which all issues can resolved. Drought, climate change, population explosions, and unforeseeable factors will continue to create problems for water managers. The diverse stakeholders also complicate management. Each stakeholder group has completing interests, and a solution that one deems optimal may not benefit another. For example, it would be in the interest of San Juan to capture more water and, using aqueducts, transfer more water to the city. However, this could negatively impact freshwater ecosystems by reducing the amount of water available. There exists a spectrum of possible responses to this situation. Even the way in which the challenge is framed can be altered by a particular stakeholder's perspective. To representatives of major cities, the problem might be that they lack access to enough freshwater to sustain the population. Conversely, representatives from non-governmental organizations concerned with freshwater ecosystems may focus on the problem of segmentation of habitats. Moreover, constant monitoring would be required to assess the outcomes of any solution implemented and to determine if additional interventions should be implemented. This combination of dilemmas, among other markers, confirms the wickedness of this dynamic resource allocation challenge.

2.2 Super-Wicked Issues

More so than wicked problems, super-wicked problems pose even greater challenges to planners. There are four additional properties that transform a wicked problem into a super-wicked problem (Levin et al., 2012). Firstly, time is a major factor in super-wicked problems and time is running out for water managers in Puerto Rico. The current trajectory of water use in Puerto Rico, projected into the future, is unsustainable. The failing infrastructure of the island coupled with projected increases in storm severity and decreases in water availability are all markers for a likely future disaster event. Water managers have a responsibility to address these issues before such disaster occurs. Secondly, the stakeholders in the system are all consumers of freshwater and thus impact freshwater availability. Thirdly, the lack of a cohesive central authority on water management and numerous unregulated, non-metered, and self-reported usage make tackling this challenge more complex. Fourthly, the current policy on water use in Puerto Rico irrationally discounts the future and diminishes the availability of future generations to access freshwater resources. Policies such as Q99, which allow river flows to be reduced to the lowest 1% of recorded flows from freshwater pulls, disregard the needs of freshwater ecosystems and rely on an immutable environment (Morris, 2008; DRNA, 2016b).

2.3 Modeling Wicked Problems

To aid in the understanding of systems and systems-of-systems, modeling is an important resource. Not only can models aid in the understanding of a system at the present, they are also instrumental in exploring future trajectories of the system as well as finding and testing points of intervention (Conklin, 2006). A general conceptual model can benefit a system researcher greatly; however, it cannot effectively assess changes to the system in the future. To take this step, stock-and-flow models can be used. At the core of any stock-and-flow model are stocks. Stocks represent discrete or continuous numbers of one specific item. Flows then increase or decrease the amount of a stock depending on inflow or outflow. The third component of this modeling system is variables. Variables are essential for conversion equations. They allow a modeler to, for example, translate the amount of people into freshwater usage using the variable that gives the volume of water used per person. Variables and links together describe the way two or more stocks interact with one another. Links, however, show the directional influence of variables on stocks and flows. Stock-and-flow models are invaluable tools for understanding systems and are especially useful for issues stemming from dynamic resource allocation.

2.4 Modeling Water in Puerto Rico

Water stocks and flows in Puerto Rico are complex. The numerous and often understudied or unreported reservoirs, catchments, and groundwater pumps make modeling the water system a challenge. Finding usage rates that represent all the freshwater being removed from ecosystems in Puerto Rico would be nearly impossible because of this. Additionally, attempting to divorce usage rates from the enormous leakage issue and looking at segmentation as it related to surface water capture further complicates a model. Finally, as with any model, declaring succinct beginning and end points is key to effective functioning. For this model (see Figure 3), inflow points were placed as rainfall and groundwater recharge. Rainfall is partly responsible for groundwater recharge, but the proportion of rainfall that becomes groundwater varies based on severity of rainfall, weather, and geographical conditions. Groundwater can also be recharged from many other sources. These two flows are

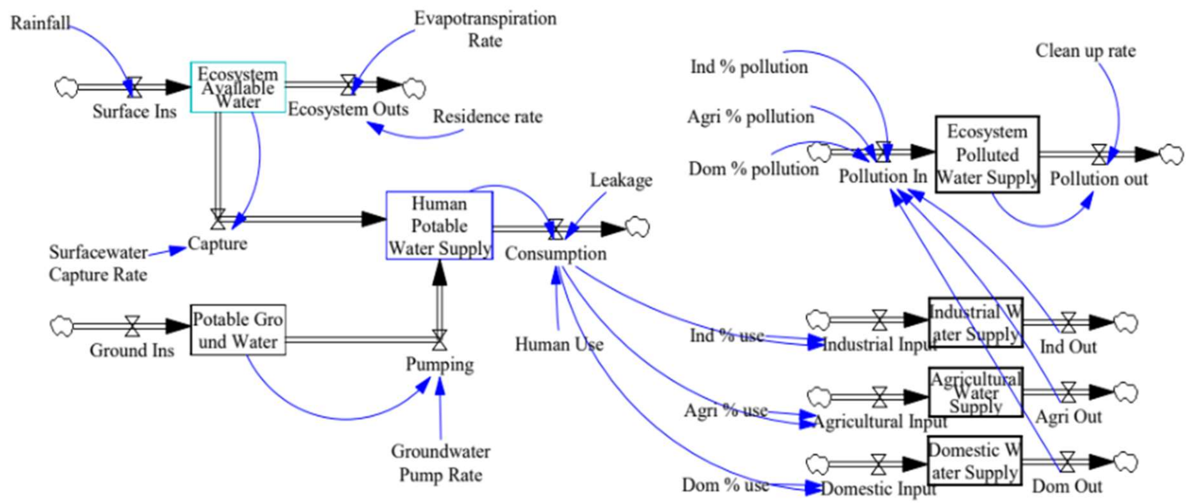

Figure 3: A stock-and-flow model depicting the transfer of freshwater in Puerto Rico. Water travels through the human system and output exists as waste.

extremely complex; however, abstracting them as variables which could be increased or decreased over time was necessary to focus the model on Puerto Rico. Rainfalls, in this model, then feed directly into the freshwater ecosystem. Water is then removed from the ecosystem into human freshwater via surface water capture in catchments and reservoirs. Groundwater also plays a major role in water management, so ground water pumping rates were included. Water removed from the human stock of freshwater then is separated into the various consuming stakeholders, such as; agriculture, industry, and domestic usage. Finally, water flows from those stakeholders into ecosystem pollution through various rates. Endpoints for this model are, for both ecosystem and polluted ecosystem water, outflows to the ocean. The conceptual waterflow model utilized in this case study which depicts the movement of water in Puerto Rico is shown in Figure 3.

3 Decision Making

3.1 Decision Space and Governance

Decision and policy makers are important players in the mitigation of wicked problems. They are able to make interventions to the current system in order to change its trajectory towards a more desirable future. For this case study, there were many decision makers involved; however, only those considered most beneficial to confront the challenge were selected as part of the participatory modeling exercise. Those selected include the government of Puerto Rico, the U.S. Federal government, applicable NGOs, local municipalities, industry, agriculture, and fisheries. Within each of these areas, there exists certain stakeholders whose perspective would greatly benefit this study (see Table 1). Each of these stakeholders have a voice in the future of Puerto Rico as well as an obligation to protect the health of the communities and ecosystems that rely on its freshwater systems.

3.2 Selection of Stakeholders

As noted in Section 1.6, a role-playing exercise was used during the process of gathering the details and looking into the wicked problem, which facilitated the understanding of the wicked problem and the system as a whole. With the acknowledgement that there are additional stakeholders involved, those chosen were found to have the greatest impact on Puerto Rico's overall water consumption and management. The seven groups included were Federal agencies, state agencies, industry production, fisheries or ecosystem dependent individuals, NGOs and wetland conservation, agriculture production, and domestic use (Table 1). Individual research was then done on the assigned stakeholders and the possible connections within them to immerse the role players. Stakeholder meetings were held to discuss priorities for water usage and how the flow of water (or lack of flow) affects their way of life. A compilation of all decision makers that were involved with these stakeholders was prepared and it was decided which decision makers would be most beneficial to addressing the problem characterized by the goal statement given in Section 1.6.

3.3 Governing Bodies

The primary governing body in Puerto Rico is the Federal government of the United States of America. A complex governance system is formed from this relationship because, as a territory of the U.S., Puerto Rico must adhere to oversight of the Federal government. Additionally, the U.S. has a stake in what happens inside of Puerto Rico. Of the federal agencies, a small number was identified as important for this study. These include the United States

Table 1: Stakeholders involved in the case study, how they currently utilize freshwater, and their decision-making authority.

Stakeholders	Level of governance	Water use	Decision making authority
Domestic Use	Non-governmental	Normal everyday use, Drinking water, personal hygiene, lawn care, lifecare buildings, Education buildings	Decide if they use more or less water per day.
Industrial Production	Commercial	Use for production, Bathrooms, Wash Stations	Can change the amount of water used per day as well as what type of water used. Can also decide how much sewage water there is.
Agriculture Production	Commercial	Water of land/ propagation, Mixing of Chemicals	Decide how much water is used on crops as well as what type of waste they produce.
NGO's/ Wetland Conservation	Non-governmental	Use for wetland and species that live there	Decides how they believe water should be treated and educates people about that.
State Agencies	Government	Protection of water, making sure water is meeting standards	Decide how clean the water is and where is goes throughout Puerto Rico as well as where it is stored.
Federal Agencies	Government	Overlooking the data of the state agencies to make sure regulations are being met	Have the oversight of what is happening and are a second check to the state.
Fishery/ Ecosystem dependent individuals	Commercial and Non-governmental	Protecting the fresh water, protecting species in the water,	Decide what water they use and what they believe is healthy enough for the environment.

Environmental Protection Agency (EPA), United States Fish and Wildlife Services (FWS), Natural Resources Conservation Service (NRCS), United States Department of Agriculture (USDA), Army Corps of Engineers, and a host of technical experts including those at the National Oceanic and Atmospheric Administration (NOAA). Each of these support aspects of the problem and therefore could be addressed by the recommendations that are an outcome of this case study.

The Puerto Rican territorial government is also a major decision and policy maker. This regional government regulates water flow and management on the island. Within the regional government, there are currently three main authorities that regulate freshwater consumption and wastewater management. The first is the Puerto Rico Aqueducts and Sewers Authority (PRASA). This agency is responsible for water quality, water management, and water supply in Puerto Rico (Acueductospr, 2019). PRASA is a government-owned corporation that serves 97% of Puerto Rico's population with water (Government Development Bank, 2018). The Puerto Rico Electric Power Authority (PREPA) is responsible for electricity generation, power distribution, and power transmission on the island (AEEPR, 2019). Like PRASA, PREPA is also government-owned and is responsible for the distribution of electricity across island. The last authority is the Puerto Rico Oversight, Management, and Economic Stability Act (PROMESA). This is an oversight board created during the Obama Presidency to help reduce the debt in Puerto Rico (Austin, 2016). This adds another layer of complexity to the system because funds must be approved by the board before they can be used. Because this board is primarily focused on fixing the debt issues within Puerto Rico, a large portion of the government's funds is allocated for other purposes.

3.4 Agriculture

Agriculture is the third largest user of freshwater behind domestic and industry consumption, at 2.1×10^5 m^3 per day as of 2010 (Molina-Rivera, 2015). Most agricultural land is located in the south of the island due to the flatter topography. Most irrigation water currently comes from reservoirs, including the Lago Caonillas in the Rio Grande de Arecibo watershed, Guajataca on the eastern side, and Toa Vaca, Guayabal, Carite, and Patillas reservoirs on the south coast (PRASA, 2015). Agriculture has been in decline for the past three decades, and Uriarte, Yackulic, Lim, and Arce-Nazario (2011) found that agricultural land use constituted less than 3% of Puerto Rico's area. Biotechnology dominates Puerto Rico's agriculture industry, and companies such as Monsanto, Dow Agro Sciences, Bayer Crop Science, and AgReliant Genetics are major agricultural stakeholders located within Puerto Rico (Santiago, Rivera, Pabon, & Garcia, 2016).

3.5 Industry

Industry uses the second largest amount of water in Puerto Rico, at 2.5 x 10^5 m^3 per day as of 2010 (Molina-Rivera, 2015). Pharmaceutical production is a major water consumer. This industry produces 10% of the pharmaceuticals for the United States (Alvarado-Seig, 2018). Pharmaceuticals comprise a large portion of Puerto Rico's industry, making them important stakeholders. Tourism is also an important economic activity in Puerto Rico, centered on the cities of San Juan and Dorado. Tourism is important to consider in the system because it can be a large determinant in population growth, which leads to an increase in both consumptive and non-consumptive water use. Their close proximity to the watershed system means that these commercial stakeholders rely on freshwater from Rio Grande de Arecibo watershed. The pharmaceutical industry uses the water pipeline that flows from Arecibo to San Juan to meet the water needs. Other areas pull from the other reservoir, Lago Dos Bocas, and the streams.

3.6 Domestic Water Usage

The largest portion of human-used water in Puerto Rico goes to domestic usage, at 9.1 x 10^5 m^3 per day as of 2010 (Molina-Rivera, 2015), including uses like drinking water, hygiene, toilets, laundry, watering of lawns, among other uses. In addition to consuming the most water, the public domain also has the greatest dependence on water availability. Local municipalities play an important role in responding to concerns of the people and in communicating these concerns to higher levels in the government. They act as the voice of the people and fight for what is needed as well as the water rights of Puerto Ricans. Another important group that advocates for local communities are NGOs. One NGO that is based in the Rio Grande De Arecibo is Caras Con Causa. This NGO is fighting for environmental needs and education in an attempt to transform the way in which young people connect to the environment and the consumption of freshwater sources. The NGO educates both elementary and secondary students regarding why water is important and ways to produce clean water. Caras Con Casa has also initiated a youth-led water monitoring database to further connect students to their environment and to provide citizen science reporting system within local communities. Currently, water quality data are only available for a few municipalities and the data are not sufficient to document the water quality in Puerto Rico. NGOs like Caras Con Casa are trying to make a change within Puerto Rico to help shift the perception of water and to help meet the water needs of the people of Puerto Rico.

4 Hazards

4.1 Definition of a Hazard

A hazard is an event that can cause a change in the system state that can lead to system degradation and/or a reduction of the system's capability to function. There are two types of hazards: natural hazards and anthropogenic hazards (Table 2). Natural hazards occur outside of human control while anthropogenic hazards are caused by human activity. Geo-hazards, such as landslides, and hydro-meteorological hazards, such as floods, storms, and droughts, are some of the main natural hazards that influence water management in Puerto Rico. Water management in Puerto Rico is also affected by human impacts such as modern climate change, land use changes, pollution, and leakage. Modern climate change is leading to an increase in sea level rise, temperature rise, changes in precipitation and evapotranspiration, droughts, floods and storm intensity. Land use changes such as river segmentation and agricultural development are impacts specifically detrimental to Puerto Rico’s freshwater ecosystem. In order to maintain a balance between water management and safeguarding the freshwater ecosystem, hazards need to be considered.

4.2 Natural Hazards

According to the U.S. Caribbean Fourth National Climate Assessment (Gould et al., 2018), since the 1950’s sea level has risen by an average of 2 mm/year on the coast of Puerto Rico and continues to rise. The projections of future sea level rise along the coast is split into three separate scenarios. These scenarios increase in intensity from intermediate-low, intermediate, and extreme. Projected sea level rise by 2050 shows an intermediate-low projection of 24 cm increase, intermediate projection of 37 cm increase, and an extreme projection of 84 cm increase.

Projected sea level rise by 2100 shows intermediate-low projection of 0.5 m, intermediate projection of 1.1 m, and an extreme projection of 3.1 m (Figure 4). As sea level rises, it creates an imbalance in freshwater ecosystems by allowing for saltwater intrusion.

Projections also show the likely increase in overall temperatures in Puerto Rico in the future (Gould et al., 2018). While temperatures have fluctuated over the years since the 1950's, there was an overall increase in 0.83°C from 1950-2018. There are two main scenarios proposed

Table 2: Natural and anthropogenic hazards, their effect on Puerto Rico, and the likelihood of current and future occurrence.

Hazard category	Type of hazard	Specific to Puerto Rico	Probability to negatively affect PR	Future Probability
Natural Hazards	Geohazards	Landslides	High	High
		Sedimentation	High	High
	Hydro-meteorological Hazards	Floods	High	High
		Droughts	Medium	High
		Storms	High	High
Anthropogenic Hazards	Modern climate change	Sea level rise	High	High
		Temperature rise	Medium	High
		Change in wet & dry season	Medium	High
		Storm intensity	High	High
	Land use change	River segmentation	Medium	High
		Agricultural development	Medium	High
	Leakage	Infrastructure damage	High	High

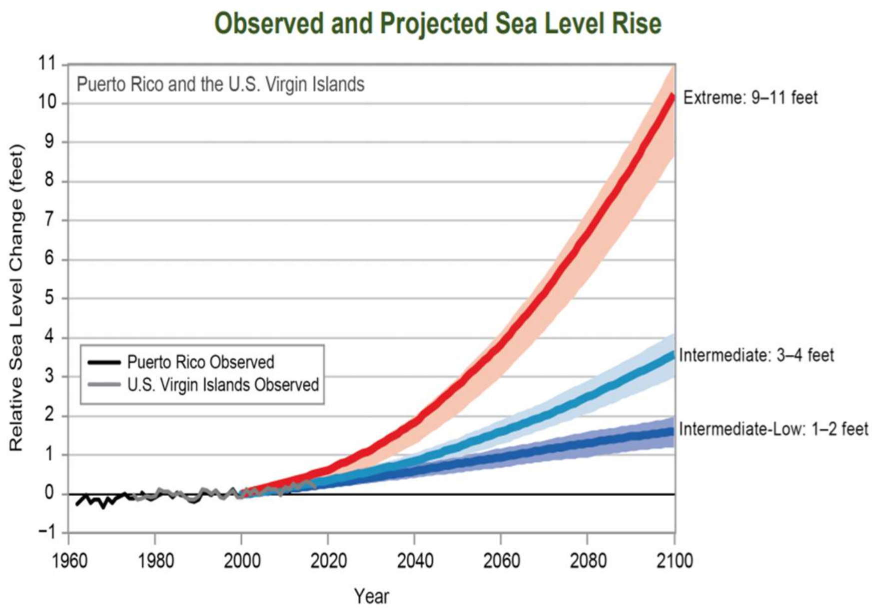

Figure 4: Observed sea level rise trends in Puerto Rico and the U.S. Virgin Islands reflect an increase in sea level of about 2.0 mm per year for the period 1962–2017 for Puerto Rico and for 1975–2017 for the U.S. Virgin Islands (Gould et al., 2018).

when temperature increase is projected for 2050 and 2100 (see Figure 5). The lower scenario explains the best-case scenario while the higher scenario explains the worst-case scenario. For the lower scenario, it is projected by 2050 that there will be at least a 1°C increase and that by 2100 there will be at least 1.1°C increase. Higher scenarios show that at least a 2.2°C increase by 2050 and temperatures can increase by about 5°C by 2100. The increase in temperature in the future will also play a role in the wet and dry season, while droughts become more intense.
It is projected that the wet season will likely become shorter with a decrease of 10% precipitation by the middle of the century (Gould et al., 2018). Although there will be an overall decrease in precipitation, the wet season will become more intense with tropical cyclones. This is extremely dangerous for the island of Puerto Rico because the steep topography and karst geology result in extreme flooding. In addition to the change in the duration and intensity of the wet season, the dry season will also change. As the temperatures increase and the precipitation declines, the dry seasons will become longer and more intense. Considering the water management problems Puerto Rico has now, drought will also take away more freshwater sources on the island.

One of the most concerning hazards that Puerto Rico faces is hurricanes. In 2017 Puerto Rico experienced devastating losses caused by Hurricanes Irma and Maria leaving billions of

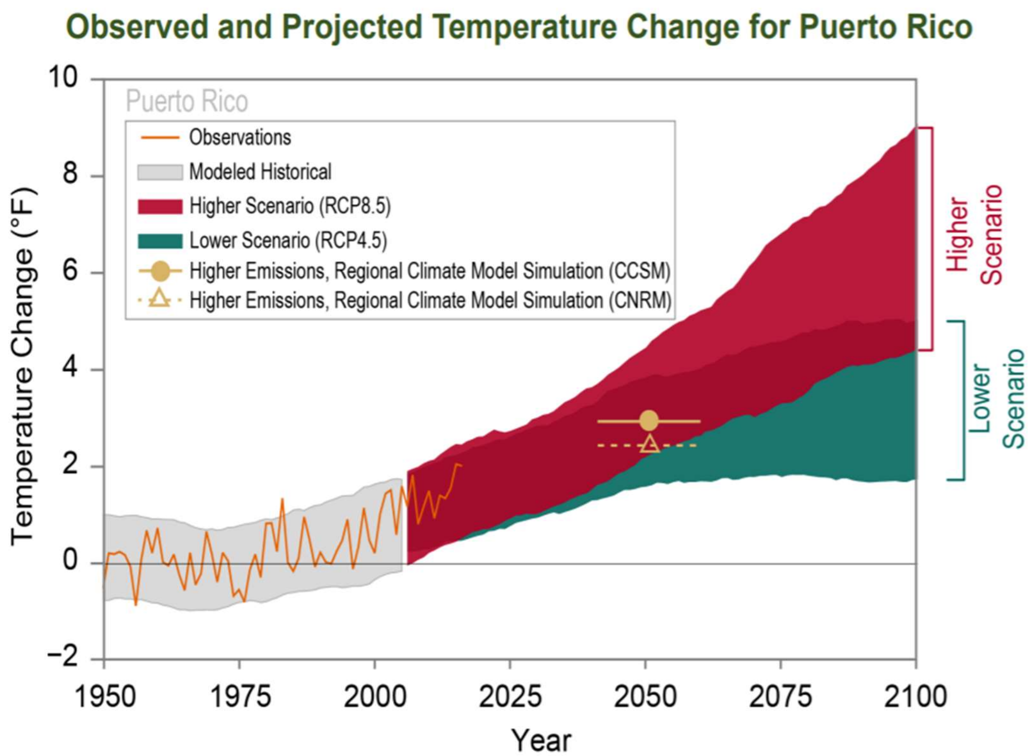

Figure 5: Observed and projected temperature changes are shown as compared to the 1951–1980 average. Observed data are for 1950–2017, and the range of model simulations for the historical period is for 1950–2005. The range of projected temperature changes from global climate models is shown for 2006–2100 under a lower (RCP4.5) and a higher. Projections from two regional climate models are shown for 2036–2065, and they align with those from global models for the same period (Gould et al., 2018).

dollars in damage. As sea surface temperatures rise, the probability of maximum intensity hurricanes in the region will also increase. Climate modeling for tropical cyclone activity projects that hurricane activity in the region will increase in frequency and intensity (Gould et al., 2018). Extreme precipitation could increase by 80 mm per 24 hours. High confidence scenarios predict that the future hurricanes that affect the island are likely to affect human health and well-being, tourism, agriculture, economic development, conservation, and danger from flooding. The increase in storm intensity means that Puerto Rico can continue to expect intense tropical storms. This leads to the limitation of freshwater as a whole because of infrastructure damage, increase in sedimentation and pollution.

4.3 Anthropogenic Hazards

Due to the intensity of rainfall, sedimentation rates continue to increase, which decrease reservoir capacity. Before Hurricane Maria, the Loíza reservoir, one of the main reservoirs used for potable water, had already lost 40% of its storage capacity due to sedimentation (Gould et al., 2018). It is estimated that because of Hurricane Maria, the most affected reservoir, Dos Bocas, lost an additional 28% of its capacity and reached 92% of its capacity filled. The least affected reservoir, La Plata, increased in capacity filled by less than 4% and reached 31% capacity filled (Vazquez et al., 2018). Most reservoirs have less than 40% of their original capacity and filling rates are predicted to increase (DRNA, 2016a). With the predicted increase in tropical storms in the region, it can be projected that there will be an increase in overall sedimentation and an increase in loss of reservoir capacity.

Landslides have also impacted much of the island, causing damage to many roads and structures in its path. After Hurricane Maria, landslides caused significant damage on the island and claimed the lives of hundreds of people. Based on soil studies conducted by the USGS, intrusive igneous rock showed the highest slope failure due to chemical weathering (Garcia et al., 2018). It was also found that soil most susceptible to landslides was also vulnerable to heavy rain events. With the projections of increased rain intensity, it is likely that there will be more landslides. This causes increased sedimentation in reservoirs, infrastructure damage, and makes it harder for rescue to get to those in crisis.

Leakage is also a massive issue in Puerto Rico and causes the people and freshwater ecosystems to lose much of the water needed to sustain the island. Before the island was severely damaged by Hurricane Maria, Puerto Rico already suffered from leakage due to aging infrastructure. According to the USDA in 2009, approximately 50% of potable water processed by PRASA was lost before delivery due to leakage, broken hydrants, and non-metered connections to the system (Miller et al., 2009). In 2013 PRASA estimated that 57.4% of all water was lost in distribution (Gould et al., 2018). As of 2015, PRASA also found that inspections performed at 53% of water management facilities showed some sort of leakage from minor to severe. Unfortunately, Hurricane Maria caused further significant damage to infrastructure which ultimately resulted in more leakage. In the future, infrastructure will continue to age while the increase in tropical storms will play a role in increasing leakage on the island.

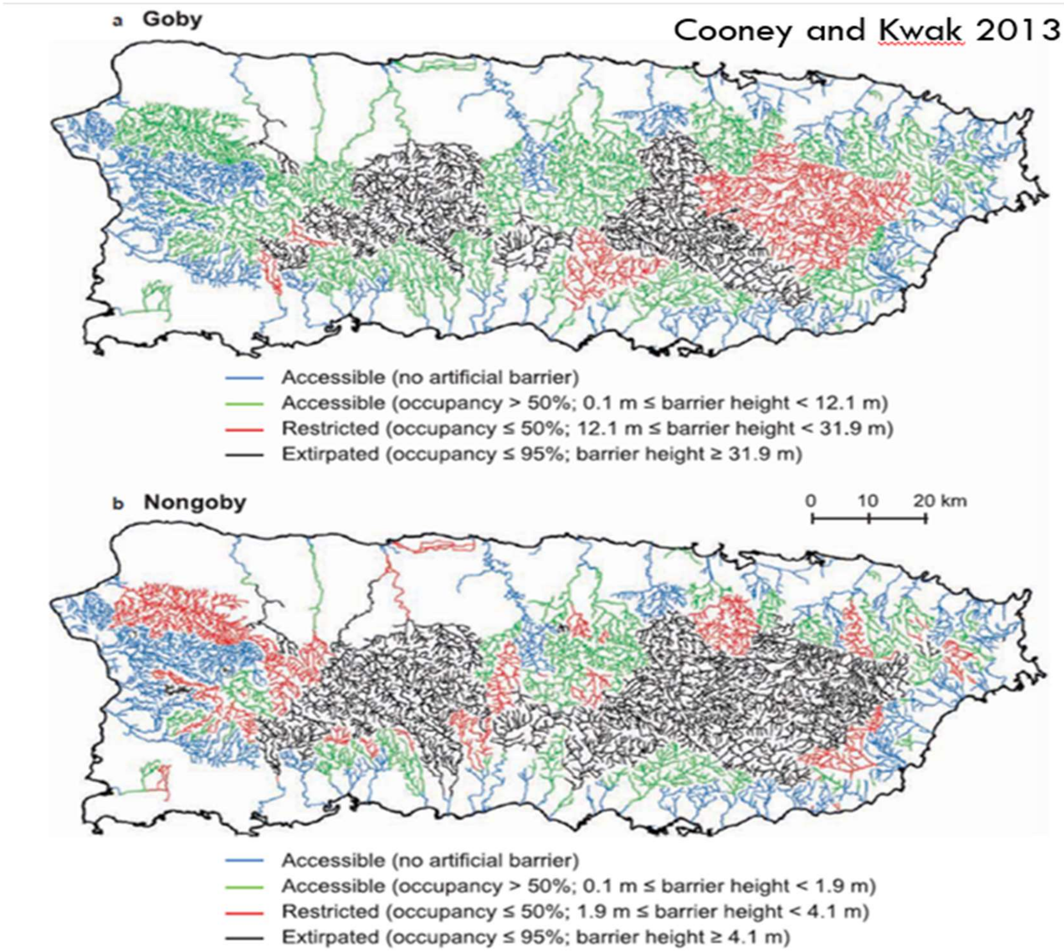

Figure 6: Accessible, restricted, and extirpated river reaches for (a) goby (sirajo goby and river goby) and (b) non-goby (bigmouth sleeper, mountain mullet, small-scaled spiny-cheek sleeper, and American eel) native diadromous fishes, limited by artificial in-stream barriers in Puerto Rico rivers (Cooney & Kwak, 2013).

Land use changes in Puerto Rico also cause problems with regards to water management in Puerto Rico. River segmentation is a hazard that affects a majority of freshwater species on the island. For example, non-goby and goby fish are heavily restricted by the segmentation (Cooney & Kwak, 2013). Gobies are fish with suckers; as such, gobies are less restricted than the non-goby because they utilize their suckers to clear obstructions such as dams (Figure 6). Still, a good portion of freshwater fish, including gobies, are restricted by damming. For the non-goby, a good portion of the watersheds upstream of major reservoirs in Figure 6 are labeled black, meaning that less than 5% of the species population can get past that barrier. For these fish it is very important to be able to migrate. When they cannot migrate, the species will die resulting in a loss of biodiversity and potential ecosystem functioning.

Another form of land-use change that affects Puerto Rico is agricultural development, which can impact the occurrence of landslides. In particular, abandoned and active coffee plantations have a landslide rate that is 4 times higher than the other areas on the island (Garcia et al., 2018). Educating the people of Puerto Rico on these hazards and others like them is very important for maintaining a balance between water management and protecting the freshwater ecosystem. Knowing all of the hazards within the system allows for a better understanding of the vulnerabilities. Specifically, for Puerto Rico, it is important that people know the hazards that affect water resources and water supplies in order to better manage the freshwater ecosystem while also making sure the water needs of the people are met.

5 Vulnerabilities

5.1 Vulnerabilities of the Rio Grande de Arecibo

A vulnerability is a property of the system that make it susceptible to the damaging effects of a hazard. Vulnerabilities are present independent of system location or hazard exposure (Office of Disaster Preparedness and Management, 2013). Within the Arecibo Watershed, there are several vulnerabilities that could lead to degradation of the system if exposed to the hazards discussed in Section 4. Vulnerabilities within the Arecibo Watershed can be grouped into six main groups impacting the functioning freshwater specific ecosystems, functioning wetland ecosystems, quantity or quality of available groundwater, quality or quantity of available freshwater, access to freshwater, and reservoir storage capacity (Table 3).

5.2 Freshwater Ecosystems in Puerto Rico

Within Puerto Rico, freshwater ecosystems play a principal role in maintaining the overall system of the Rio Grande de Arecibo Watershed. These freshwater ecosystems include over ten rivers, lakes, and reservoirs. Those that have a USGS surface-water station include the following: Lago Dos Bocas, Lago Caonillas, Lago Jordán, Lago Viví, Lago Pellejas, Lago Adjuntas, Lago Garzas, and the Río Viví. Together, these freshwater ecosystems cover a drainage area of 426.0 km^2 (USGS, 2016). Within these freshwater bodies, there are over 3,000 species that utilize these ecosystems daily and seasonally. These species include goby fish, which migrate between freshwater and saltwater at one or more portion throughout their life cycle. Gobies are more likely to be vulnerable to changes in the freshwater environment (see Figure 4). Species that rely on migration are also more vulnerable to degradation of habitat, loss of habitat, loss of genetic diversity, and loss of species due to segmentation. Segmentation in the Arecibo watershed is caused by the creation of stream barriers (dams and reservoirs). These stream barriers cause a shift in the ecosystem producing decreased species richness and diversity (Section 4.3 and Figure 4, U.S. Fish and Wildlife Service, 2018).

Stream barriers hinder endemic species from migrating to the sea throughout their life cycle, potentially creating a loss of genetic diversity. These barriers also create a limited opportunity for freshwater species to access upstream habitats creating a loss in breeding and feeding sites (Figure 4). The modified flow of water hinders the flow of nutrients and sediments from reaching other ecosystems that have an interconnected relationship with the freshwater ecosystems. Instead of reaching connected wetlands or other freshwater bodies of water, the sediments are deposited in the reservoir. The modified flow of the water also creates a shift in habitat, often forcing benthic habitats to be covered by sediments or substrates. This increased sedimentation would shift the concentration of nutrients, create reduced visibility for species finding food, and change the structure of the freshwater ecosystem. Due to the changes within the native ecosystem there is an increase in the ability of invasive species to successfully enter the ecosystem (U.S. Fish and Wildlife Service, 2018). Droughts would also hinder stream flow and create a modified flow to and from freshwater ecosystems. Freshwater ecosystems are vulnerable to salinity changes due to salt intrusion, which is caused by changes in rainfall and freshwater inflow (Colón-Rivera et al., 2014). Most of the 3,000+ species within the freshwater ecosystem are vulnerable to changes in salinity.

5.3 Wetlands in Puerto Rico

Within Puerto Rico, there are eight types of wetlands (see Table 3; Environmental Laboratory, 1978). Like the freshwater ecosystem, wetland ecosystems are vulnerable to degradation of habitat, loss of habitat, loss of genetic diversity, loss of species, and invasive species. The largest difference in the vulnerabilities between these ecosystems is that the wetlands rely on freshwater ecosystems for nutrient loads, sediment transport, species migration, and stream flow. Wetlands within the Arecibo watershed are vulnerable to losing biological function due to reliance on the connected freshwater ecosystems. Freshwater wetlands are delicate ecosystems that rely on many factors to function properly. One of these factors includes the stable salinity of the freshwater wetlands. When salt intrusion and increased flooding continually occur in freshwater wetlands, there is a decreased survival rate in species adapted to freshwater allowing invasive species to pervade the ecosystems. Due to this, the most affected by these vulnerabilities include the many species that are present within the wetlands and local communities. Extreme flooding will create an overload of sediments and smother wetland roots and systems, further deteriorating the function wetlands (Spalding, 2014). Wetlands, especially mangroves, act as a physical barrier that protects coastal areas from erosion, flooding, and storm surges. Mangroves have the ability to reduce erosion by binding soils and collecting sediments needed to maintain a functioning wetland (Spalding, 2014). Due to their role as protection from hazards, wetlands are vulnerable to degradation caused by increased flooding, droughts, storm surges, and salt intrusion. All of these factors are impacted by climate change and will continue to create a vulnerability within the wetlands of Puerto Rico.

5.4 Freshwater and the Community

Quantity and quality of available groundwater and surface freshwater are vulnerable to contamination and fluctuation of the quantity of stock. The available freshwater stock depends on the inflow of rainwater and the outflow of runoff. The available groundwater stock is the result of recharging, outflow, and extraction (Figure 1). Groundwater recharge depends on factors such as infiltration capacity, rainfall distribution, and climate factors (Şen, 2015). Due to an increasing evapotranspiration and runoff rate caused by the steppe and karst topography, the water has a low residence time within Puerto Rico, creating a shortage in freshwater and groundwater. In Arecibo, the total withdrawal rate of surface/groundwater was 447,000 m^3/d with a total of 92 thousand people served in 2010 (USGS, 2010). Those most affected by these vulnerabilities include communities relying on freshwater/groundwater, industries utilizing potable water, and the ecosystems where the water enters daily.

The water supply for local communities is vulnerable to impractical infrastructure location, loss of electrical services, loss of sufficient water, and loss of transportation services. Properties built in areas along the coast and within mountains are most vulnerable to destruction due to flooding, landslides, and hurricanes (Santos-Hernandez, 2007; see Section 4). Hurricanes cause physical destruction but also increase social insecurity within communities. Failures within Puerto Rico's public services after Hurricane Maria included loss of electricity for eight months. This impacted 70% of all water supply systems and wastewater treatment plants (Resilient Puerto Rico Advisory Commission, 2018). Roads and bridges were destroyed or covered with debris, which stopped transportation of water to those affected. Transportation of water should not be necessary if public service would have resilient infrastructure that would provide potable water to residents during natural disasters. However, due to the destruction of vital immensities during natural disasters transportation of water is vulnerable (Resilient Puerto Rico Advisory Commission, 2018). Thie loss of transportation also prevented the access to healthcare services, education services, and job opportunities. The quality of available water supply is vulnerable to reduced water quality caused by anthropogenic pollution, biological contamination, and salinity changes. These include wastewater, stormwater run-off, direct, and indirect pollution.

5.5 Narrowing the Focus of Vulnerabilities

Within the Rio Grande de Arecibo Watershed there are two reservoirs, Lago Caonillas and Lago Dos Bocas. Reservoirs are artificial lakes used for water storage, flood control, power generation, and recreation. These reservoirs are vulnerable to capacity loss due to sedimentation and aging. Increased sedimentation can be caused by increased streamflow during flooding (Section 4), which often results in exacerbated erosion in Puerto Rico. Increased erosion within the Rio Grande de Arecibo watershed is caused by intense precipitation, high winds, flooding, agriculture development, and urban development (Yuan et al., 2015). These hazards cause a larger amount of sediments to flow into the reservoirs. Reservoirs built on steeper slopes with less vegetation are more vulnerable to capacity loss caused by an increase of sediment flow into reservoirs (Yuan et al., 2015). Sun-grown coffee areas which are found throughout Puerto Rico, are more vulnerable to severe bank erosion due to lack of vegetation which typically secure sediments within the land (CWP, 2008). Reservoirs naturally age over time but aging can be accelerated due to anthropogenic activities. Both of the reservoirs within the Rio Grande de Arecibo Watershed are over 70 years old making them more vulnerable to leakage, deficient spillways, degradation to maintenance instruments, sedimentation, and failure due to design flaw (Hansen et al., 2018).

Table 3: Vulnerabilities within the Rio Grande de Arecibo watershed and its corresponding impact on the system.

Vulnerability	The system	What is impacted by the vulnerabilities?
Degradation of habitat	Freshwater wetlands: 1. Aquatic 2. Flats 3. Marsh 4. Swamp Saltwater Wetlands: 1. Aquatic 2. Coastal Flat 3. Marsh 4. Swamp	Species within these environments
Loss of habitat	Freshwater, wetland ecosystems	Species within these environments
Loss of genetic diversity	Freshwater, wetland ecosystems	Species within these environments
Invasive species	Freshwater, wetland ecosystems	Species within these environments
Loss of species	Freshwater, wetland ecosystems	Species within these environments
Salinity changes due to salt intrusion	Freshwater, wetland ecosystems	Communities relying on freshwater
Changes in freshwater ecosystem	Wetland ecosystems	Species within these environments
Contamination	Quantity/Quality of Available Groundwater	Communities relying on potable water Freshwater / Marine ecosystems
Loss due to leakage	Quantity/Quality of Available Groundwater, Access to Freshwater	Communities relying on potable water; agriculture; and industries
Over consumption with no time for recharge	Quantity/Quality of Available Freshwater	Communities relying on potable water; agriculture; and industries

Over-saturation due to flooding	Quality/Quantity of Available Freshwater	Freshwater /Marine ecosystems
Loss of electrical services	Access to Freshwater	Access to healthcare; domestic water services
Spatial distribution flaws	Access to Freshwater	Domestic water services
Aging	Reservoir storage capacity	Communities relying on potable water; agriculture; industries
Capacity loss	Reservoir storage capacity	Communities relying on potable water; agriculture; industries; freshwater/marine ecosystems

Several of the vulnerabilities have the possibility to be mitigated by reservoir removal, and native vegetation addition throughout areas that have high erosion rates. Reducing vulnerabilities with the system is often the only way to reduce risk created by natural hazards. All of the vulnerabilities have accelerated effects due to anthropogenic activities that cannot be mitigated by the communities of Puerto Rico alone.

6 Foresight

6.1 What is Foresight

Foresight is the understanding of what the spectrum of possible futures looks like and having an idea of what could happen in the future. Exploring the spectrum of plausible futures for a system must be based on an understanding of the hazards and their probability density function, as well as knowledge of the system's vulnerabilities. Knowing the potential hazards and the inherent vulnerabilities is critical in order to encompass all plausible futures and aspects on how the future of the system might be affected. Scenarios for hazards in combination with conceptual and other models can be used to create pictures of plausible futures of the system and thus, the full spectrum can be constructed. Scenarios also include indicators which are entities or things that might affect the future. Indicators are the changes that can be made in the system that influence possible futures. These indicators have varying degrees of importance and can have a wide range in which they can occur. Moreover, they can include the multiple aspects associated within the realm of climate change, which impacts the probability density function of many hazards and can lead to greater risks. Other indicators include non-climate related changes that can transform the system such as land use changes, population change, and economic or governmental changes that all can affect the spectrum of plausible futures. Once these indicators are found and understood, multiple scenarios can be created, again painting pictures of what plausible futures look like ranging from the best possible future to the worst possible future.

Identifying those scenarios that are associated with undesirable futures provides the foresight needed as a tool for designing interventions to avoid these futures. Focusing on the more desirable futures, the associated scenarios can be used in a back-casting to identify the steps needed to be taken to create a more desirable future. The back-casting also provides knowledge of which indicators should be changed to move the system towards the desirable future. However, there is always uncertainty in understanding the indicators and futures. Risk assessments are another way in which interventions can be identified that would reduce the risk associated with undesirable futures.

6.2 Using Foresight

In order to meet the water needs of the population of Puerto Rico while safeguarding the freshwater ecosystems, the future needs and challenges need to be addressed to best design possible interventions. The set of intervention considered necessary or helpful to make progress towards desirable futures (see Section 7) can then be used to formulate recommendations (see Section 9). Without foresight of possible system trajectories and associated future problems and the understanding of the system as a whole, interventions made would be only temporary, and not create resilience to survive future complications. The problems facing water needs of the people as well as trying to sustain freshwater ecosystems will only be exacerbated by future challenges. The hazards and vulnerabilities considered in Sections 4 and 5 are critical in order to integrate both resources to provide a way to understand what the future might look like. Especially for the hazards, most important is the future climate of Puerto Rico. The most important indicators and variables concerning Puerto Rico are hurricanes, sea level rise, temperature, precipitation, land use change, and population. Hurricanes are of concern especially because of their devastating impact on Puerto Rico and reaction time and reconstruction time is difficult. The most recent Hurricane Maria in 2017 resulted in billions of dollars in damages, and exacerbated water management issues.

There is a wide range of plausible sea level rise projections in Puerto Rico, and even a moderate and definitely a higher range scenario could have devastating impacts on northern parts of the island. Temperature and precipitation changes will affect how water resources are used, distributed, and the overall availability. Climate models show different future projections for precipitation, but all projections show either an overall decrease in rainfall, or a decrease in rainfall but an increase in intensity of extreme events (Gould et al., 2018). Land use change poses a threat to ecosystems in particular, limiting their connection to resources including water. These land use changes include man-made reservoirs, which dramatically impact the surrounding freshwater ecosystems. With increased rates of sedimentation coupled with growing water use, more reservoirs will need to be created to serve consumers. Finally, population changes and migration of people on the island will dictate how much water will be used in the future, and where areas of concern will be located. In the following, these different indicators are broken down into sub-categories and five scenarios are discussed for the individual indicators: population, sea level, air temperature, precipitation, and hurricanes.

6.3 Population Changes in Puerto Rico

In 2018, the population of Puerto Rico was at around 3.2 million, but current trends show that the population of Puerto Rico has been decreasing since 1998 (Krogstad, 2016). However, the water use of the island has continued to grow (Molina-Rivera and Gómez-Gómez, 2008). A study of water use in California showed that an increase in income results in an increase in water usage and it can be expected that this relationship also explains the increased water use in Puerto Rico (Molina-Rivera & Gómez-Gómez, 2008). GDP of Puerto Rico has increased rapidly from $30 billion in 1990 to $61 billion in 2000, and most recently $98.5 billion in 2010 (World Bank Group, 2018). Future population projections show a very wide range anywhere from 2.9 million to as low as 2.0 million for the years 2025 and 2050, respectively, but all of them indicate a further decrease of the population. Projections of the United States Census Bureau indicate a population of 2.9 million in 2025 and 2.3 million in 2050 (Stone, 2017). These projections are not accounting for impacts of future hazards such as hurricanes that would lead to an increased emigration. A decrease in population could reduce cross-domestic water consumption. However, it is unclear to what extent a potential income increase would compensate for such a drastic population decrease and actually lead to an increase of cross domestic consumption.

6.4 Sea Level Rise Scenarios

As discussed in Section 4, projections of future sea levels for Puerto Rico show a wide range of plausible sea level rise, including three different scenarios of Intermediate-Low (0.3-0.6 m), Intermediate (0.9-1.2 m), and Extreme (2.7-3.6 m) (Gould et al., 2018). These are further broken down into more specific estimates for the years 2050 and 2100. However, for a comprehensive view on the spectrum of plausible futures, it is important to consider the full range of plausible sea level rise, and not focus on specific estimates. The long tail of the probability density function of sea level rise cannot and should not be excluded from scenarios used to assess the impacts. 61% of the population in Puerto Rico are in coastal municipalities that are extremely at risk (Crespo-Acevedo & Flores, 2017). Additionally, 15% of the population live in areas where flooding is prevalent, and 11% of the population are subject to areas likely to experience future inundation (Acevedo, 2017). Using the NOAA Sea-Level Rise tool (NOAA, 2019), the impact of sea level rise on the coastal communities can be assessed for a range of sea level rise values. Figures 7-9 show coastal inundation for sea level rise of 0.6 m, 1.2 m, and 3.6 m. A sea level rise of the order of 0.3-.6 m would mostly impact south coast wetlands, flooding them and destroying habitat, marsh will move inland (Figure 7). Wetlands and water bodies southeast of San Juan would also experience expansion into previously dry areas. Metropolitan areas south of San Juan will experience increased flooding and inundation of residential areas. A sea-level rise on the order of .9-1.2 m would also flood and inundate the eastern coast of the island (Figure 8) and spread more into the areas mentioned before.. Finally, a sea level rise on the order of 2.7-3.6 m would be disastrous to the island, especially the large cities like San Juan (Figure 9). The metro area surrounding San Juan including important key infrastructure such as the airport east of San Juan would be completely inundated. The impacts of inundation and flooding can be seen for lower sea level rise values, but worsen as the rise increases. Increased sea level will destroy residential areas and critical infrastructure as well as wetlands that provide ecosystem services, and will migrate people to other parts of the island. Flooding and inundation

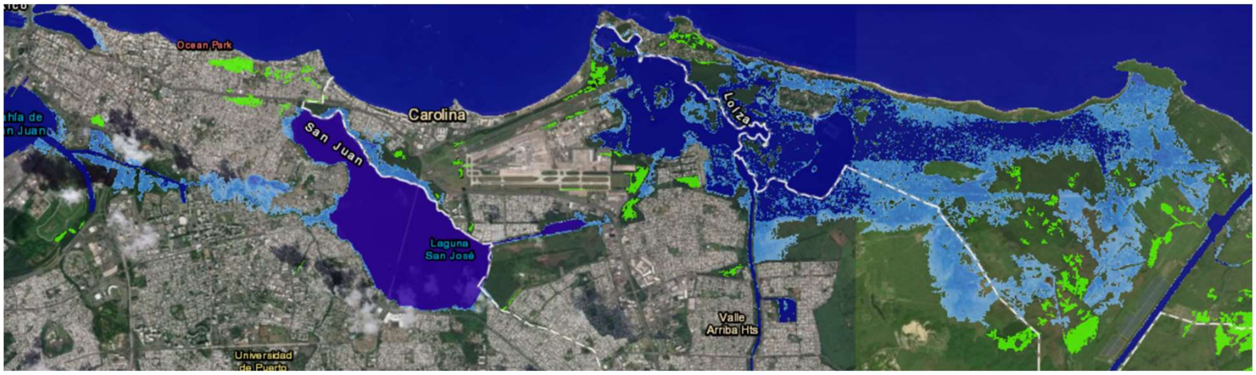

Figure 7: 0.3 to 0.6 m sea level rise effect on the San Juan area (NOAA, 2018*)*.

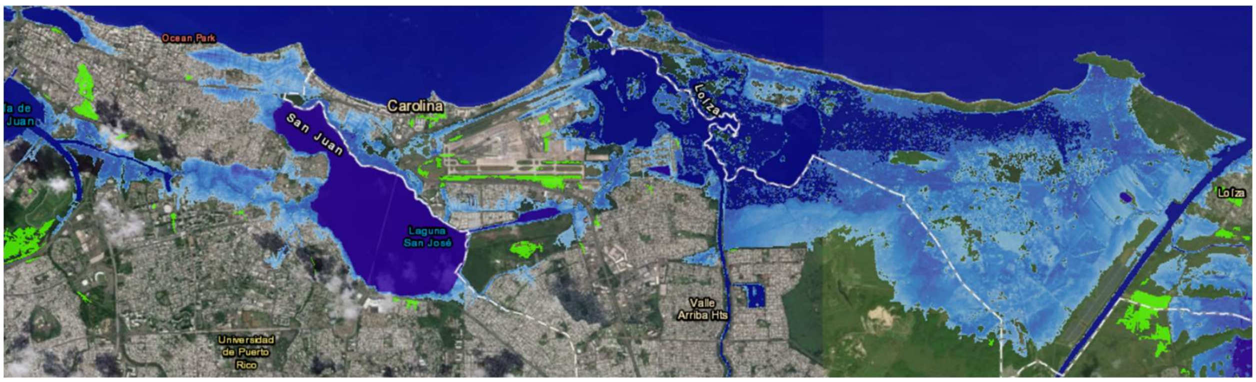

Figure 8: 0.9 to 1.2 m sea level rise effect on the San Juan area (NOAA, 2018).

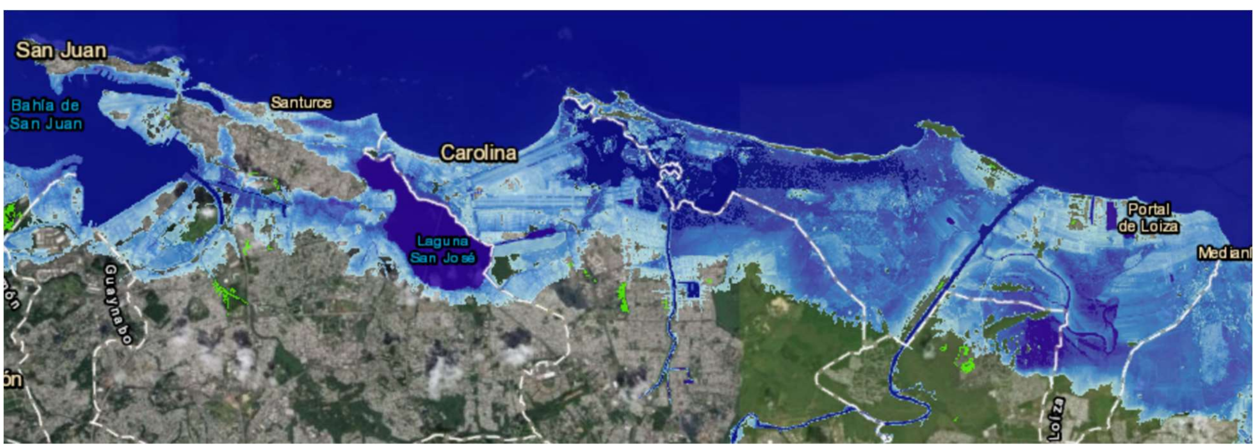

Figure 9: 2.7 to 3.6 m sea level rise effect on the San Juan area (NOAA, 2018).

of certain infrastructure can lead to contamination of freshwater sources. For example, sewage plants or landfills might be flooded. If people were to leave areas at risk of inundation and move away to more rural areas, the infrastructure there would not be able to support such a large influx of people. This would further strain water resources in these newly populated areas, and the creation of new housing would further fragment freshwater ecosystems. Sea level rise combined with other factors can also lead to saltwater intrusion (Kirwan & Gedan, 2019), and the probability of saltwater intrusion into groundwater increases with higher sea level rises. The impacts of sea level rise may increase emigration and lead to a steeper decrease in population than currently projected. Finally, the spread of the Zika virus by mosquitoes can be related to increased flooding in nutrient rich neighborhood areas (Yee et al., 2019). When neighborhoods near the San Juan estuary were transformed into residential areas, wetlands could not protect from flooding in these areas (Yee et al., 2019). Combined with higher sea level and increased temperatures, Zika virus has the possibility to become more prevalent.

6.5 Temperature Rise Scenarios

As discussed in Section 4, projections show a future overall increase in temperature across the island affecting not just humans but the freshwater ecosystems as well. A mean temperature rise is likely to lead to an overall increase in energy use for several reasons including the use of air conditioning. Some estimates suggest a doubling in energy demand by the year 2100, due to projected average global temperature increases of 5°C without interventions (Gould et al., 2018). The San Juan area in particular will have the most visible energy use changes (Gould et al., 2018). Higher temperatures and more frequent heat waves will lead to more deaths through cardiovascular diseases and strokes (Gould et al., 2018). Under certain scenarios for temperature increase, raising livestock on the island will also need to include enclosed air-conditioned areas (Ortiz-Colon et al., 2018). Increased temperatures will lead to an overall decrease in productivity of raising cattle and dairy on the island. Combined temperature rise and decreased precipitation can lead to more frequent droughts which put stress on all groups of the island including the people, agriculture, and freshwater ecosystems. Increased droughts will increase reservoir withdrawal, leading to decreased stream flow. Droughts will continue to force the island to ration water (Gould et al., 2018). Increased frequency and duration of droughts may trigger migration of people from the most affected areas to other areas of the island, therefore putting more strain on the receiving areas. Stream flow is an important factor in the movement of migrating species and the ecosystems surrounding it, as well as for providing water resources to agriculture areas. Thus, when droughts occur, thousands of dollars' worth of agricultural goods are lost (Van Beusekom et al., 2016). Certain crops will become less productive, and with greater water demands in general, agriculture may not be a viable option for Puerto Rico in the future. This would increase demand of foreign foods to replace what cannot be grown in situ. Increased temperature and changes in precipitation will also lead to the change of life zones on the island. Puerto Rico is home to many different habitats, and due to these stated climate related hazards, life zones will shrink and grow depending on their dependence of water resources (see Figure 10; Khalyani et al., 2016). Trends show a shift from more humid wet zones to a drier environment, changing vegetation types and shrinking large forested areas, which would be detrimental for endemic species (Khalyani et al., 2016). Agricultural crops, such as coffee, will change in these areas, which will narrow the current life zone. This shrinking of life zones will also impact where people live and could lead to increased water demands from different parts of the island that previously did not supply large quantities of water. A migration of life zones would impact ecosystems severely and also likely increase the pressure on water management and inter-basin water transfer.

6.6 Rainfall Change Scenarios

As discussed in Section 4, projections of precipitation show a wide range of plausible changes in precipitation. It is important to understand how increased intensity of rain or extreme rainfall will affect the island and its freshwater resources. Some models suggest an overall decrease in moderate rainfall over 25 mm in a 24 hour period and an increase in probability of extreme rainfall over 75 mm in a 24 hour period (Hayhoe, 2013). The increased probability of extreme rainfall is due to overall climate trends as well as products of cyclones (Kossin et al., 2017). Increased rainfall can lead to flooding of residential areas, damaging houses and infrastructure. Loss of potable water due to infrastructure leakage is already very high at around 50-60% (Section 2). Extreme rainfall can put further stress on the system increasing overall leakage. If this leakage gets too bad, infrastructure will have to be repaired costing the territory millions, even though current leakage should lead to repairing. In more elevated areas, intense extreme rainfall can create erosion and create landslides (Larsen et al., 1993). Roads are likely to continue to be destroyed, creating the need for further infrastructure repair. Extreme rainfall will increase sedimentation in reservoirs overall decreasing capacity (U.S. Fish and Wildlife Service, 2018). Increased storage capacity will lead to further decreases in stream flow, as well as the need to increase groundwater pumping. When sedimentation of reservoirs becomes too

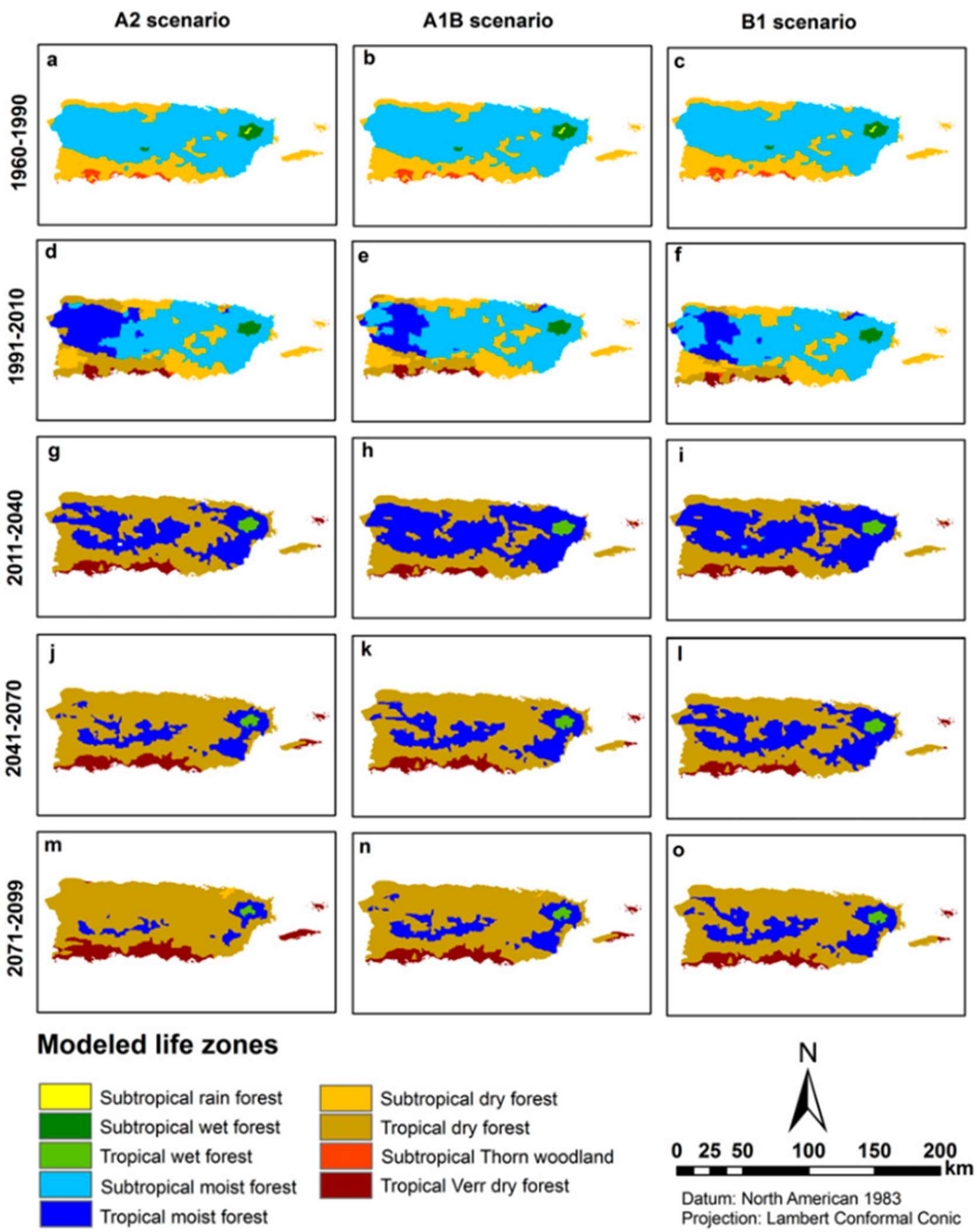

Figure 10: Modeled life zone changes for three temperature change scenarios (Khalyani et al., 2016).

much of a problem or decreases storage capacity dramatically, new reservoirs could be created to have more storage capacity for useable freshwater. Increased sedimentation is also detrimental towards aquatic bottom dwelling wildlife as well as towards submerged vegetation (U.S. Fish and Wildlife Service, 2018). Increased rainfall can damage crops directly or through erosion or flooding. Due to the topography and karst geography on the island, retention time on the island is short, so extreme rainfall creates destructive flooding. This will not allow ecosystems to use this water resource.

6.7 Hurricane Projections

As discussed in Section 4, modern climate change is likely going to increase the frequency and magnitude of hurricanes impacting Puerto Rico. As a result, there is increased probability of severe infrastructure damage requiring costly recoveries. Without significant federal support, this would put Puerto Rico further in debt. Infrastructure for the public water service is likely to be impacted, too, which would further increase water leakage and lead to increased loss of potable water. Hurricanes will increase flooding spreading disease by both contamination as well as spread of mosquito-borne illnesses (Yee et al., 2019). Water quality would suffer due to contamination, and people therefore would have a harder time of receiving freshwater after a hurricane has passed. Hurricanes will also destroy wetlands that act as a natural and important barrier for municipalities. Crops will be damaged, as well as a decreased yield of production for the year after.

6.8 The Future of Puerto Rico

Based on these future scenarios and projections, the best possible desirable future will have to incorporate all of these indicators and hazards. The way in which water is used must be viewed as what it would look like for future generations on the island. The desirable future is meeting the needs of the people while safeguarding the freshwater ecosystems. The methods of using reservoirs is detrimental to the quantity of water as well as detrimental to the surrounding environments. Municipalities and infrastructure need to start moving people away from coastal areas, and into areas that are safe not just with respect to sea level rise and hurricane flooding. People also need to live in the best possible life zone where water can be used most effectively with the smallest amount of damage to the surrounding ecosystem.

Table 4: Climate change scenarios and their projected impacts on Puerto Rico

Scenario	Ecosystem impacts	Human impacts
(Scenario 1) Sea Level Rise	• Increased saltwater intrusion of groundwater sources • Destruction of wetlands due to creation of new residential areas	• Increased movement away from flood-prone areas • Inundation of residential areas near metro areas • Increase in mosquito transmitted diseases • Inundations of critical infrastructure including airports • Decrease in population on island
(Scenario 2) Temperature rise and decreased Precipitation	• Ecological life zones will shift moving people/wildlife • Increased reservoir use, decreased streamflow	• Heat related illnesses will increase • Increased energy demand • Decreased crop production • Increased water rationing, further strain on water
(Scenario 3) Increased Intensity of extreme rainfall	• Increased erosion • Increased sedimentation of reservoirs, decreased capacity	• Flash flooding
(Scenario 4) Hurricane Projections	• Increased pollution of water and ecosystems	• Damage to infrastructure • Increased flooding • Increased exposure to disease/contamination • Migration of people into new areas

7 Interventions

7.1 Desirable Futures for Puerto Rico

The long-term sustainability of Puerto Rico is dependent upon a constant monitoring of the system, the determining of potential future scenarios, and the vision of desirable futures that meet the needs of the people while safeguarding the freshwater ecosystem. As such, interventions are required to make those futures possible. Working within the context of systems thinking and using the participatory approach to interventions, viable options for Puerto Rico were developed that include mitigation to a variety of climate change effects including sea level rise, increased temperatures, and fluctuations in precipitation. The importance of transparent governance is also discussed, as is the need for regional scale climate models, the application of risk assessments, and management policies that account for sound water management and ecosystem health. Imperative to this process is an understanding that wicked problems have no defined solution, only better or worse options. Moreover, realistic options may not necessarily be simple and will likely require great effort to achieve.

Using the systems thinking framework and the participatory approach to interventions, this study determined a set of desirable futures for Puerto Rico that would seek to meet the needs of the people while safeguarding the freshwater ecosystems. The range of desirable futures proposed in this study are able to address the water management crisis on the island through mitigation of climate stressors, adaptation to SLR, and regulatory management. Moreover, these management strategies proposed may not be mutually exclusive to one desirable future, rather, may exist as a viable option for all sustainability targets. An overview of these futures, along with their applicable interventions, has been outlined in Table 5.

7.2 Viable Options

The first among these desirable futures addresses the likelihood of SLR and requires interventions with regards to the impact of flood inundation on coastal communities which could be the largest future cost facing the island. Given the wide range of plausible future SLR (Section 4), a desirable future would be one where resilience to rising sea levels would allow for a prospering community with an adaptable economy. Some viable options for the system include

Table 5: Outlines the desirable futures proposed for Puerto Rico which allow the system to mitigate and adapt to a variety ever-fluctuating hazards and vulnerabilities. Viable options are also proposed as well as their linkage to the system as a whole.

Sustainability Goal:

- *Resilience to rising water levels will allow for a prospering community with an adaptable economy*
- *Community and ecological resilience to heat, drought, and water/food shortages*
- *Community and ecological resilience to fluctuations in river flow, mudslides, and potential impacts to infrastructure*
- *An increase in governing transparency that utilizes the participatory decision making necessary to achieve desirable futures in Puerto Rico*

Key vulnerabilities: coastlines, ecosystem function, human populations, potable water availability

Key hazards: sea level rise, increased temperatures, variable rainfall, increased storm intensity

Proposed intervention	**Linkage of intervention to hazard**
Raise infrastructure, designation of flood zone categories and statewide integrated response	SLR
Rezone migrating habitats such as mangrove and wetlands	SLR
Management guidelines that protect and regulate water consumption, use of cisterns	Increased temperature and drought
Conservation recharge areas implemented into land-use planning initiatives	Increased temperature and drought, variable precipitation
Improve water transfer infrastructure and incentivize citizen reporting	Increased temperature and drought, variable precipitation
Buffer zones applied to agricultural areas	Variable precipitation
Treated sewage discharge hydrology focused	Increased temperature and drought, variable precipitation
Human dimensions: Implementation of participatory decision making, government transparency	Non-climate stressors
Human dimensions: State support for community organizations, synch community and government sentiment	Non-climate stressors
Human dimensions: Economic transition	Non-climate stressors

raising infrastructure to withstand flood inundation, designation of flood zone categories during extreme storm events, inclusion of a statewide integrated SLR management response, relocation of communities from flood-prone areas to further inland, and tax incentives to allow for ease and feasibility of relocation. Migrating habitats including mangrove and wetland communities should be rezoned to prevent future building and to protect these valuable ecosystems. Coastal municipalities that become completely inundated with water would require strategic government relocation of coastal populations to either inland or stateside regions, while transition services and job placement support would also be made available to displaced citizens.

The second desirable future seeks to adapt the system to changes in a 2.2ºC temperature rise in conjunction with decreased precipitation, which is one of the possible climate change trajectories discussed in Section 4. In a preferred future, Puerto Rico would maintain community and ecological resilience to heat, drought, and water or food shortages, which may accompany predicted trends in temperature and precipitation. An important tool to inform possible interventions includes regional risk assessments, which are required to calculate the hazards and plausible scenarios that can occur such as the impacts of overconsumption of freshwater on the island. Currently, there is not enough data regarding how much water a single Puerto Rican uses per day (compared to that of a national low and high average) which can inform estimates of total population carrying capacity. This risk assessments should also apply to other sources of water consumption, including for that of agricultural and industrial sectors, which together also utilize a large portion of the island's freshwater. Such information would allow for more targeted management policies that regulate and minimize water consumption during droughts. These policies might include mandatory use of cisterns for supplemental use during water shortages, decentralization of storage capacity from major reservoirs which are vulnerable to sedimentation, and utilization of conservation recharge areas through necessary rezoning and land-use planning initiatives to ensure ample water is conserved during periods of high precipitation for later use during drought. In the face of impending drought, Puerto Rico must find a way to minimize the need to extract water from freshwater ecosystems and groundwater, reduce the loss of water through leakage, evapotranspiration, and sedimentation, reduce overall water needs, and ensure that current sources of freshwater are not contaminated by poor wastewater treatment.

The third desirable future addresses system adaptation for less frequency of precipitation, but with greater intensity. In a preferred future, Puerto Rico would maintain community and ecological resilience to fluctuations in river flow, increased mudslides, and damage to infrastructure. To achieve this, the system requires mapping future of future flood zones to inform a change in land-use plans that ensure critical infrastructure does not lie in these high-risk areas. Other options include a publicly available integrated mapping of water transfer infrastructure and effective implementation of citizen reporting. Water pipes should avoid tree roots or other structures that could threaten breakage during tropical storm events that produce heavy precipitation, weaken the soil, and cause infrastructure collapse. Buffer zones applied to agricultural areas would limit excess runoff and protect surface water contamination. Moreover, treated sewage management policy should be hydrology focused rather than minimum nutrient content focused to account for the water fluctuations in the system.

7.3 Participatory Decision Making

A transition in the governance of Puerto Rico to one of increased transparency and decision making is essential in order to achieve the aforementioned desirable futures. Current government sentiment on the island is one of a general distrust due to government use and misuse of resources, proven instances of government corruption, cultural ties to years of colonial occupation, and current territorial status. To mitigate these perceptions, and restore community participation and trust in government, a shift in cooperation, coordination, and transparency of regulatory bodies at the local, territorial, and federal level will be essential. This shift will allow for a synchronizing of community sentiment and public policy, which can be further facilitated through governmental support for community organizations that promote conservation of water resources and sustainability education. Moreover, elimination of political and governmental stove-piping is critical in order to facilitate well-directed action and implementation, which can often times be the most difficult component of intervention execution.

7.4 Advantages and Disadvantages of Competing Options

Within the system, there are a variety of competing societal agents who stand to either gain or lose from each option. With regards to domestic water consumption, the largest use of water on the island, the advantages of intervention greatly outweigh the costs. Strictly speaking, financial austerity is the largest disadvantage to Puerto Ricans, because implementation of the interventions will come at considerable financial cost. Occupants of the island can also expect to significantly reduce their overall consumption of freshwater, which will require an ideological shift in the perception of what it means to be "middle class" – a newly gained societal norm. Yet, failure to implement the interventions proposed in this study will come at a much higher cost to the citizens, since reduction and even elimination of precious freshwater sources will result in the eradication of surrounding ecosystems, mass migration of human populations from the island, and the inevitable abandonment of Puerto Rico's future.

On the other hand, industry and agriculture stand to lose the most from efforts to improve water standards. Management regulations that seek to regulate the amount of water extracted from either surface or underground sources will require industry and agriculture, the two largest extractors of water behind domestic consumption, to limit intake and improve wastewater quality. In both instances of intervention, greater economic value is placed on the water resource than on the economic services provided, which may indirectly challenge the current economic model for Puerto Rico. In such a case that this were to occur, both agriculture and industry would be required to impose methods that greatly restrict the amount of water utilized. At a minimum, the agricultural sector might be required to install both rainwater collection and ground watering systems, in addition to natural buffer zones that limit contamination into surface water sources. More extreme cases may mean elimination of monocultures, implementation of new farming practices, and regulation on specific types of crops that can be grown. There will also be stricter requirements for wastewater management policies with regards to manufacturing companies, with potential regulation by either the government or a third-party entity. Thus, increased regulation of both water consumption and wastewater generation for economic sectors will greatly benefit not only the human communities of Puerto Rico, but also the ecological habits of the island. But likewise, it may also create a transition in Puerto Rico's economy, as large-scale farming and manufacturing companies transition out of the territory. As such, planning for a sustainable, ecological Puerto Rican economy would allow the island to ensure a desirable future.

8 Discussions and Conclusions

8.1 The Wicked Water Problem in Puerto Rico: Hazards, Vulnerabilities, and Foresight

This case study addresses the complexity of the Rio de Arecibo watershed as a model for understanding the wicked problem of addressing the amount of available freshwater in Puerto Rico. Its overarching goal was to utilize systems thinking as a framework for conceptual development and understanding in order to determine the best approach for meeting the needs of the people while safeguarding the freshwater ecosystem. Through a participatory modeling exercise, the authors of this study enveloped the intricacies of stakeholders within this system and applied that understanding to the development of potential futures and to the consideration of viable options for intervention.

Within Puerto Rico's water system, a variety of both natural and anthropogenic hazards combined with relevant system vulnerabilities result in a number of high risks. Among the risks are those associated with potential climate impacts as they relate to sea level rise increasing temperatures, and extreme fluctuations in the frequency and amount of precipitation. With respect to these hazards, vulnerabilities in the system were identified and include the viability of a functioning Arecibo freshwater ecosystem, the quantity and quality of available freshwater, and a functioning wetland ecosystem. Additional points of focus determined to be of critical importance for Puerto Rico include predicted changes to regional population, the utilization of unsustainable agricultural practices, and projected declines in the storage capacity of the Lago Dos Bocas and Lago Caonillas reservoirs, both of which feed into the Rio Grande de Arecibo.

Future scenarios for climate impacts in Puerto Rico were developed based on Gould et al. (2018). Using scenario classifications of low, medium, and high, the potential impact of sea level rise on both the natural and human environment could be identified. Additional scenarios for climate-related impacts included an overall rise in temperature of 2.2°C and a 10% decrease in overall precipitation by 2050, less frequency of precipitation but with greater intensity, and an increase in frequency and intensity of tropical storms. In general, it is expected that Puerto Rico will experience a greater demand for energy sources, a shift in human and ecological populations, prolonged periods of drought, declines in economy due to decreased agricultural production, and an increase in disease and health hazards due to polluted water systems. Thus, as the ecological functioning of habitats decline, so will the health of the humans that rely upon them.

8.2 Determining Viable Options for Interventions

Through the participatory approach utilized in this case study, some viable options for interventions were identified, which, if implemented, could improve the ability for the system to reach a desirable future. The desirable futures considered include increasing Puerto Rico's resilience to SLR, drought, and variable precipitation. Some human dimensions to the system were also identified, including increasing government transparency and overall use of participatory decision making, which would be necessary in order to achieve the desirable futures for the island. Some of the more prominent interventions to mitigate sea level rise include implementation of a statewide integrated response, raising and potential relocation of infrastructure, designation of flood zone categories, and rezoning migrating habitats to preserve ecosystem function. Interventions that target increased drought and variable precipitation include applying management guidelines that protect and regulate water consumption, identifying conservation recharge areas into land-use planning initiatives, improving water transfer infrastructure and incentivizing land-use planning initiatives, and treating sewage discharge through hydrology focused monitoring programs. Interventions that target the human dimensions of the system focused mainly on governmental processes such as the implementation of participatory decision-making, government transparency, state support for community organizations, and a transition in Puerto Rico's economy from that of industrial manufacturing and agriculture to one that ensures the availability of economic prosperity for local communities.

8.3 Obstacles to Moving Forward

As a territory of the United States, the Puerto Rican government and population have very little authority to alter the political and economic situation in Puerto Rico. For more than 100 years, the United States has utilized the island territory as a source of natural resources, wealth, and for the purposes of extraction – without considering the cost to culture or local welfare. Large industry and agricultural corporations thus made their way to the island to seek profit from its lush environment and subsidized economic policies, while shipping its wealth to U.S. shareholders. This industrial economic model causes the intrinsic value of natural resource to Puerto Rico to be overlooked. Yet society and its economy are fundamentally intertwined, and both are inherently dependent upon the available natural resources – including water. In the modern industrialized society, however, extraction, contamination, and overuse of water sources continue to create economic wealth at the detriment of both society and the environment.

Prior to the Industrial Revolution, it was believed that the planet's natural wealth was infinite, and profiteers did not imagine that natural abundance could eventually end. Meeting the challenges currently facing modern society – water shortages, extreme weather, deteriorating conditions for food production, ecosystem loss, and sea-level rise – requires a new framework that links solutions for society and economy to the environment (Griggs et al., 2013). In moving away from a former definition of sustainable development that placed society, economy, and Earth into independent silos, a better framework redefines sustainable development as a "development that meets the needs of the present while safeguarding Earth's life-support system, on which the welfare of current and future generations depend" (Griggs et al. 2013). Contemporary economic systems discount the interests of future generations and tend to destroy the very social foundations that maintain functioning societies (Davies, 2017). As a territory of the United States, this type of economic system has been interwoven into the very fabric of island's culture and changing it will require a shift in where society places its value. Thus, for real progress to be made in Puerto Rico, local, territorial, and national policies should place value on the island's natural capital and social foundations, and a cost on actions that are unusable, unsustainable, and that threaten the long-term resiliency of the island.

8.4 Linking to Sustainable Development Goals (UN)

In 2012, the United Nations convened governments from around the world in order to create a set of sustainable development goals (SDGs) for humanity under a unified framework (Stafford-Smith et al., 2017). Considered to be the "the road to dignity" for humankind, the U.N. again convened in 2015 to agree on these SDGs – 17 global goals with 169 associated targets – to be achieved by 2030 (UN, 2015). What followed was a new paradigm for understanding the connection between a functioning planet and a thriving society. Using this new framework, world leaders and policy makers can now formulate comprehensive plans for maintaining Earth's natural resources while providing for an enormous human population. Central to the concept of sustainable development is the food-water-energy nexus, which underpins several important

SDGs that relate to this case study. As global demand for all three increases, greater consideration must be made for utilization of water – a finite resource. Decision-makers in all three domains are beginning to focus their policy and practice on water resource management, ecosystem protection, water supply and sanitation (UN Water, 2017).

Because many of these issues are inextricably linked, the problems addressed in this case study also relate to the food-water-energy nexus. For example, SDG 6, which addresses sustainable water security, aims at universal access to clean water and basic sanitation, and efficient allocation of integrated water-resource management (UN, 2015). SDG 2, sustainable food security, seeks to end hunger and achieve long-term food security and better nutrition through sustainable systems of production, distribution and consumption. SDG 16, peace and justice for sustainable societies, addresses other interlinked SDGs through government transformation and the building of effective, accountable, and inclusive institutions at all levels. These SDGs, combined with suggested interventions for the island's water management problem, offer insight into how sustainable development may hold the key to a more productive and more desirable future for Puerto Rico.

9 Recommendations

9.1 Infrastructure Improvements to Meet water Needs

Recognizing that

- Clean water is a limited resource in Puerto Rico;
- Climate change processes will further reduce the availability of water;
- The water needs of the people in Puerto Rico are not fully met;
- Wastewater treatment cannot handle additional runoff from storm surges;
- Sea level rise may pose additional risks to infrastructure;
- Water delivery depends on reliable energy sources;

Understanding that

- Approximately 60% of water is lost due to water line leaks;
- Leaks are not located or repaired efficiently;
- Puerto Rico's energy supply is vulnerable to storm damage, and energy demands are expected to double by 2100;
- Lack of financial and workforce resources present a major obstacle to PRASA

Acknowledging that

- PRASA is incrementally installing smart meters to improve leak detection
- PRASA is planning to expand its workforce;
- PRASA has implemented solar energy supply for three water treatment plants, and PREPA plans to introduce redundancy into the energy supply.

It is recommended that

- An island-wide reporting system be established that would facilitate crowd-sourcing of leakages with minimal time delay;
- Agencies collaborate to raise awareness of leakages and scarce water;
- PRASA construct additional wastewater treatment plants to handle runoff from increased precipitation and storm surges;
- PRASA retain additional staff to facilitate water quality testing, plant inspections, and locating and repairing leaks;
- Puerto Rican government policy mandate that new developments be relocated landward and existing developments elevated above sea level;
- PRASA and PREPA collaborate to expand alternative energy sources, including solar and backup power generation.

9.2 Participatory Governance for Sustainable Policy Making

Recognizing that

- It is sometimes unclear who is responsible for some infrastructure and services, which hinders repair and maintenance;
- Water management conflicts occur because reservoirs are managed by PREPA, water supply by PRASA, and water resources protected by DNER;
- There is limited funding from the federal and state levels;

Understanding that

- A sustainable approach to water management is needed;
- Participatory leadership is more effective in progressing towards sustainability;
- Collective understanding of the issues is critical to sustainability leadership;
- Puerto Rico lacks representation at the federal level;

Acknowledging that

- Puerto Rico's recovery plan includes: clarifying responsibility for infrastructure and services;
- Rebuilding infrastructure to meet modern codes and enforcing water infrastructure regulations;
- Modernizing access to timely, accurate, and comprehensive information for decision-making;
- Prioritizing spending to focus on water, education, and the natural environment.

It is recommended that Puerto Rico's policymakers

- Collaborate on decision-making with relevant agencies and other stakeholders, including farmers and industrial actors;
- Collaborate with federal agencies to establish a shared scientific database for scientific research and data collection (e.g. water quality monitoring);
- Collaborate with outside agencies to optimize funding allocation to mitigate the effects of climate change and improve water management;
- Consider the impacts of climate change to revise policies regarding the construction and maintenance of infrastructure, particularly water supply infrastructure.

9.3 Reducing Waste and Pollution

Recognizing that

- Puerto Rico's waterways are frequently exposed to raw sewage discharge;
- Leaching and runoff from landfills is a major source of groundwater pollution;
- Greenhouse gas emissions exacerbate climate change;

Understanding that

- Approximately 4 million tons of solid waste is generated per year in Puerto Rico, with a recycling rate of 10%;
- Landfills are Puerto Rico's only current disposal option;
- Sewage treatment sludge is disposed of in landfills;

Acknowledging that

- Of 29 active landfills, regional authorities have cooperated with the EPA to close or mitigate 13;
- 4 alternate disposal are sites planned: 2 clean material recovery facilities and 2 composting facilities;
- The Department of Education and 'Hogar Crea' consortiums promote waste reduction.

It is recommended that Puerto Rican agencies and NGOs

- Expand initiatives to promote waste reduction and recycling through education to increase effectiveness;
- Collaborate with federal agencies to determine alternative waste disposal, such as Waste-to-Energy;
- Collaborate with the EPA to identify landfills for closure that threaten the environment;
- Develop ecosystem water quality monitoring and reporting program for the Rio Grande de Arecibo and other surface water;
- Organize watershed clean-up teams to remove waste and abandoned vehicles from waterways and surrounding areas
- Create DNER program to inspect and enforce pollutant discharge regulations.

9.4 Freshwater Storage

Recognizing that

- Severe droughts periodically reduce water supply, and will become more common in the future;
- Ground and surface water storage are limited by Puerto Rico's geography;
- Water management conflicts occur because reservoirs are managed by PREPA, water supply is managed by PRASA, and DNER is responsible for protecting water resources; decision-making is not shared.

Understanding that

- Of 17 reservoirs, 9 dams generate energy; the rest provide clean water storage;
- Reservoirs in large river basins provide only transient storage capacity due to high sedimentation rates that are expected to increase under climate change;
- Wetlands buffer against pollution and saltwater intrusion;
- There is confusion over whether man-made water storage should be administered as a natural resource.

Acknowledging that

- USDA's Natural Resources Conservation Service has helped fund irrigation water reservoirs;
- Foundation for Puerto Rico is funding a two-year program to install water cisterns in six regions.

It is recommended that

- Policymakers seek to expand decentralized water storage capacity through an extended rainwater capture and cistern programs for individuals, farmers, and remote areas;
- Collaborate with federal agencies to fund construction of additional irrigation reservoirs and other water catchments;
- DNER protect and expand wetland buffers to capture rainwater and sedimentation;
- DNER, EPA, USDA, and other agencies collaborate on water management education programs for farmers.

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