Exploring drought and annual rainfall in Puerto Rico

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Exploring drought and annual rainfall in Puerto Rico

By

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Abstract

As a consequence of climate change, the frequency and intensity of droughts in Puerto Rico are projected to increase, making mitigation a high priority. The overall purpose of my thesis project is to better understand the characteristics of drought occurrence in Puerto Rico by examining its spatial accumulation, duration, frequency, and severity, the trends in annual rainfall and dry days, and the factors that affect freshwater availability. My research aims to determine whether drought conditions are becoming more intense, where drought conditions in Puerto Rico occur most frequently, and whether the local climate is exhibiting an overall drying trend. In chapter one, I provide a background on drought by describing the different types of drought, factors that influence drought conditions, and water use and resources in Puerto Rico. In chapter two, I examine drought events from 2000 to 2020 by analyzing the spatial distribution, characteristics, and effects of recent drought occurrences. In chapter three, I analyze rainfall, streamflow and reservoir data; and examine water use per capita, population, and issues in water storage and transport infrastructure. In chapter four, I summarize my thesis and provide conclusory statements. From 2000 to 2020, drought conditions occurred in some areas more frequently than others in an uneven distribution across the territory. Drought conditions most affected the southeast region of the main island of Puerto Rico, most frequently occuring the municipalities of Salinas, Cayey, and Guayama. Moderate droughts have occurred roughly every two to three years since 2000, lasting an average of about 5 months. While no severe droughts were registered by USDM from 2000 to 2014, severe droughts occurred in 2015-2016, 2019, and 2020, lasting 48, 13 and 8 weeks, respectively. However, the findings in this rainfall analysis indicate that Puerto Rico is not getting drier when it comes to annual rainfall or annual dry days. My research clearly illustrates that although annual rainfall is increasing rather than decreasing, water availability continues to be limited by lack of storage capacity, dilapidated infrastructure, and competing water uses. Further studies on monthly and seasonal rainfall would be helpful to further investigate how rainfall regimes are changing across Puerto Rico.

Chapter one: Introduction to drought

Abstract

Climate change is causing the frequency and intensity of climate disasters to increase. In Puerto Rico, drought risk, intensity and extremes are also expected to increase in the future. In this chapter, I provide a background on drought by describing the different types of drought, factors that influence drought conditions, and water use and resources in Puerto Rico. Recent droughts in 2015 and 2019 led to mandatory water rationing. Aging water management infrastructure, decreasing capacity of reservoirs, and climate change projections underpin the importance to evaluate drought, rainfall and water resources in Puerto Rico. Downscaled climate models indicate that temperatures, total annual dry days, and maximum consecutive dry days will increase island-wide, while rainfall is projected to decrease (Henareh et al. 2016). Droughts are a departure from normal conditions, the phenomenon is considered a normal part of climatic variability. The effects of drought vary due to the intensity, duration, and spatial coverage of the drought event. There are several types of drought, including meteorological, agricultural, hydrological, socioeconomic and ecological drought.

Introduction

Background

Costly climate disasters are on the rise. According to the NOAA National Center for Environmental Information who tracks the number of billion-dollar disasters in the US each year, 2021 saw 20 disasters. The year 2020 broke the record for the highest number of billion-dollar events at 22 disasters, while the average number of yearly disasters from 1980 to 2020 is 7 disasters (Figure 1). The previous record high was 16 disasters, occurring in 2011 and 2017 (NOAA NCEI 2021). While the frequency of natural disasters is increasing overall, the annual number of billion dollar drought disasters in the United States has remained relatively the same (NCEI 2021; Figure 1), though this apparent lack of

increase could be more related to the wide-reaching and less punctual nature of drought (less costly due to lack of infrastructural damage). As a consequence of climate change, the frequency and intensity of droughts are projected to increase. According to the Fourth National Climate Assessment, climate change is attributed to an increase in the frequency and intensity of extreme events (Gould et al. 2018). For drought specifically, rising temperatures and changing rainfall regimes are effects of climate change that will likely lead to more frequent and intense periods of drought (Gould et al. 2018).

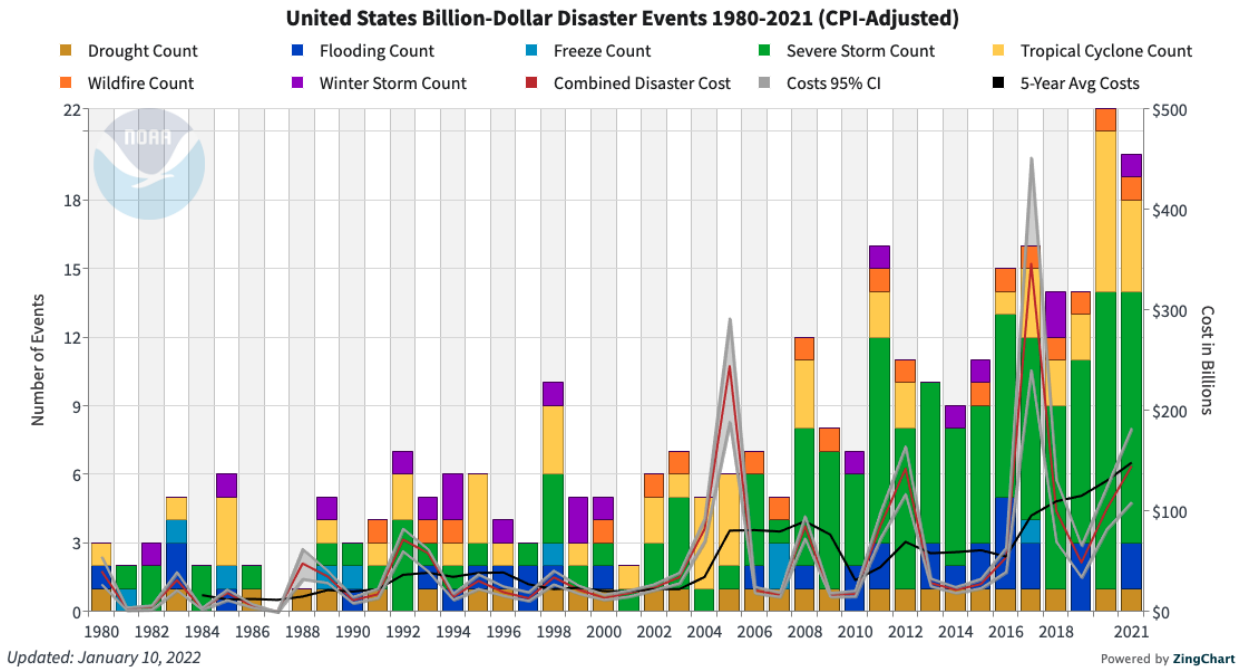

Figure 1. Number of billion-dollar disasters from 1980 - 2021. Source: NOAA National Centers for Environmental Information (NCEI) 2022.

According to downscaled climate projections for Puerto Rico, drought risk, intensity and extremes are also expected to increase in the future (Bowden et al. 2020; Henareh et al. 2016; Gould et al. 2015). This rising frequency and intensity of drought events make mitigation a high priority. However, drought is considered to be a difficult hazard to understand due to its complexity and the difficulty involved in its detection and definition (Wilhite 2000).

Puerto Rico experienced periods of drought in 2015, 2017, and 2019. For two of the three drought years, 2015 and 2019, water rationing was required for 1.2 million and 250,000 residents, respectively (DNER 2016; CNN 2019). Now, in the context of an economic recession, aging water management infrastructure, and decreasing capacity of reservoirs, it is of utmost importance to evaluate drought, rainfall and water resources in Puerto Rico.

Thesis structure

My research aims to determine where drought conditions in Puerto Rico occur most frequently, whether drought conditions are becoming more intense, and whether the local climate is exhibiting an overall drying trend. The overall purpose of my thesis project is to better understand the characteristics of drought occurrence in Puerto Rico by examining its spatial accumulation, duration, frequency, and severity, the trends in annual rainfall and dry days, and factors that affect freshwater availability.

In chapter one, this chapter, I provide a background on drought by describing the different types of drought, the factors that influence drought conditions, climate change, and water use and resources in Puerto Rico. This information provides helpful context for the thesis, and provides evidence for the need to better understand and manage drought and freshwater resources in Puerto Rico.

In chapter two, I examine drought events in Puerto Rico from 2000 to 2020 by analyzing the spatial distribution, characteristics, and effects of recent drought occurrences in three ways. First, to identify the regions where drought conditions most frequently occur, I determine the spatial distribution of accumulated drought exposure through GIS analysis. Second, I examine the characteristics of recent droughts by analyzing their duration, frequency, and intensity. Third, to understand the effects of recent drought in the most frequently affected region, I explore the agricultural production and natural protected areas located in select municipalities.

In chapter three, to determine whether droughts are becoming more severe and potential influencing factors, I analyze rainfall, streamflow and reservoir data; and examine water use per capita, population, and issues in water storage and transport infrastructure in Puerto Rico. I also examine regional variation for meteorological and hydrological drought. First, I analyze rainfall data to determine whether annual rainfall is decreasing and whether dry days are increasing in frequency. Second, I analyze streamflow data to determine how the severity and regional variation of hydrological conditions in key rivers during the 2015 drought and other drought years. Third, I examined reservoir level data to compare the onset and severity of hydrological drought in important reservoirs. In chapter four, I review my findings from chapters two and three, discuss their potential implications and recommend opportunities for future drought research. I will briefly discuss factors relating to socioeconomic drought including population, water storage and infrastructure and water consumption. Although I will not analyze agricultural drought, it is helpful to keep in mind that future freshwater availability in Puerto Rico may also need to satisfy an elevated demand for agricultural water as the island works to improve food security through increased agricultural production. The effects of drought on agricultural, forests and natural habitats are further discussed in chapter three.

Defining drought

Drought is a natural phenomenon that results from a deficiency in precipitation. When people think of drought, they might imagine a desert or an arid landscape. However, it is important to note that aridity, or dryness reflecting a region's naturally low rainfall, is a continuous component of the area's climate regime and is not to be confused with drought, which is a temporary departure from normal rainfall conditions (Wilhite 2000). While droughts are a departure from normal conditions, the phenomenon is considered a normal part of climatic variability. The effects of drought vary due to the intensity, duration, and spatial coverage of the drought event. The *intensity* of drought is the degree of

precipitation shortfall and or severity of impacts and is measured by rainfall or indexes. The *duration* of drought is the length of time its effects last. Droughts usually take two to three months to establish and can last for years. Droughts also differ in terms of their spatial characteristics. The *spatial coverage*, or extent of the areas affected by severe drought, evolve gradually, and regions of maximum intensity (i.e., epicenter) shift from season to season. The magnitude of drought is associated with timing of onset, intensity, and duration.

There are several types of drought, including *meteorological, agricultural, hydrological, socioeconomic,* and *ecological drought* (Figure 2). A *meteorological* drought, sometimes referred to as climatological drought, occurs when there is a deficiency in precipitation relative to normal conditions (Wilhite 2000). Since normal conditions vary greatly across the globe, the parameters for meteorological drought are region-specific (Wilhite 2000). Furthermore, the effects of meteorological drought can depend on the timing of the event due to seasonal variation in precipitation.

An *agricultural drought* occurs when deficient precipitation affects soil moisture, which in turn, inhibits plant growth or yield. The timing of an agricultural drought influences the impact that dry conditions may have on crops. For example, dry conditions in the early stages of growth may have less of an impact than the same dry conditions later in the growth process, when the plant requires sustained subsoil moisture conditions (Wilhite 2000). Furthermore, since different crops require different growing conditions, the impacts of drought on a crop also depend on the growth cycle and water demand of a particular crop.

Hydrological drought occurs when dry conditions become evident in surface and groundwater, such as streamflow, reservoirs, and aquifers. Hydrological drought can be exacerbated by water management and consumption. During a hydrological drought, conflicts for water use may arise between domestic, agricultural, and industrial sectors.

The definitions for meteorological, agricultural, hydrological and socioeconomic droughts are anthropocentric because their focus is centered around deficiencies for human needs and not necessarily the effects of deficient rainfall on ecological function. *Socioeconomic drought* occurs when water deficiency causes an insufficient supply of an economic good such as food, hay, or potable water (Wilhite 2000). *Ecological drought* is a newer concept, defined as "an episodic deficit in water availability that drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedbacks in natural and/or human systems" (Crausbay et al. 2017). The concept of ecological drought arose out of a perceived need to include ecosystem water demand when considering drought, rather than focusing solely on the immediate needs of the human population. Crausbay et al. 2017 highlighted that it is important to consider the effects of drought on ecosystems given that humans rely on ecosystem services for a variety of needs due to the context of the coupled human-natural systems in which we live.

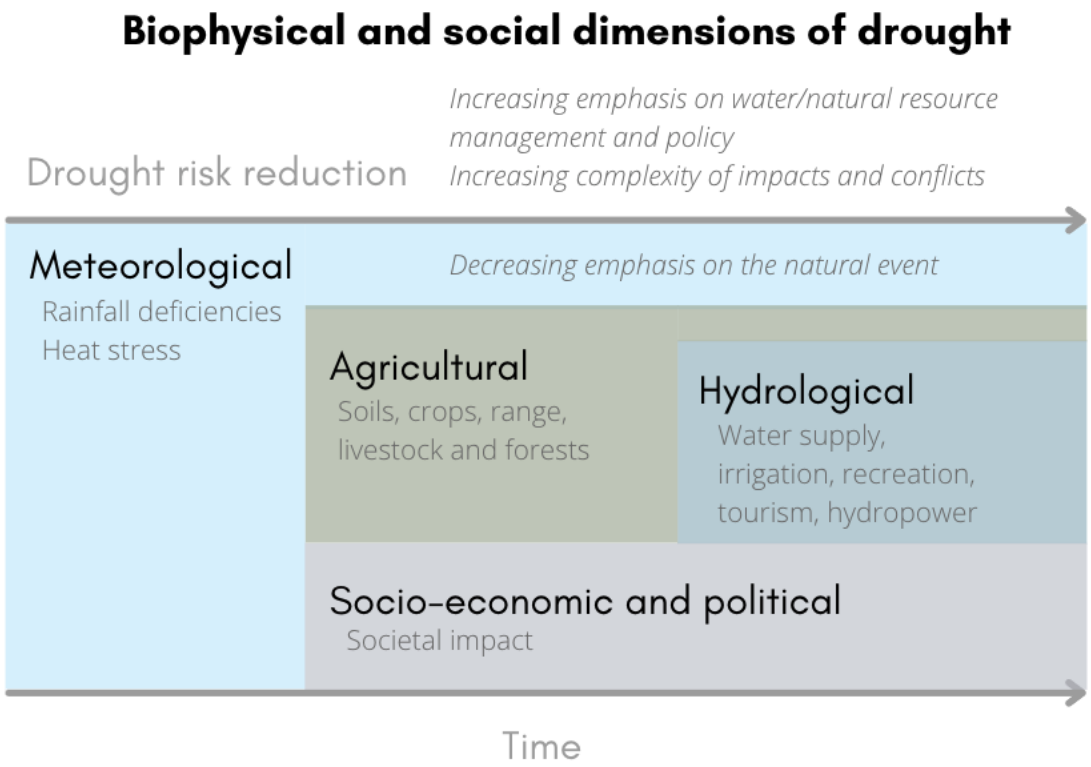

Figure 2: The sequence of the drought occurrence and their associated characteristics. Adapted from the National Drought Mitigation Center.

Factors that influence drought conditions

Since all types of drought begin with meteorological drought, or below normal rainfall, it is important to understand the dynamics that control rainfall in the Caribbean. As previously mentioned, regional rainfall is influenced by natural climate variability. Climate variability, in turn, is influenced by large-scale climate and ocean dynamics such as El Niño Southern Oscillation and the North Atlantic Oscillation. Both phenomena cause variations in temperature and precipitation and have been associated with drought events in areas of the Caribbean and elsewhere. Rising sea surface temperatures have also been associated with an increase in rainfall for the Caribbean region, particularly during the early rainfall and late rainfall seasons (Glenn et al. 2015). In Hawaii, below normal rainfall has been linked to El Niño events (Frazier 2017).

Mote et al. 2017 found a direct link between the Saharan Air Layer (SAL) and drought in eastern Puerto Rico. The Saharan Air Layer is a dry mass of dust-rich air that forms over the African Saharan desert from late spring to early fall (Mote et al 2017). Studies suggest that particles in the SAL inhibit the formation of convective clouds, resulting in a reduction in rainfall. Other local scale climatic factors are also associated with drought, such as high temperatures, high winds, and low relative humidity (Wilhite 2000). Projections show SAL emissions may decrease as greenhouse gas concentrations continue to increase. Recent modeling carried out by NASA indicates that in the next 20 to 50 years, Saharan Dust activity will decrease by 30% or more (Streiff 2021). Decreased SAL emissions would likely mean increased rainfall and a higher incidence of Atlantic basin cyclones, both of which are suppressed by the presence of SAL emissions (Amato et al. 2016).

While drought is influenced by large-scale and local climate dynamics, it can also be exacerbated by social and infrastructural factors on a local scale. All types of drought stem from a prolonged

deficiency in precipitation caused by “persistent large-scale disruption in the global circulation pattern of the atmosphere” (Wilhite and Pulwarty 2016), but certain types of drought can arise due to social factors. Agricultural, hydrological, and socioeconomic drought are considered phenomena that arise from the “interplay between the natural characteristics of the event and the human activities that depend on precipitation and water management to provide adequate supplies to meet societal and environmental demands” (Wilhite and Pulwarty 2016). In the context of deficient rainfall, soil water or freshwater supply may become limited due to inadequate management of available freshwater, leading to agricultural or hydrological drought.

In other words, the severity of the effects of drought and the type of drought that is declared are influenced by human activity. Consequently, when analyzing a specific drought event, it is important to consider a variety of social factors, such as human population, water use, resource management, and infrastructure. As previously discussed, meteorological drought is considered to be a rainfall deficiency relative to normal conditions. As such, meteorological drought is the only type of drought to be regarded as being caused solely by climatic forces, without the influence of social factors. Nevertheless, the climate projections for more intense and frequent droughts in the future resulting from climate change caused by anthropogenic activities imply that meteorological drought is now linked to large-scale social influence as well.

Climate change and drought

According to the Intergovernmental Panel on Climate Change (IPCC), the frequency of droughts and heatwaves have increased since the 1950s (IPCC 2021). In addition to increased drought conditions across the globe, many island groups can expect to see increased aridity (Masson-Delmotte and Moufouma-Okia 2016). According to the IPCC, warmer conditions over land increase atmospheric

evaporative demand and the severity of droughts; and greater warming over land than over the ocean, causes a shift in patterns of atmospheric circulation, contributing to regional drying (IPCC 2021).

In the Caribbean, significant warming trends in mean air temperature and temperature extremes are clear, especially since the 1950s (IPCC 2021). In the coming decades, Caribbean rainfall in the months of June, July and August will likely continue to decrease (IPCC 2021). Increased evapotranspiration due to higher temperatures will likely cause increase severity of agricultural and ecological droughts in the Caribbean region (IPCC 2021).

In Puerto Rico, downscaled climate models show consistency in indications that temperatures, total annual dry days, and maximum consecutive dry days will increase island-wide. Rainfall projections are less certain, with some models indicating drastic reductions (Henareh et al. 2016) and others less drastic reduction or even increases for some parts of the island (Bowden et al. 2018).

Temperatures in Puerto Rico are projected to increase significantly more than average global warming. The island is expected to warm about 8° C by 2100 in comparison to the projected global increase of 3 to 5°C (Hayhoe 2013, Henareh et al. 2015). Rainfall is projected to decrease between 312 and 916 mm between the time periods 1960-90 and 2071-2099, depending on the IPCC global greenhouse gas emission scenarios used in the model (Henareh et al. 2015). Furthermore, total annual dry days (days with less than 1 mm of rainfall) and maximum consecutive dry days are projected to increase (Henareh et al. 2016). Consequently, drought intensity and extremes are also expected to increase in Puerto Rico in the future (Gould et al. 2015). Overall, projections point toward a drier and warmer future for the island.

Water resource conflicts and drought

Although 71% of the Earth's surface is covered in water, only 1% is freshwater that is accessible to humans (USGS 1998). The majority of water on the planet is saltwater, and most of the existing

freshwater is inaccessible because it exists in glaciers, ice caps or in deep groundwater aquifers. While freshwater resources are limited, the demand for water is rising. In 2021, the global population is about 7.7 billion people. By 2100, the world population is expected to increase to 11.2 billion (United Nations 2017). The expanding global population will require an intensification in agricultural production, and as nations continue to develop, water consumption will increase with more water-intensive societal habits such as industrialization and an increased incorporation of meat and dairy into the global diet. Even in current climate conditions with our current human population, conflicts for water use are quite common.

Competition for freshwater resources can occur on different spatial scales. Bodies of water often overlap political boundaries, making it necessary for water managers from different counties, states, or even countries to collaborate in the management of water resources. On a local level, conflicts for water usage arise between agricultural, domestic, and industrial sectors. Natural resource managers may also disagree with other entities that manage water supply regarding the amount of water that should be allotted to maintain ecosystem health. Puerto Rico is not exempt from conflicts regarding water use and allocation. During the 2015 drought, a conflict arose regarding water allocation between the domestic and agricultural sectors. Farmers in the southwestern region complained that when water was scarce, the priority access was allocated to domestic use in nearby urban areas despite the farmers' perceived legal right to water resources (Personal communication focus group participant, 2016).

To ensure water is available for those who need it, managers must prepare for extreme events, particularly in regions where both drought exposure and intensity is projected to increase, as is the case for Puerto Rico.

Study site

Puerto Rico is the smallest of the Greater Antilles islands and is located at 18°N and 66°W. Island topography consists of coastal plains, hills, and a central mountain range with land elevation ranging from sea level to 4390 ft (1338 m) (Gould et al. 2015). The Island's climate is tropical, with average temperatures ranging between 60 and 90°F (15.56 to 32.2 °C), a variance caused by elevation and seasonality (Gould et al. 2015). Rainfall in Puerto Rico ranges significantly within a relatively small geographic region, with some areas receiving as little as 30 in (762 mm) of average annual rainfall, and others up to five meters (Colón 2009). The large range of annual rainfall is caused by interactions between climate-ocean dynamics and the physiography of the island.

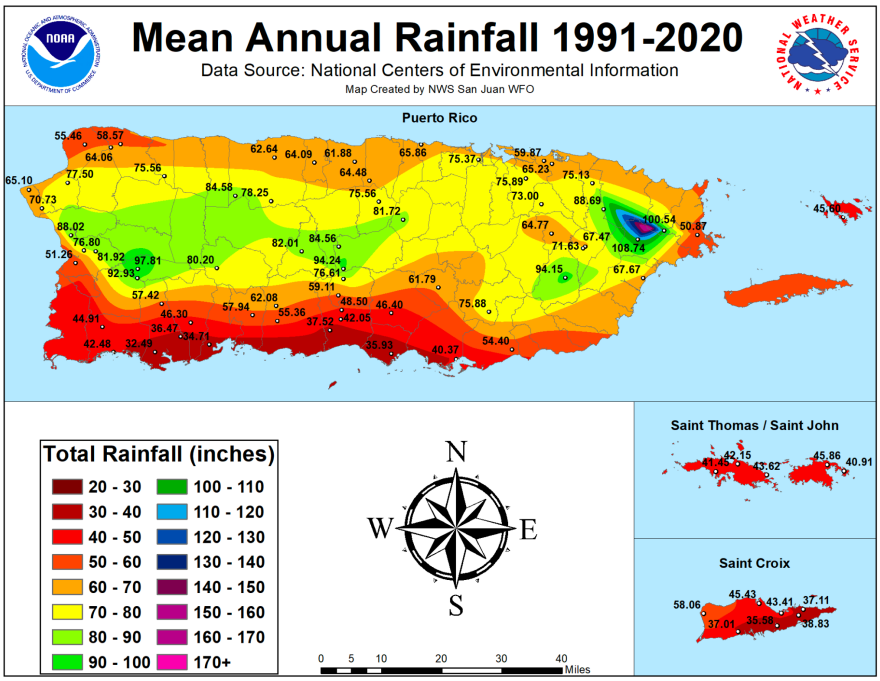

Figure 3: Mean annual rainfall in Puerto Rico and the US Virgin Islands from 1991 to 2020. Source: Map created by NWS-WFO San Juan. Data: NCEI, 2021.

Rainfall in Puerto Rico results from orographic lift and frontal systems. Orographic rainfall occurs when winds force moist air up the mountainside. As it rises, the moist air cools, forming clouds and then falling as rain. Because the moisture has already fallen while the air mass rises one mountainside, the

opposite side of the mountain does not receive much rain and is usually dry in comparison (Figure 3). This dry region is referred to as a rain shadow. Winds blow over Puerto Rico's central mountain range, forming orographic rainfall and causing a rain shadow in the southern region. This is why municipalities in the central mountains receive significant rainfall, while southern municipalities are much more arid. The island also receives frontal systems, such as the cold fronts from the north, and tropical disturbances from the ocean to the east (Lugo et al. 2011).

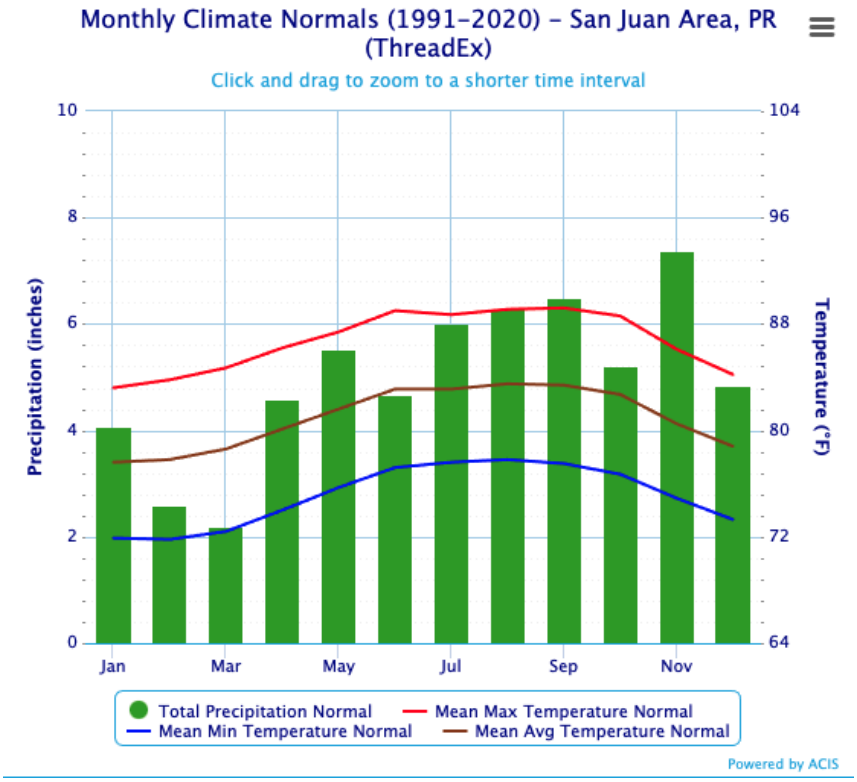

Figure 4: Monthly rainfall and temperature normals in San Juan, Puerto Rico from 1991- 2020. Source: NOAA NWS, 2022.

While rainfall in Puerto Rico is distributed throughout the year, there is a relative dry season from January to April followed by a wetter season from May to October (Larsen 2000). There is also a relatively drier period during the summer months, which is commonly referred to as the 'mid-summer drought'. However, it should be noted that the mid-summer "drought" is an element of annual rainfall

trends and is therefore not technically a drought; as droughts are a departure from normal conditions and not a yearly pattern (Magaña et. al. 1999). Figure 4 shows the average rainfall in a climograph of San Juan.

Puerto Rico has a complex network of rivers and streams that discharge rapidly to the ocean. Due to the absence of natural lakes, island residents primarily rely on human-made reservoirs for freshwater storage. In the dry southern region, however, 40 percent of water is supplied by aquifers, where over-extraction has induced saltwater intrusion (Lugo et al. 2011). The public water company, Puerto Rico Aqueduct and Sewer Authority (PRASA), supplies water to the majority of the population. Due to the PRASA's complex grid of aging piping and infrastructure, between 50 and 60% of managed water is lost (PRASA 2015), over three times the US national average of 16 percent (EPA 2015). Leaking infrastructure causes water reserves to be more quickly depleted in drought scenarios. Though some of the water lost to aging infrastructure may help to recharge aquifers, the loss is problematic in scenarios of severe drought where water reserves become more scarce and the lost water is unavailable when needed most.

In 2008, DNER reported that 78 percent of water used in Puerto Rico comes from surface water, whereas the remaining 22 percent is groundwater. Of the surface water consumed, 70 percent is from human-made reservoirs, and the remaining 30 percent is taken directly from rivers (DNER 2008). Eighty-nine percent of water use in Puerto Rico is for domestic purposes, nine percent is used for agricultural purposes and the remaining water is used for industrial and energy purposes (DNER 2008). Aquifers are a key source of water in the southern region, providing about 31 percent of water used for domestic and agricultural uses in the region. Half of the groundwater used in the south is for domestic and other use by AAA, the remaining half is for agricultural and industrial use (DNER 2008). According to the DNER, various factors have caused a decline in the recharge of the southern aquifers in the last

several decades, including a decrease in irrigated area, increased use of reservoir water for domestic use, and increased efficiency of irrigation water use (DNER 2008).

For the conservation and optimal use of water resources in Puerto Rico, the Department of Natural and Environmental Resources created the Water Plan Office (la Oficina del Plan de Aguas). The Office updated the 1996 Integrated Water Plan, which contains short- and long-term measures to manage water and address the following management challenges: 1) the degradation of supply sources, 2) the inefficient use and exploitation of the resource, 3) the deficit in the availability of the resource in particular areas and limitations for the development of new sources of supply, and 4) the absence of criteria that ensure the maintenance of the environmental functions of aquatic systems.

Drought conditions in Puerto Rico are monitored by a variety of entities, including Puerto Rico's Executive Drought Committee, the National Oceanic and Atmospheric Administration, the National Weather Service, the US Geological Survey and the US Drought Monitor (USDM). The USDM combines a variety of drought-related data to produce weekly drought maps. In Chapter two, I will go into detail about the US Drought Monitor and explore the spatial distribution of drought conditions from 2000 to 2020 using USDM geospatial data.

The demand for freshwater significantly influences a region's drought vulnerability because it determines how quickly the local water supply is consumed. In periods of normal precipitation, the demand for freshwater resources in Puerto Rico are met without issue, allowing consumers to develop the impression that water resources are endless and to consume as such. However, in periods of drought, the normal demand for freshwater often exceeds the available supply, making increasingly important factors such as per capita water use, population, surface and groundwater withdrawals, and water supply infrastructure.

In recent years, drought has inconvenienced some and greatly affected others in Puerto Rico, leading to significant agricultural losses, mandatory water rationing, and effects on wildlife. Climate

projections downscaled for Puerto Rico and the Caribbean region indicate droughts may become more frequent by midcentury. My research focuses on whether recent drought conditions and annual rainfall are changing to help understand how the local climate has been shifting in recent decades.

With this research I aim to identify where drought conditions in Puerto Rico occur most frequently, whether drought conditions are becoming more intense and frequent, and whether the local climate is exhibiting an overall drying trend. I will study these factors by analyzing 20 years of data from the US Drought Monitor and 40 years of rainfall data across the island. The results will indicate whether current conditions are trending toward the drier conditions predicted by downscaled climate projections for midcentury.

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Chapter two: Spatial distribution of accumulated drought exposure in Puerto Rico from 2000 to 2020

Abstract

In this chapter, I analyze drought in Puerto Rico from 2000 to 2020 in three ways. First, I determine the spatial distribution of accumulated drought exposure to identify the regions where drought conditions most frequently occur. Second, I discuss the duration, frequency, and intensity of drought events, and third, I explore the effects of drought conditions in the most frequently affected region. Third, I will discuss land use characteristics in the areas identified as most frequently affected by drought conditions.

Understanding the characteristics of drought and the areas where conditions have repeatedly accumulated in the last 21 years provides a helpful long-term view of drought in the past, and a potential indication where drought may continue to accumulate in the future. To generate a long term view of drought in Puerto Rico, I processed 21 years of drought condition polygons from the US Drought Monitor and joined to a hexagon grid using GIS software, yielding a map that displays 21 years of non-consecutive drought weeks in one image. To analyze the duration, frequency, and intensity of droughts, I downloaded tabulated .csv data of drought weeks from the USDM website.

To generate a long term view of drought in Puerto Rico, I processed 21 years of drought condition polygons from the US Drought Monitor and joined to a hexagon grid using GIS software, yielding a map that displays 21 years of non-consecutive drought weeks in one image. To analyze the duration, frequency, and intensity of droughts, I downloaded tabulated .csv data of drought weeks from the USDM website.

In Puerto Rico, moderate droughts have occurred roughly every two to three years since 2000, lasting an average of 21 weeks (about 5 months). While no severe droughts were registered by USDM from 2000 to 2014, severe droughts occurred in 2015-2016, 2019, and 2020, lasting 48, 13 and 8 weeks, respectively. The sole extreme drought event since 2000 occurred from 2015 into 2016 and lasted 33 weeks.

The purpose of this chapter is to better understand contemporary drought events in Puerto Rico in the 21st century. For this purpose, I will answer the following research question and subquestions: **Research question 1a: What is the spatial distribution of accumulated drought exposure in Puerto Rico from 2000 to 2020? Research question 1b: What are the characteristics of 21st century droughts in Puerto Rico (duration, frequency and spatial extent)?**

Introduction

As mentioned in the introductory chapter, drought is defined as a temporary departure from normal rainfall conditions. In this chapter, I explore the spatial accumulation, duration, frequency, and intensity of drought events in Puerto Rico in the last 21 years through data provided by the US Drought Monitor. To determine the accumulated, non-consecutive drought exposure across Puerto Rico from 2000 to 2020, I will use the USDM downloadable shapefiles of weekly drought conditions. In an analysis of drought characteristics (duration, frequency, and intensity) from 2000 to 2020, I use tabulated excel data containing the weekly percentage of land area exposed to each drought classification from 2000 to 2020. I will also describe the impacts of drought on land and species in the affected regions. For context, I will begin the chapter by providing a general overview of drought in the 20th and 21st centuries.

Drought history in Puerto Rico

During the 20th century, the island endured five major periods of drought exposure: 1966 to 1968, 1971 to 1974, 1976 to 1978, 1993 to 1995, and 1997 to 1998 (Larsen 2000). The most severe drought period was the 1966 to 1968 drought when average annual rainfall reached 32% below normal (Larsen 2000). Another major drought was that of 1993 to 1995 when the island received 18% below average annual rainfall and experienced mandatory water rationing and $165 million in agricultural

losses (Larsen 2000). At the time of this publication, Puerto Rico's driest year since 1900 was 1967 when the island's average annual rainfall was 1065 mm (Larsen 2000).

During the 21st century, there have been seven short term, low intensity droughts in Puerto Rico (2000, 2002, 2005, 2007, 2008, and 2017). From 2015 to 2016, a major period of drought was registered by the US Drought Monitor (USDM), provoking an emergency declaration by Puerto Rico's governor (DRNA 2016) and a USDA Disaster Declaration in 20 municipalities (USDA 2015). These declarations were swiftly followed by water rationing for an extensive portion of the population and orders for restrictions in water use (DRNA 2016). Apart from the effects felt by the general population, the 2015 drought had consequences in natural habitats and agriculture. According to the official drought report that was published by the Puerto Rican Department of Natural and Environmental Resources, the drought period of 2014 to 2016 induced multiple fish kills, wildfires, and agricultural losses of $13 million (DNER 2016). While the island's average annual rainfall is 1687 mm (66 inches) (Daly et al. 2003), the preliminary values for annual rainfall for the years 2014, 2015, and 2016 were 1485, 1312 and 1885 mm, respectively (58, 52 and 74 inches) (NOAA 2017) resulting in a period of extreme drought from 2015 through 2016. These values are averaged for the island, and as such do not represent the severity of the drought in the most affected areas. This period of drought reached the extreme drought category for about 8 months and covered up to 25% of Puerto Rico's land area. Severe drought lasted for 12 months and covered 45% of Puerto Rico, while moderate drought occurred for about 20 consecutive months and covered 68% of the land area (Álvarez-Berríos et al. 2018). Drought conditions concentrated around the southeast region of the main island and covered Vieques and Culebra.

Understanding trends in the location and spatial extent of drought recurrence enables us to better understand the effects of drought on agriculture and natural landscapes. A clear understanding of drought trends allows for improved and targeted application of drought mitigation and assistance strategies. For example, Kuwayama et al 2018 used data from the US Drought Monitor to estimate the

impacts of incremental drought on crop yields of soybean and corn in the US in an effort to help policymakers improve the design of USDA drought assistance programs (Kuwamaya 2019). In Puerto Rico, Álvarez-Berríos et al. 2018 found that while drought from 2000 to 2017 has more frequently affected the east region of the island, drought-related conservation practices have been focused in the west. These findings were taken into consideration by the Caribbean Area Natural Resources Conservation Service to help guide their resource conservation efforts in Puerto Rico. Understanding the areas where drought has repeatedly accumulated in the last 20 years, including new data from droughts in 2019 and 2020, provides a helpful long-term view of drought in the past, and a potential indication where drought may continue to accumulate in the future. In this chapter, I first pose the question: **What is the spatial distribution of accumulated drought exposure in Puerto Rico from 2000 to 2020?**

Based on the spatial extent of the droughts of 2017, 2019 and 2020, which primarily affected the southern coast and east side of the main island of Puerto Rico, I expect that the distribution and accumulation of drought weeks will increase in the southern coast as I update the map from Alvarez et al. 2018. Because it lasted a significant number of weeks, the areas most affected by the 2019 drought will see an increase in the total number of drought weeks. The extent of the 2019 drought changed significantly over time, and it will be interesting to see the areas that were affected most. The updated map will likely appear fairly similar to that of Alvarez et al 2018, as the number of drought weeks that will be added from years 2017 to 2020 is fairly low compared to the total number of weeks since 2000. In other words, the drought distribution in the updated map will likely maintain the general drought distribution to that of Alvarez et al. 2018. Additionally, the latest and most significant droughts mainly affected the same region as the most frequently drought affected area from 2000 to 2016.

Data and methods

The United States Drought Monitor

The United States Drought Monitor publishes weekly maps that display the extent of drought conditions across the United States, Puerto Rico, and US affiliated Pacific and Virgin Islands. The USDM also makes tabulated data available for download.

The US Drought Monitor (USDM) is collaboratively managed by the National Drought Mitigation Center (NDMC) at the University of Nebraska-Lincoln, the United States Department of Agriculture (USDA), and the National Oceanic and Atmospheric Administration (NOAA). Since 2000, the USDM has used a variety of drought indicators to produce geospatial information that indicate areas of weekly drought exposure, such as the Palmer Drought Severity Index, Climate Prediction Center (CPC) Soil Moisture Model Percentiles, USGS Weekly Streamflow Percentiles, Standardized Precipitation Index, and drought indicator blend percentiles (USDM 2022).

Next, I will briefly describe four components used to develop the USDM drought classification, starting with the Palmer Drought Severity Index (PDSI). The PDSI is a water balance-based index that uses precipitation, temperature, and soil moisture capacity data to describe the intensity and duration of meteorological drought (Alley 1984). PDSI values of -2.0 or less indicate drought conditions. Soil moisture anomaly conditions are mapped for the United States by the NOAA NWS Climate Prediction Center, though this information is not currently available for Puerto Rico and is not considered for local drought maps. In Puerto Rico, root zone soil saturation maps developed by Puerto Rico Agricultural Water Management (PRAGWater.com) are used. Another indicator incorporated into the USDM drought classification is the USGS Weekly Streamflow Percentiles. A streamflow percentile is the day's percent of the flow values for that particular day during the period of record. A percentile below 20 is considered moderate drought, while exceptional drought is considered 2 or below (USDM 2018). The Standardized Precipitation Index is based on rainfall proximity to normal values. An SPI value of -0.8 or below indicates drought conditions. In addition to the aforementioned parameters, the USDM incorporates opinions from local experts in the creation of the weekly drought exposure maps. This aforementioned

information is combined to classify drought severity as abnormally dry (D0), moderate drought (D1), severe drought (D2), extreme drought (D3), or exceptional drought (D4).

			Ranges				
Category	Description	Possible Impacts	Palmer Drought Severity Index (PDSI)	CPC Soil Moisture Model (Percentiles)	USGS Weekly Streamflow (Percentiles)	Standardized Precipitation Index (SPI)	Objective Drought Indicator Blends (Percentiles)
D0	Abnormally Dry	Going into drought: • short-term dryness slowing planting, growth of crops or pastures Coming out of drought: • some lingering water deficits • pastures or crops not fully recovered	-1.0 to -1.9	21 to 30	21 to 30	-0.5 to -0.7	21 to 30
D1	Moderate Drought	• Some damage to crops, pastures • Streams, reservoirs, or wells low, some water shortages developing or imminent • Voluntary water-use restrictions requested	-2.0 to -2.9	11 to 20	11 to 20	-0.8 to -1.2	11 to 20
D2	Severe Drought	• Crop or pasture losses likely • Water shortages common • Water restrictions imposed	-3.0 to -3.9	6 to 10	6 to 10	-1.3 to -1.5	6 to 10
D3	Extreme Drought	• Major crop/pasture losses • Widespread water shortages or restrictions	-4.0 to -4.9	3 to 5	3 to 5	-1.6 to -1.9	3 to 5
D4	Exceptional Drought	• Exceptional and widespread crop/pasture losses • Shortages of water in reservoirs, streams, and wells creating water emergencies	-5.0 or less	0 to 2	0 to 2	-2.0 or less	0 to 2

Table 1. Ranges for drought indices used for each drought severity classification used in the US Drought Monitor. Source: US Drought Monitor 2021.

Data produced by the USDM has several applications. First, local government officials use the USDM drought in order to officially declare a drought and put adaptive measures in place. For example, the Puerto Rico Drought Management Committee uses data from the United States Drought Monitor to determine the region's level of exposure to drought conditions and to identify the stage of the drought management plan and corresponding actions: drought alert stage (D0, D1), drought warning (D1, D2),

and the extreme drought warning stage (D3, D4) (DRNA, 2016). Second, the USDM also influences access to federal drought assistance programs. The USDM drought map helps determine eligibility for financial assistance, such as the USDA's Livestock Forage Disaster Program, to cover agricultural losses caused by drought.

Visualizing long-term drought exposure

While the USDM weekly maps provide a short-term glimpse of the spatial extent of drought exposure, they do not provide a long-term view of where drought conditions have accumulated over time. In order to view a more extended period of accumulated drought exposure, I will combine weekly data into one layer using Geographical Information Systems software ArcGIS Pro. Data is available since the year 2000, allowing for the display of 21 years (1096 weeks from 2000 to 2020) of accumulated drought conditions across the region. Weekly data consists of polygons showing the spatial extent of drought and severity classifications from moderate (D0) to exceptional drought (D4).

Tessellation grid for spatial analysis

Tessellations are nets of regular shapes that form a grid that can be used in spatial data analysis to manage issues with irregularly shaped polygons. The three options for tessellation grids are squares, triangles, and hexagons. In order to represent polygon data with its curves, a circular shape could do this most effectively. Since hexagons are the most circular-shaped polygon that can tessellate to compose an evenly spaced grid, hexagons were selected for this tessellation grid (ArcGIS Pro 2018). In this particular analysis, the tessellated grid was comprised of 5 km^2 hexagons. Five square kilometers is an ideal size in case the resulting data will be used to measure drought in local landscape features such as forested areas, farms, and natural protected areas.

Consolidating and preparing desired spatial data

The data is downloaded as annual collections of weekly polygons of drought extent and severity for the continental United States, Hawaii, and Puerto Rico. All layers of drought condition categories were first merged into a single layer of overlapping polygons to facilitate further geoprocessing. Next, the merged layers were clipped to Puerto Rico's coastal boundaries to remove data on the continental United States and Hawaii. Areas categorized as 'abnormally dry' were then excluded from the analysis because they are considered zones in transition to or from drought and not regions of officially declared drought (Personal communication Odalys Martinez NWS 2017).

Processing spatial data on Puerto Rico drought

The polygon layers were selected by drought severity and merged together, resulting in three shapefiles of moderate, severe and extreme drought classifications. Each shapefile had 1096 layers of data for each of the 1096 weeks of the study period.

Generation of hexagon tessellation

Next, a hexagon tessellation was generated. The size of the hexagons was 5 km^2 (1.93 square miles). In order to link the drought polygons into the hexagon grid, points were generated at the centroids of all hexagons by using the geoprocessing tool 'point to feature'. Centroids are the geometric center of a feature (ESRI 2018).

Joining drought data to the hexagon grid

Afterward, the three layers of geospatial drought data were joined to the centroid point layer. In order to track the total number of weeks each centroid point was exposed to drought conditions, the automatic 'join_count' column in the attribute table was renamed to "DX_weeks" (D1, D2, and D3) in

each new layer to track number of weeks the point/hexagon experienced drought in each severity classification during the study period. If the drought polygon intersected the centroid point, it counted as one week of drought conditions for its corresponding hexagon. Later, all three layers of centroid points for each severity classification were merged into one layer of all drought weeks represented in points. Afterward, the centroid points that contain the drought severity data were merged back to the hexagon tessellation grid. The result layer is a grid of 5 km^2 hexagons that contain drought severity and classification data in Puerto Rico from 2000 to 2020 (Figure 5). Using the symbology function, the layer has the ability to display number of weeks in moderate, severe or extreme drought. The layer can also display the number of weeks of exposure in any drought classification. The numbers of drought weeks must be considered non-consecutive weeks. The final output of this analysis is a map displaying the total number of weeks that the region was exposed to moderate, severe, or extreme drought, revealing accumulated, non-consecutive drought exposure across Puerto Rico from 2000 to 2020 (Figure 5).

Using tabulated USDM weekly drought data to evaluate drought characteristics

On USDM websites, tabulated data is downloadable by state on their data download page. By selecting Comprehensive Statistics > State "Puerto Rico" > Percent Area > Cumulative area, a full record will be downloaded with weekly drought percentages of Puerto Rico land area in abnormally dry (D0), moderate drought (D1), severe drought (D2) and extreme drought (D3). Data from January 2000 to December 2020. I then summarized the number of drought weeks per category per year and calculated the average duration of drought for moderate and severe drought categories. This tabulated USDM data was used to characterize the frequency, intensity and duration of drought events from 2000 to 2020.

Results

Spatial distribution and frequency of non-consecutive drought

From 2000 to 2020, drought conditions occurred in some areas more frequently than others in an uneven distribution. Drought exposure ranged from a minimum of 0 weeks in the west, to 169 weeks in the southeast (Figure 5). The east side of Vieques was exposed to 95 weeks of drought conditions. Drought conditions most affected the southeast region of the main island of Puerto Rico, most frequently affecting the municipalities of Salinas, Cayey, and Guayama where the maximum number of drought weeks were 169, 167, and 157 weeks, respectively, representing about 15 percent of the total period (1096 weeks). Most eastern municipalities and those along the south coast have had over 60 non-consecutive weeks of drought conditions since 2000.

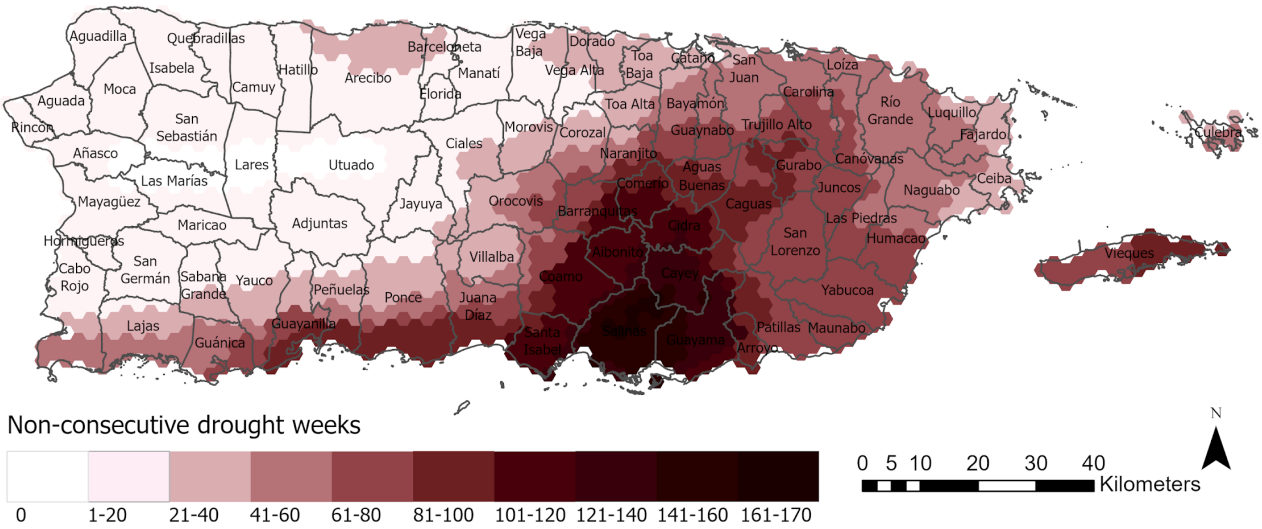

Figure 5. Non-consecutive drought weeks from 2000 - 2020. Note that the map shows the frequency of drought weeks regardless of intensity. Moderate, severe, and extreme drought are included, while abnormally dry is excluded. The map shows frequency of drought exposure and does not depict intensity of drought conditions. Data source: US Drought Monitor 2021.

Meanwhile, the western half of Puerto Rico has had relatively infrequent drought conditions with 0 to 20 weeks of non-consecutive drought, apart from the northern region of Arecibo with between 21 and 40 weeks, and the southern municipalities with between 41 and 100 weeks. The municipalities of

Añasco, Las Marías, San Sebastián, Lares, and Utuado had regions within their border that were not exposed to any drought conditions during the 21-year period. Overall, the least drought-affected municipalities in Puerto Rico from 2000 to 2020 were Lares, Utuado, and Las Marías, while the most affected municipalities were Salinas, Guayama, and Cayey.

Characteristics of droughts in the 21st century

In the following three sections, I answer the question: **What are the characteristics of 21st century droughts in Puerto Rico (duration, frequency and spatial extent)?**

Drought frequency

Since the United States Drought Monitor began publishing data in 2000, the frequency of drought conditions appears to be increasing in frequency. Figure 7 shows an increasing trendline with an r^2 value of 0.33, which falls between a moderate and weak fit. While not a strong fit, these results indicate a possible increasing trend in the frequency of drought conditions on the Island, particularly evident in the last decade.

Since 2000, Puerto Rico has been exposed to moderate drought every 2 to 3 years, aside from a longer period without moderate drought conditions from 2009 to 2013 (Figure 6) (USDM 2021). Among the 10 periods of drought, the average duration of moderate drought has been 19 weeks (4.75 months). Seven of the 10 periods of moderate droughts were under 15 weeks (3.75 months). Severe drought occurred more recently in 2015, 2016, 2019, and 2020. To date, the only occurrence of extreme drought in Puerto Rico registered by the US Drought Monitor was in 2015 to 2016. There has been no exceptional drought registered in Puerto Rico since the initiation of the USDM drought monitoring in 2000. Abnormally dry conditions have occurred each year from 2000 to 2020, and the average annual number of abnormally dry weeks is 26 weeks (6.5 months). While droughts in Puerto Rico have occurred

occasionally since 2000 when the USDM began publishing drought maps, several of the most recent droughts have lasted longer than those in the previous decade, and have been slightly more spatially expansive.

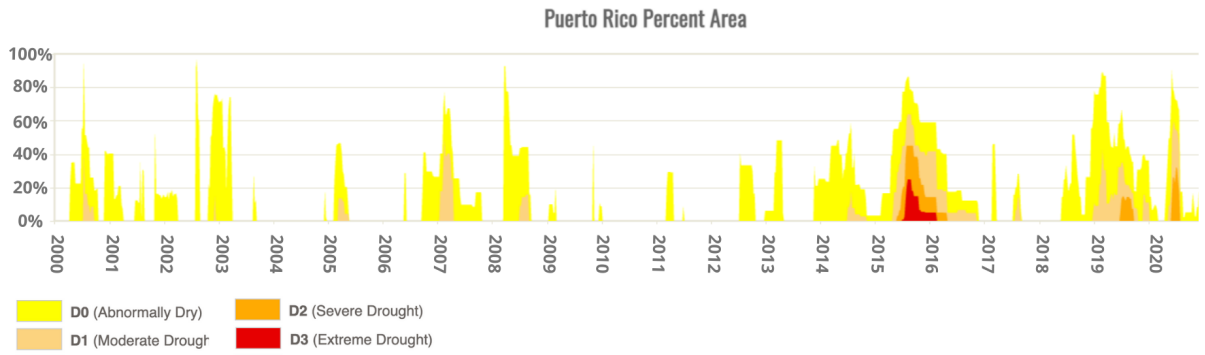

Figure 6. US Drought Monitor time series of drought conditions in Puerto Rico from 2000 to 2020 in percentage of total land area. Source: US Drought Monitor 2021.

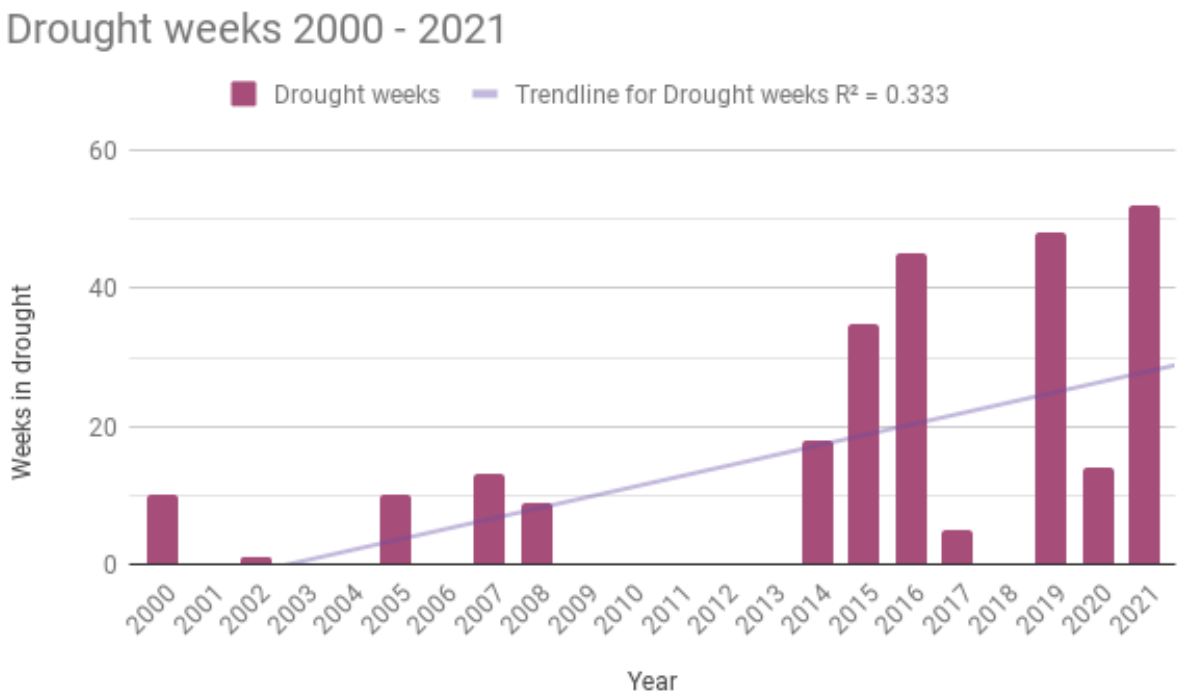

Figure 7. *Drought weeks in Puerto Rico from 2000-2021 Source data: US Drought Monitor. r2-value = (Moderate fit) 0.50 <**0.333**< 0.25 (Weak fit)*

Drought intensity

The highest level of drought severity reached in the study period was extreme drought. Extreme drought is described as drought conditions that feature major crop and pasture losses, widespread water shortages, and water rationing. Extreme drought conditions have a Palmer Drought Severity Index between -4.0 to -4.9, a CPC Soil moisture model percentile between 3 to 5, a USGS streamflow percentile of 3 to 5, a Standardized precipitation index of -1.6 to -1.9 and an objective drought indicator blend percentile of 3 to 5 (USDM 2018, Table 1).

Severe drought conditions occurred in June of 2015 to May of 2016, and July to September of 2019, and June to July of 2020. Severe drought tends to cause plant and crop stress, hay scarcities, and water rationing. Severe drought conditions have a Palmer Drought Severity Index between -3.0 to -3.9, a CPC Soil moisture model percentile between 6 to 10, a USGS streamflow percentile of 6 to 10, a Standardized precipitation index of -1.3 to -1.5 and an objective drought indicator blend percentile of 6 to 10 (USDM, 2018, Table 1).

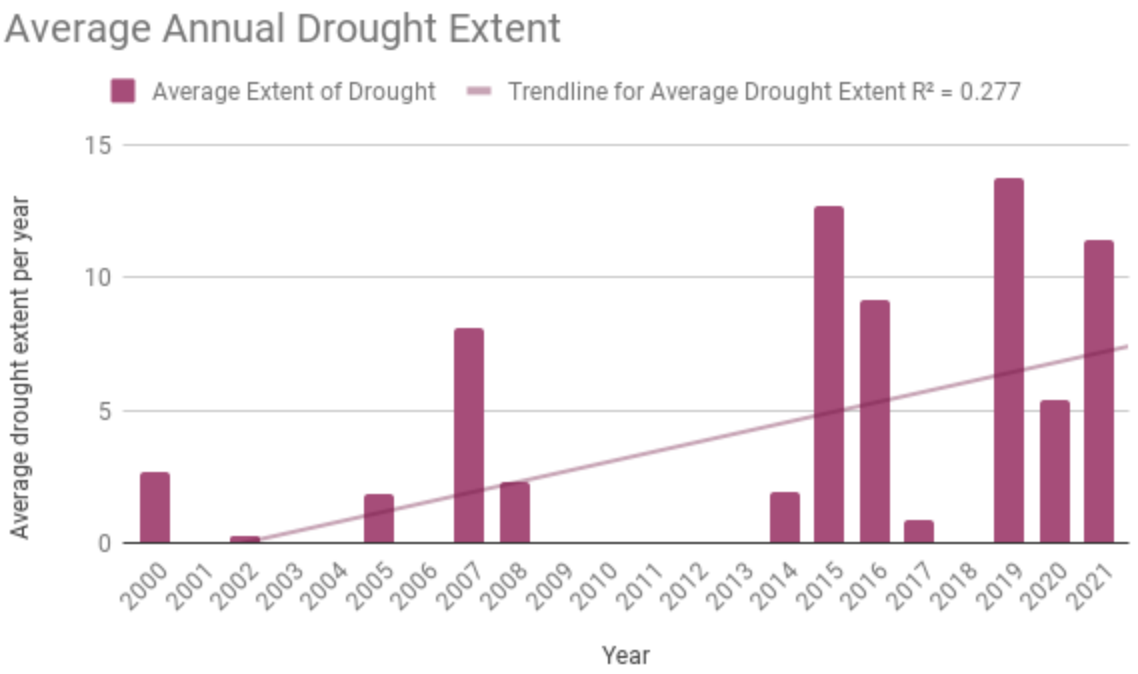

Figure 8. *Spatial extent of drought in percentage of land area in Puerto Rico from 2000-2021 Source data: US Drought Monitor.*

Duration of droughts of different classifications, from 2000 to 2020

As dry conditions develop and worsen, the USDM drought classification increases from 'abnormally dry' to 'moderate', to 'severe', to 'extreme' to exceptional. Abnormally dry conditions are generally registered well before an official moderate drought begins because abnormally dry conditions represent periods of transition either in or out of drought periods. When an area is first registered as abnormally dry, it may indicate a short term dryness that has slowed the planting or growth of pastures or crops (USDM 2018). Abnormally dry conditions are designated by a Palmer Drought Severity Index between -1.0 to -1.9, a CPC Soil moisture model percentile between 21 to 30, a USGS streamflow percentile of 21 to 30, a Standardized precipitation index of -0.5 to -0.7 and an objective drought indicator blend percentile of 21 to 30 (USDM, 2018). Between 2000 and 2020, there were a total of 555

weeks of abnormally dry conditions, which represents about 51 percent of the entire study period (Table 2).

Since 2000, drought conditions in general appear to be lasting longer. Figure 8 shows an increasing trendline with an r2 value of 0.33, which falls between a moderate and weak fit. While not a strong fit, these results indicate a possible increasing trend in the duration of drought conditions on the Island, particularly evident in the last decade.

Between 2000 and 2013, periods of abnormally dry conditions lasted for an average of 15 weeks (about 3.5 months) before moderate drought was first registered (USDM data, 2017). Before the moderate drought of 2014, abnormally dry conditions lasted 32 weeks. The 2014 moderate drought subsided after 18 weeks, and conditions remained abnormally dry for another 25 weeks before redeveloping into a moderate to extreme drought event that would last 80 weeks (about 20 months or 1.7 years). The 2015 to 2016 drought was the longest consecutive drought in the 21st century to date.

From 2000 to 2020, there were ten periods of drought. Seven droughts were classified as moderate by the United States Drought Monitor, two reached severe and one reached extreme drought classification (Figure 5, Table 2). On average, moderate drought conditions lasted about 21 weeks, (~5 months). In 2014, however, there were 18 weeks of moderate drought which was soon followed by 80 weeks of consecutive moderate drought from 2015 to 2016 that at its peak, reached the extreme drought classification level. The drought from 2015 to 2016 reached extreme drought, while the 2019 and 2020 droughts were classified as severe. Severe drought conditions occurred for a total of 69 weeks of extreme conditions, representing about 6 percent of the entire study period (Table 2). Extreme drought conditions occurred between July of 2015 to February of 2016 for a total of 33 weeks of extreme conditions, representing about 3 percent of the entire study period (Table 2). Of the total drought weeks that occurred from 2000 to 2020, the drought period of 2014 to 2016 accounted for 27% of total weeks

under abnormally dry conditions, 47% of weeks in moderate drought, 70% of weeks in severe drought and 100% of weeks in extreme drought (Table 2).

The 2017 drought lasted for 5 weeks in late July and the month of August and was classified as moderate drought. The drought affected the most of the southern coastal region. The year 2019 drought had two periods of drought. The first period lasted for 43 weeks from the first week in January to late October and affected much of the island at some point of the year, with the location of drought conditions shifting significantly rather than worsening over one region. This drought reached the severe category for 13 weeks. The second period was classified as moderate drought, beginning in the first week of December and lasted until the first week in January of 2020, coinciding with the magnitude 6.4 earthquake in southwest Puerto Rico.

The year 2020 had two main periods of drought, with the first lasting 11 weeks from May through July and affecting the entire southern coast and the majority of the eastern half of the island. The drought classification reached severe category, further complicating efforts to control the coronavirus pandemic, particularly among the residents in southwest Puerto Rico who were displaced by the 6.4 magnitude earthquake in early January and the 140,000 residents who were affected by mandatory water rationing.

While near normal rainfall has been observed over the past few weeks across the local area, rainfall deficits continue to be observed across Puerto Rico and the U.S. Virgin Islands. Low soil moisture and below normal streamflows continue across eastern Puerto Rico as well as areas in the southern slopes of the island. Low water levels are still observed at some reservoirs and aquifers, particularly across eastern Puerto Rico.

Agricultural businesses are still struggling to provide appropriate feed and water to their livestock and crops, particularly across the U.S. Virgin Islands. Drought conditions peaked in Puerto Rico during the first week of July, with 32% of the island in severe drought, including nearly the entire

southern coast and portions of the east central interior extending north to near the San Juan metro area. With the onset of the peak of the Atlantic Basin tropical cyclone season, July has brought above normal rainfall to the islands, resulting in drought conditions improving. Enhanced chances for much above normal rainfall from July 29th to August 2nd with a possible tropical cyclone in the area must be noted.

		Total weeks in drought category per period			
Year	Weeks D0 before D1	**Abnormally dry** D0	**Moderate** D1	**Severe** D2	**Extreme** D3
2000	13	31	10	0	0
2002	6	28	1	0	0
2005	4	14	10	0	0
2007	17	43	13	0	0
2008	15	26	9	0	0
2014	32	52	18	0	0
2015 - 2016	75	99	80	48	33
2017	2	12	5	0	0
2019	30	53	48	13	0
2020	3	45	14	8	0
2000 - 2020	**19.7** (average)	**555**	**208**	**69**	**33**

Table 2. Drought duration and intensity. Weeks under abnormally dry conditions prior to entering moderate drought in drought years and total weeks in drought classifications from 2000 - 2020 in Puerto Rico. Data source: USDM 2021.

Important land use in drought affected areas

In the follow section, I explore the protected areas and agricultural activity exists in the most frequently drought affected region from 2000 to 2020. In the most drought affected municipalities of Salinas, Guayama and Cayey (100+ weeks), there is significant agricultural activity and twelve natural protected areas, including the Carite Commonwealth Forest and the Jobos Bay National Estuarine Research Reserve. The Carite Commonwealth Forest is home to nine endangered animals, including three critically endangered species of coquis and two critically endangered predatory birds (eg; Golden Coquí, (Eleutherodactylus jasperi) and Puerto Rico Sharp-skinned Hawk (*Accipiter striatus venator*))(DNER 2008). Carite Forest is home to 204 species of trees, of which 176 are native and 43 are endemic. The endangered Uvillo tree (*Eugenia haematocarpa*) can be found in the Carite forest. During the 2015 drought, the Puerto Rico Department of Natural and Environmental Resources reported that Carite forest showed signs of drying and increased risk of wildfires (DNER 2015).

The Jobos Bay National Estuarine Research Reserve is home to several endangered species, including the Peregrine Falcon (*Falco peregrinus*) and the West Indian manatee (Trichechus manatus)(Laboy et al. 2008). The Jobos Bay Reserve has a mangrove forest with white, red, buttonwood and black mangrove trees. Black mangrove *(Avicennia germinans*) is highly susceptible to changes in hydrological regimes (Laboy et al. 2008). A site profile on Jobos Bay prepared by the PR Department of Natural and Environmental Resources and the National Oceanic and Atmospheric Administration stated that drought or flooding can cause extensive mortality of black mangrove, and that competing uses of groundwater and surface water in the area is leading to less freshwater input into the Bay and an increased risk of inland saltwater intrusion (Laboy et al. 2008). The 2015 drought had significant effects on the Bay, such as vegetation mortality, defoliation and a reduction or absence of certain species such as crabs, aquatic birds and manatees (DNER 2016).

Also within the most drought-effected municipalities are protected areas Montes Oscuros Scenic Easement, Planadas - Yeyesa Nature Reserve, the Guayama Research Area, Punta Pozuelo Protected

Natural Area, Aguirre Commonwealth Forest, Culebras Protected Natural Area, and Carite Commonwealth Forest, the Jájome Protected Natural Area, La Robleda Protected Natural Area and Las Piedras del Collado Nature Reserve.

In 2015, the top crops produced in Salinas, Guayama and Cayey were plantain (4.7 million lbs), watermelon (1.6 million lbs), as well as papaya, squash, experimental soybean and corn (PRDA and USDA Caribbean Climate Hub 2019). Agriculture in this region relies on groundwater and surface canals. The reservoirs nearest to agricultural irrigation districts supply water to areas of agricultural production through surface canals. The capacities of reservoirs that supply water to the southern coastal area have been declining, with sedimentation resulting in capacity losses ranging from 22 to 82% their original capacities (Harmsen 2019).

Conclusion

In this analysis, United States Drought Monitor data appear to indicate that the duration, frequency and spatial extent of drought may be increasing in Puerto Rico, aligning with climate change projections for the region. I found that from 2000 to 2020, drought conditions have most frequently occurred in the southeast coastal municipalities of Salinas, Guayama and Cayey, a region with significant agricultural activity where substantial quantities of crops such as plantain, watermelon and papaya are produced, and an area that hosts twelve natural protected areas home to several endangered flora and fauna. Furthermore, I determined that abnormally dry conditions persisted between two to 32 weeks before the drought classification increased to moderate drought, and that the average length of moderate drought in Puerto Rico is 21 weeks (about five months).

The map of accumulated drought exposure provides an important insight into recent drought trends on the island by showing us how drought conditions have concentrated over some regions more than others. Citizens, farmers and other interests in the most drought affected region in eastern and

southeastern Puerto Rico may benefit from implementing practices that help to ameliorate the effects of drought, such as water cisterns, rainwater catchment systems, and drought-related agricultural practices.

With this geospatial information, a number of useful spatial analyses can be carried out by using GIS programs to identify potential effects of recent drought based on accumulation over wild lands, agricultural regions, and habitats. Heavily exposed areas of interests, such as agricultural land and forests, can be identified and flagged as potential locations for the implementation of adaptive measures.

My research offers new insight about the characteristics of drought in Puerto Rico from 2000 to 2020, where drought conditions have most frequently affected according to the US Drought Monitor, as well as frequency, duration and severity. In the future, as spatial data on drought continues to be collected, this strategy can also be repeated to visualize longer-term trends in drought accumulation in Puerto Rico. As the US Drought Monitor continues publishing the weekly drought maps in the next decades, it will be interesting to follow whether the other areas of Puerto Rico receive more drought exposure, or whether conditions continue to accumulate in the southeastern region.

Drought from 2000 to 2012

In 2000, a brief drought caused abnormally dry conditions in the municipalities of Ponce and Guayama and moderate drought conditions for Arecibo, Canóvanas, and Mayagüez. In 2002, abnormally dry conditions affected all five municipalities between October 2002 and April 2003, and were categorized as moderate drought conditions for Ponce and Guayama in December 2002. In 2005, a brief moderate drought developed for the Guayama, Mayaguez, and Ponce areas and a period of abnormally dry conditions developed for Canóvanas. In 2007, a brief period of moderate drought conditions developed for Guayama and Canóvanas in January and Ponce in February. By May of 2007, moderate drought conditions had ceased for the three municipalities. Abnormally dry conditions developed in

Mayagüez from February to April of 2007. In 2008, another brief period of moderate drought conditions began in Guayama in July and Canóvanas in August. By September, moderate drought conditions had ceased for both locations. Meanwhile, Ponce, Mayagüez, and Arecibo experienced abnormal dry conditions for varying durations throughout 2008.

Drought from 2013 to 2016

In November of 2013, abnormally dry conditions began in Ponce and Guayama, persisting until July of 2014 when conditions escalated to moderate drought in both municipalities. By September of 2014, conditions returned to normal in Ponce, while moderate drought continued in Guayama until October, when conditions de-escalated to abnormally dry. In Canóvanas, abnormally dry conditions persisted from March to November of 2014, temporarily escalating to moderate drought in July. Arecibo also experienced abnormally dry conditions from March to May of 2014 and again in August of the same year. Meanwhile in Mayagëz, abnormally dry conditions were registered for the single month of July of 2014.

In 2015, drought conditions developed for all five municipalities. In each municipality, moderate drought conditions were preceded by months of abnormally dry conditions. Moderate drought conditions developed in Guayama and Canóvanas in May. In July, moderate drought also developed in Ponce and Arecibo. By August, moderate drought was registered in Mayagüez, though it lasted only two months. In Arecibo, moderate drought lasted for three months, and conditions were back to normal by October of 2015. In Ponce, moderate drought lasted until August of 2016. Meanwhile, in Guayama and Canóvanas, moderate drought conditions escalated to severe drought in June of 2015, follow by extreme drought in July of 2015. In Canóvanas, extreme drought lasted three months until September 2015 before de-escalating to severe drought in November and moderate drought in December of 2015. Guayama was one of the municipalities most affected by the 2015 drought where extreme drought

lasted from July 2015 until February of 2016 when conditioned decreased from extreme to severe drought. Guayama continued with severe drought for two months until May of 2016, when conditions reduced to moderate drought until October of 2016. For more detailed information about the 2015 drought, see Chapter Two.

Drought from 2017 to 2019

In August of 2017, Ponce and Guayama registered one month of moderate drought conditions. In mid to late 2018, Ponce, Guayama, Canóvanas and Arecibo began registering abnormally dry conditions at different points in time. Moderate drought conditions develop in Ponce by February of 2019, Guayama and Arecibo by March, and in Canóvanas by June. While moderate drought conditions lasted only a month in Arecibo and two months in Canóvanas, conditions escalated to severe drought in Ponce and Guayama. In Mayagüez, abnormally dry conditions lasted from February to June of 2019, never escalating to drought conditions. While not included in this analysis, a severe drought also developed in 2020.

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Chapter three: Exploring rainfall and recent drought in Puerto Rico

Abstract

Climate change projections indicate droughts may increase in intensity and frequency. The purpose of this chapter is to determine whether droughts in Puerto Rico are becoming more intense through an analysis that, in part, updates Matthew Larsen's 2000 paper, entitled *Analysis of 20th century rainfall and streamflow to characterize drought and water resources in Puerto Rico.* In this chapter I carry out a similar analyses and recreate figures to facilitate comparison. To this end, I analyze rainfall, streamflow and reservoir data to examine recent meteorological and hydrological droughts in Puerto Rico from 1980 to 2019. In addition to the update of Larsen's paper, I analyze dry days as a proxy to climate change through potential changes in the rainfall regime.

More specifically, I analyze rainfall data to determine whether annual rainfall is decreasing and whether meteorological droughts are increasing in intensity. I examine hydrological drought through USGS streamflow and reservoir level data. To analyze annual rainfall and whether it is already exhibiting a decreasing trend as projected, I extracted data at the coordinates of the rainfall stations used in Larsen 2000 from a gridded daily rainfall product called Daymet. A rainfall product was the selected option considering that many of the land-based stations I aimed to analyze had significant gaps in data during key drought events of the study period. I calculated long term averages, analyzed the severity and regional variation, and the timing and severity of meteorological drought for each location.

First, I determined the long-term average determined by calculating average annual rainfall accumulation from 1980 to 2019 for each of the 12 locations. Then, I calculated the average rainfall for 2014 to 2016 to determine severity of the most recent period of extreme drought. Next, I determined the departure from the long-term mean at each location using a rainfall index. Regional variation in rainfall was evaluated by coupling locations from each region into pairs. To place recent rainfall data into historical context, I use deciles to determine the distribution of rainfall level occurrence over a chosen

period of time. By comparing rainfall deciles in locations in the North, East, South and West regions, the severity of rainfall deficiency can be evaluated in terms of its regional occurrence in Puerto Rico.

To measure of an increase or decrease in drying trends island-wide and in the four regions, daily rainfall data was used to calculate total annual dry days (TDD). If TDD are increasing, it may suggest an overall drying of the climate and/or a shift in rainfall patterns toward dry conditions between rainfall events. A trend in maximum consecutive dry days (MCDD) will indicate whether there is an overall trend in how periods of dry days might be changing over time. An increase in MCDD would indicate a lengthening of dry periods from 1980 to 2019, whereas a decrease in MCDD would indicate shortening dry periods or a shift in rainfall patterns toward more frequent rainfall events. Mann-Kendall trend test is a non-parametric statistical analysis used to identify a trend in a series. The test can also identify trends in data series that may have seasonal variation (Addinsoft 2020).

I looked at potential influencing factors in the need for water rationing during recent drought by examining trends in water use per capita, population, and issues in water storage and transport infrastructure in Puerto Rico. In addition, I analyzed the regional variation of drought.

To regional variation for meteorological and hydrological drought. First, I analyze rainfall data to determine whether annual rainfall is decreasing and whether dry days are increasing in frequency. Second, I analyze streamflow frequency and flow percentiles to determine how the severity and regional variation of hydrological conditions in key rivers during the 2015 drought and other drought years. Third, I examined reservoir level data to compare the onset and severity of hydrological drought in important reservoirs. In chapter four, I review my findings from chapters two and three, discuss their potential implications and recommend opportunities for future drought research.

The findings in this study indicate that Puerto Rico is not getting drier when it comes to annual rainfall or annual dry days. Daymet data indicate that average annual rainfall is increasing across the island. There is a statistically significant decrease in TDD and MCDD. However, US Drought Monitor data

suggest a possible increase in the frequency, duration, severity and the spatial extent of droughts in Puerto Rico. While rainfall data point to a overall wetting trend island-wide, US Drought Monitor data point to intensifying droughts which aligns with regional climate change projections of increasingly intense droughts. US Drought Monitor data provides a more complete view of drought.

Overall, in this chapter I sought to determine whether Puerto Rico is becoming drier by answering the following questions: **Research question 2a: Is there a decreasing trend in annual rainfall from 1980 to 2019? Research question 2b: Is there an increasing trend in annual dry days from 1980 to 2019? Research question 2c: How does the recent severe drought of 2015 compare to the droughts in the 1990s?** I conclude the chapter by exploring how factors that influence the need for rationing, such as population, water use, and reservoir storage capacity have changed since the previous major drought period in the 1990s.

Introduction

Climate change, rainfall, and drought

The global climate is changing. Carbon dioxide emissions are increasing, causing an accelerated rise in atmospheric CO^2 concentrations. According to the World Meteorological Organization, in the five-year period of 2015-2019 CO^2 was 18% higher than in 2011-2015. The evidence of climate change is well-established. Global temperatures are rising, the ocean is warming, sea level is rising, ocean acidity is increasing, and ice is melting in the poles (World Meteorological Organization 2020). Furthermore, the risk of food insecurity and climate-related illness and deaths has increased (WMO 2020). Global climate projections from the Intergovernmental Panel on Climate Change predict an increase in precipitation (Figure 9) (Meehl et al. 2007).

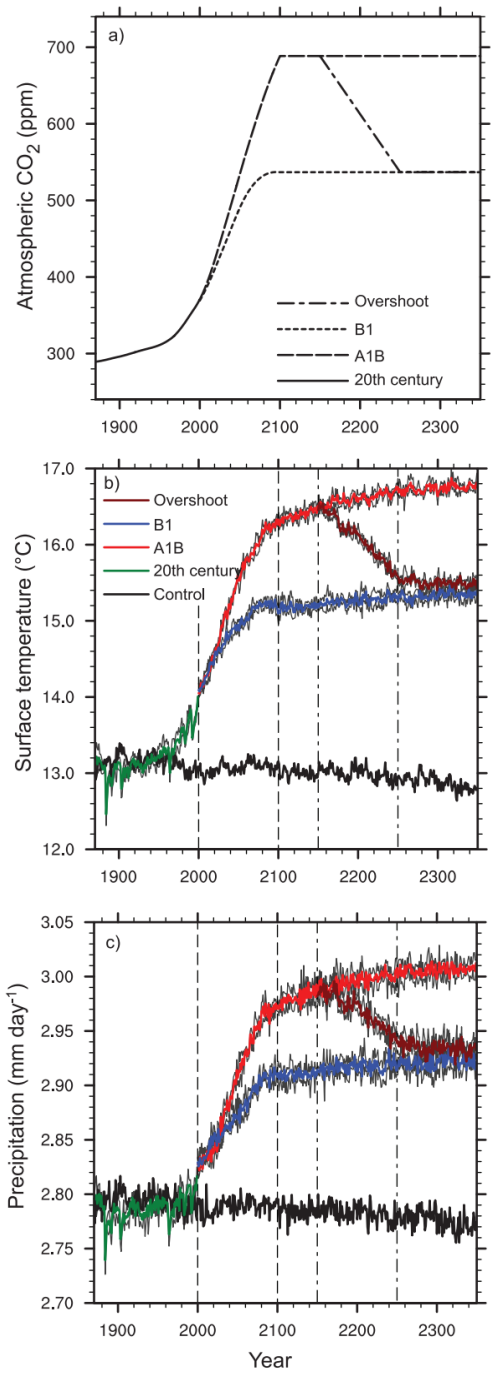


Figure 9. Global projections for atmospheric carbon, surface temperature, precipitation according to A1B and B1 scenarios. Source: Yoshida et al. 2005 via IPCC 2007.

In the Caribbean, climate change is predicted to be felt more intensely. By 2050, temperatures in the Caribbean are projected to increase by 4.6–9°C depending on the greenhouse gas scenario (Henareh et al. 2016). In the last 70 years, the temperature in Puerto Rico has already increased by 1.5°F (Runkle et

al. 2017, Figure 10). Contrary to global projections (Meehl et al. 2007), island rainfall is projected to decrease by up to 10% of annual rainfall by 2050 (Bowden at al 2018; Henareh et al. 2016). Decreasing rainfall is projected to cause an increase in drought intensity and extremes (Henareh et al. 2016). However, different climate projections are inconsistent when it comes to extreme rainfall events, with one projection predicting less frequent extreme daily rainfall (Bhardwaj et al. 2018), while another model predicts an increase in rainfall events exceeding 3 inches per day (Hayhoe et al. 2013).

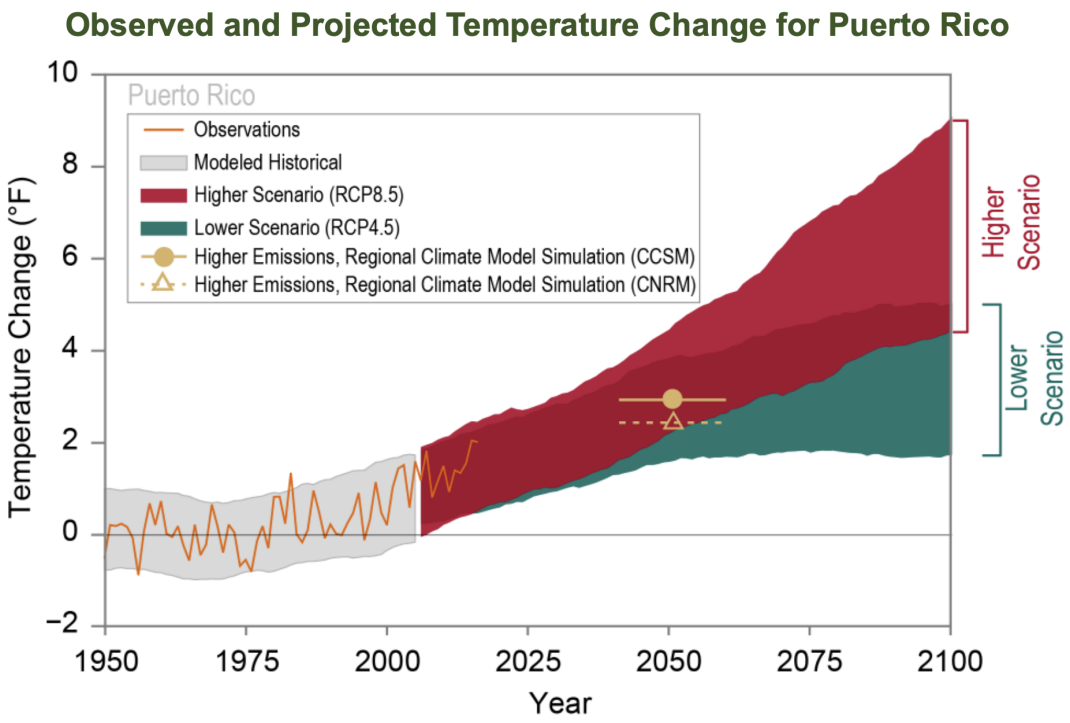


Figure 10. Observed and projected temperature change for Puerto Rico in high and low scenarios. Source: NCA4.

As previously mentioned, dry days are considered days with precipitation less than 1 mm. Maximum consecutive dry days (MCDD) are the maximum number of consecutive days with less than 1 mm in rainfall within a particular year. In their study of climate extreme changes in the Caribbean region, Peterson et al. 2002 found that MCDD decreased from 1955 to 2000. The decreasing trend of MCDD was echoed in an analysis of drying trends in the Puerto Rico metropolitan area by Mendez Lazaro et al.

2014. They studied data from four rainfall stations and found there has been a shift in rainfall patterns from 1955 to 2009. All metro area stations showed an increase in annual rainfall between 1955 to 2009. They also found that the seasonal distribution of monthly rainfall had changed. The relatively dry months of January and February showed a statistically significant increase in monthly rainfall since 1955, whereas monthly rainfall for the months of June, August, and December had decreased (Méndez-Lázaro et al. 2014).

This dynamic also aligns with the findings of another study by Méndez Lázaro and Martínez 2012 that annual precipitation is increasing overall, with a monthly increase in winter months and a decrease in summer months. Furthermore, Van Beusekom et al. 2015 analyzed rainfall from 20 sites in Eastern Puerto Rico, finding that between 2001 and 2013, rainfall increased at a rate of 0.1 mm per day. Méndez-Lázaro et al. 2014 also found that total annual dry days decreased at three of the four stations from 1955 to 2009, whereas MCDD decreased for two of the four metro area stations (Méndez-Lázaro et al. 2014).

Ramseyer et al. 2019's downscaled climate modeling predicted that rainfall in the early rainfall season, April to July, will decrease in the El Yunque National Rainforest, while dry days are projected to increase. According to the climate projections by Henerah et al 2016, total annual dry days (TDD) and maximum consecutive dry days (MCDD) are projected to increase for Puerto Reico (Henareh et al. 2016). Given that rainfall in the US Caribbean is projected to decrease, while rainfall is reportedly increasing in Puerto Rico, **is there a decreasing trend in annual rainfall from 1980 to 2019? Is there an increasing trend in annual dry days from 1980 to 2019?**

Drought impacts to the environment, water supply and agriculture

For most of the population, the most easily observable effect of drought is that domestic access to freshwater is reduced. Residents of Puerto Rico are no strangers to water scarcity in times of severe

drought. Many people store water in cisterns to avoid interruptions. In addition to domestic water restrictions, drought can negatively affect local food supply and impact the environment through the various stages of drought progression.

As a meteorological drought is sustained, soil dries. As described in chapter one, this stage of drought is referred to as agricultural drought. Reduced soil moisture decreases productivity of plants, reduces crop yield, and makes crops more vulnerable to pests and disease (Holupchinski et al. 2018). Since about 90% of US Caribbean agriculture relies on rainfall, operational costs may increase as producers purchase water to maintain crops (Álvarez-Berríos et al. 2018). Reduced crop yield and increased operation costs mean that local products will be more expensive. Furthermore, reduced availability of local crops during times of severe drought cause islands to increase their dependency on imported food (Holupchinski et al. 2018). Drought conditions have devastating effects on the dairy and livestock sector. Due to the sector's reliance on rainfed grass and rangelands for livestock feed, lack of rain affects their food supply; reducing milk production and decreasing future yields (Holupchinski et al. 2018). Desiccated rangelands also pose a risk due to the increased fire susceptibility.

As agricultural drought continues, surface water becomes affected and hydrological drought begins. Decreased water levels in freshwater streams alter microhabitats. The reduction in water level causes water temperatures and dissolved oxygen to increase and connectivity to the ocean may be lost. Drought changed the fish and macroinvertebrate assemblages in streams in eastern Puerto Rico (Ramirez et al. 2018). In 2014, a fish kill occurred when hypoxic conditions resulted from low water levels in La Plata reservoir (DNER 2016). As streamflow decreases, the amount of freshwater that reaches estuary ecosystems is reduced, causing increased salinity, increased mortality of freshwater plants, and changes to habitat and species assemblages (Murray et al. 2018).

Tropical forests and the species that call the habitat home have adapted to handle periods of drought. However, the increasing intensity and duration expected with climate change can exceed the

drought-tolerant threshold (Crausbay et al. 2018). During a period of drought, tropical trees may reduce fruiting, increase litterfall, and, when conditions worsen, suffer mortality. A reduction in the availability of fruits and insects can affect some bird populations (Crausbay et al. 2018). With climate change and increased intensity and duration of drought, the species composition in Caribbean forests may be altered over time to favor those that are drought-tolerant (Crausbay et al. 2018). O'Connell et al. 2018 found that soil in the Luquillo mountains emitted increased CO^2 under drought conditions. They also found that the drought recovery period lasted up to 65% the length of the drought after rainfall returned (O'Connell et al. 2018).

Characterization of drought in Puerto Rico in the 20th *century*

In the 1990s, multiple periods of drought occurred in Puerto Rico. Research hydrologist Matthew Larsen published a paper titled *Analysis of* 20th *century rainfall and streamflow to characterize drought and water resources in Puerto Rico* and evaluated two periods of 1990s drought (1994-1995 and 1997-1998) by comparing value of rainfall, streamflow of rivers that feed key reservoirs and reservoir levels data to historical values. Larsen also evaluated the 1990s data alongside other major periods of drought in the 20th century, during the 1960s and 1970s. He found that the most severe period of meteorological drought was the three-year period of 1966 to 1968 in which the rainfall was 20 percent below normal. He ranked the driest years of the 20th century and found that the driest year was 1967. Eighty percent of the driest years of the 20th century occurred in the latter half of the century. Three of the driest years occurred in the 1990s. The years 1997, 1994 and 1991 occupy the second, third and sixth ranking of driest years, making the nineties the driest decade of the 20th century.

Larsen (2000) goes on to discuss the regional variation in timing and severity of 20th century droughts. Droughts affected some regions more than others. While the drought in '93 - '95 was the most severe for Mayagüez, the droughts from '66 - '68 and '76 -'78 were the most severe for Arecibo,

Canóvanas, and Ponce. In his streamflow analysis, Larsen (2000) found that from December of 1993 to May of 1996, river discharge was in the 1st to 10th percentiles for all four of the rivers studied (Río de la Plata, Río Grande de Loíza, Río Gurabo and Río Tanamá), indicating conditions of severe drought. Meanwhile, streamflows during 1997 to 1998 did not reach such low levels for an extended period. For comparison, in the drought of 1966 to 1968, streamflow reached severe drought levels for about 36 percent of the time. Larsen found that the responses of water levels in the three reservoirs of Loíza, Guajataca and La Plata to the 1990s droughts coincided. However, there was substantial variation in the time it took to return to normal levels according to the post-drought rainfall received in each corresponding watershed. Overall, the author states that while the meteorological drought of '93 - '95 was not much more severe than those in '66 - '68, '71 -' 74 and '76 - '78, the need for mandatory water rationing was probably influenced by factors such as water management and consumption. Larsen (2000) states that increasing population, over consumption, and decreasing storage capacity have made rationing necessary under conditions that, in the past, might not have been required. Larsen's 2000 paper is one of the few in-depth publications on drought in Puerto Rico. In 2022, about twenty years after his publications, an updated publication is needed. Consequently, I pose the question: how have factors that influence the need for rationing, such as population, water use, and reservoir storage capacity changed since the previous major drought period in the 1990s?

Water infrastructure and population in Puerto Rico

As mentioned in chapter one, Puerto Rico Aqueduct and Sewer Authority's 2015 water balance report states that between 50-60% of the water managed by the company is lost as a result of broken pipes, commercial losses and unbilled consumption (PRASA 2015), a 10-20% increase in water loss since the 1990s (Larsen 2000). This rate of loss is more than triple the average in the United States (EPA 2015). The former Executive Director of PRASA, Elí Díaz, stated that the agency lacks a detailed inventory of

their complex system of pipes (Centro de Periodismo Investigativo 2019), making the system difficult to maintain.

The accumulation of sediment in reservoirs hinders water storage capacity in Puerto Rico. Of the 38 reservoirs in Puerto Rico, 11 supply water to the island's 3.5 million inhabitants (Centro de Periodismo Investigativo 2019). The reservoirs were constructed in-stream, meaning water is collected directly in the river channel. As flowing water enters the reservoir, velocity slows, and suspended sediment settles and accumulates over time. Figure 11 shows the loss of capacity for key reservoirs since their construction up until their estimated capacity prior to Hurricane María in 2017. According to Ferdinand Quiñones, a hydrologist that manages the website called Water Resources of Puerto Rico (Recursos de Agua de Puerto Rico), it is probable that reservoirs lost more than 12% of their capacity due to heavy sediment load caused by the heavy rains of Hurricane Maria (Centro de Periodismo Investigativo 2019). In a recent news article, limnologist Jorge Ortíz-Zayas (2019) pointed out that even though Puerto Rico has one of the highest number of reservoirs per capita, the retention rate is limited by the lack of sediment control and maintenance plans for the reservoirs (Centro de Periodismo Investigativo 2019; Primera Hora 2020). In 1998, sediment was removed from Loíza Reservoir at a cost of about $65 million (Lugo et al. 2011). The sediment removal added about 20 years of capacity to the reservoir (Primera Hora 2014). During the drought of 2015, a reported 500,000 cubic feet sediment was removed from La Plata Reservoir (Primera Hora 2015).

The current Executive Director of Puerto Rico Aqueducts and Sewers Authority, Doriel Pagán, shared in May of 2020 that the lack of rainfall and increased water consumption caused by the COVID-19 virus resulted in a reduction in water reserves (Primera Hora 2020). She requested that FEMA remove sediment from PRASA reservoirs, a process that would cost an estimated $300 million dollars (Primera Hora 2020).

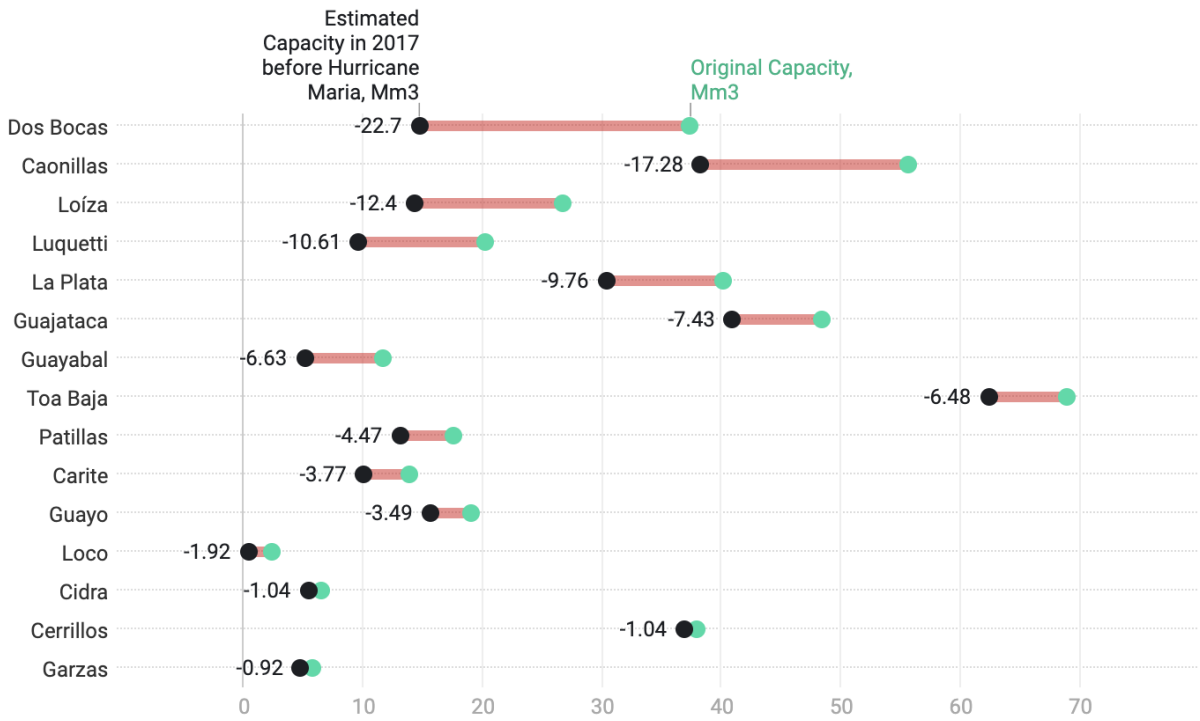


Figure 11: Capacity loss of key reservoirs in Puerto Rico, showing original capacity versus estimated capacity pre-María in 2017 (in million cubic meters, MCM). Data provided by hydrologist Ferdinand Quiñones.

Human population influences public water consumption, and at its peak in 2005, the population of Puerto Rico was 3.7 million people (US Census Bureau 2006). In 2020, there were an estimated 2.8 million people living on the archipelago (United Nations 2020). Overall, per capita water consumption has decreased since 1995. In 2015, consumption rate per capita was 371 liters per person per day (98 gallons), 163 liters (43 gallons) less than 534 liters (141 gallons) per capita consumption in 1995 (Figure 12). Contrary to the significant reduction in per capita consumption, total water withdrawals for public supply have increased. From 1995 to 2015 when the latest USGS report on estimated water use in Puerto Rico was published, total water withdrawals for public supply went from 1.6 million cubic meters (431 million gallons per day) to 2.4 million cubic meters (625 million gallons per day) (USGS, 2015). Total water withdrawals had been steadily increasing until 2015 when total withdrawals decreased. Likely due

to the drought, groundwater withdrawals increased in 2015, contrasting with the slow decline in groundwater withdrawals.

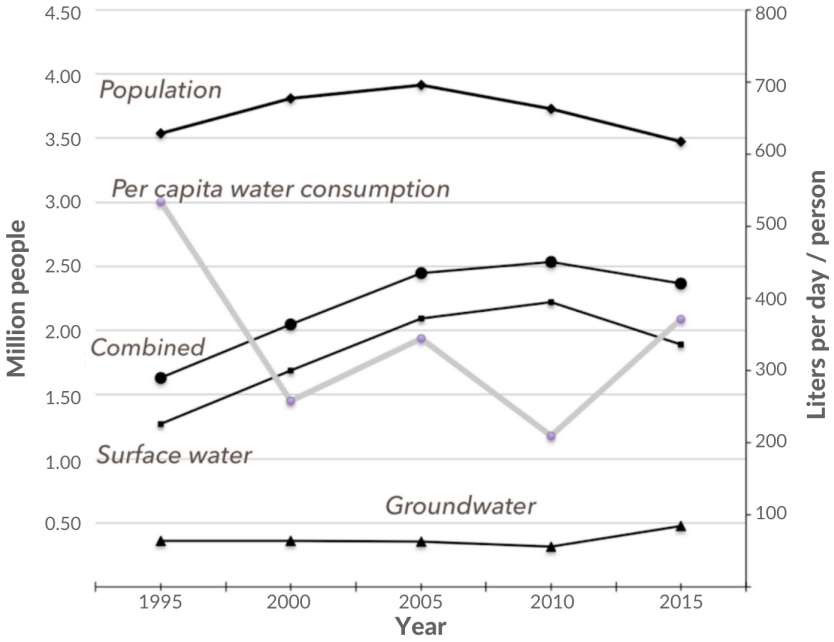


Figure 12: Estimated water use reports per capita, surface water, ground water, combined and population 1995, 2000, 2005, 2010, 2015. Data source USGS.

Since 2000, there have been three droughts that required mandatory water rationing: the droughts of 2015, 2019 and 2020. The 2015 drought led to mandatory rationing for 6 months and affected up to 1.2 million people in the San Juan metro area (DNER 2016). In 2019, rationing was required for about 4 months, affecting up to 70,000 people in northwestern Puerto Rico (Hola News 2019). Though not examined in this study, a drought in 2020 required rationing for about 140,000 people within and near the metro area (Telemundo 2020). Rationing was not required for short term droughts in 2000, 2002, 2005, 2007, 2008, and 2017 (USDM 2020).

As listed in Larsen 2000, the driest years of the 20th century occurred in the latter half of the century, and the driest decade was the last decade of the century. While several publications found that

rainfall in Puerto Rico appears to be increasing, downscaled climate change projections predict that rainfall will decrease over time (Bowden et al. 2018). Therefore, *given that climate change projections indicate rainfall will likely decrease, is annual rainfall already decreasing across Puerto Rico? Furthermore, how does the intensity and duration of the 2015 drought compare to historical droughts?*

This characterization of recent drought will offer an update on current trends in meteorological drought in Puerto Rico. The findings will contribute to our understanding of local climatic changes through the evaluation of drought frequency and intensity in comparison to data from the previous century. By applying similar methods, locations and stations in this study, my findings can be easily compared to those in Larsen (2000). Overall, my results from both components of the project, drought characterization and the spatial distribution of recent drought accumulation, help us gain important insights into drought occurrence on the Caribbean island of Puerto Rico.

Data and methods

I will analyze rainfall data to determine whether rainfall is decreasing and whether droughts are increasing in severity in Puerto Rico. I will characterize meteorological drought using rainfall data, while streamflow, and reservoir level data will provide insight into hydrological drought. I will replicate many of the methods used in Larsen's 2000 paper to facilitate comparison of the two study periods. Thus rainfall data will be analyzed to determine the severity of meteorological drought, while streamflow and reservoir levels will be evaluated to determine the expression of drought in the region's hydrology. In order to properly analyze deficiencies in rainfall and hydrology during drought years, it is necessary to establish historical average values to provide "normals" to allow for comparison. For this, a minimum of 31 years of data is required. In this study, 40 years of historical data from 1980 to 2019 will be used to determine the long term averages.

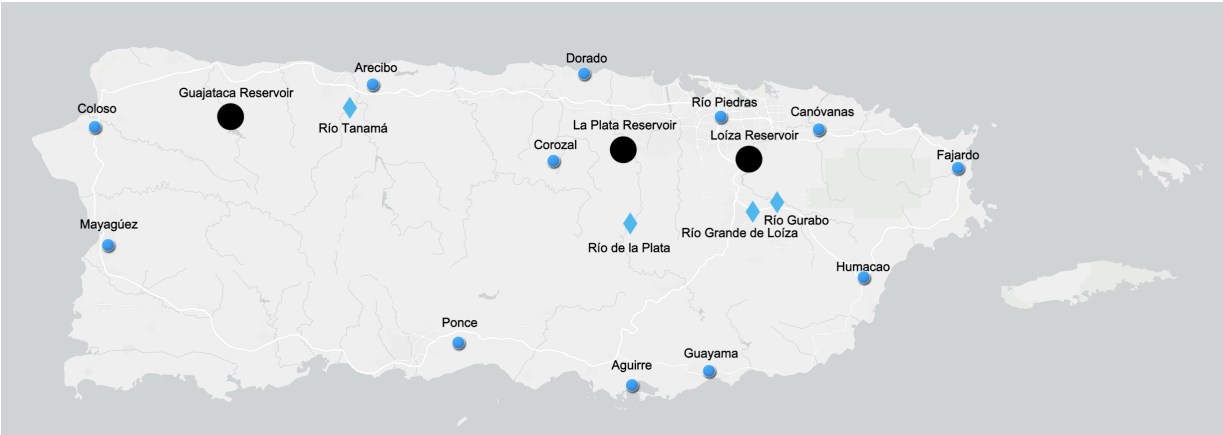


Figure 13. Location of extracted pixels for rainfall data (blue circles), streamflow gauging stations (blue diamonds) and reservoir level gauging stations (black circles).

Rainfall data analysis

Identifying alternatives for use of rainfall data with gaps

Larsen 2000 used rainfall data from 12 stations across Puerto Rico. However, the rainfall data for those stations has significant gaps since 2000. Furthermore, many important stations are missing data for key drought years. In multiple cases, nearby stations also lacked data in periods needed to help fill gaps. In a consultation about the situation with an experienced hydrologist from the USDA Forest Service who has published papers on rainfall, climate and hydrology in Puerto Rico, they advised against attempting to fill the data gaps myself because the local rainfall varies significantly and is difficult to extrapolate. The expert suggested using a rainfall product and relying on the product creators' responsibility to have correctly carried out the extrapolation. As a result, I decided to select a rainfall product as an alternative to the use of incomplete rainfall station data. Figure 13 shows the location of stations and data extraction used in this chapter.

Rainfall product selection

A climate data product is a data set that has various inputs such as observations from stations or satellites and has been processed (eg: filling gaps) to form a continuous time series of rainfall data. I used

a selection process to identify a rainfall product suitable for the study. In the selection process, twelve rainfall products were compared for suitability (Table 3).

	Product	Rainfall (Y/N)	Main data source	Data availability	Spatial resolution	Temporal Resolution	Link
1	Daymet	Y	Station-based with other input	1980 - 2019	1km x 1km grid, North America	Daily	https://daac.ornl.gov/DAYMET/guides/Daymet_V3_CFMosaics.html
2	Global Precipitation Climatology Project (GPCP)	Y	Gauge-based analysis	1979 - present	0.5° x 0.5° Global (~50km)	Daily	https://psl.noaa.gov/data/gridded/data.cpc.globalprecip.html
3	CMORPH Precipitation	Y	Satellite data	1998 - present	8km x 8km Global	30 minutes, updated monthly	https://www.ncdc.noaa.gov/cdr/atmospheric/precipitation-cmorph
4	Climate Prediction Center (CPC) morphing technique (CMORPH)	Y	Satellite microwave observation	2003 - present	0.07° x 0.07° Global	30 minutes	https://www.cpc.ncep.noaa.gov/products/janowiak/cmorph_description.html
5	Advanced Hydrological Prediction Service (AHPS)	N	Gauges, satellites, radars, super computers	n/a	n/a	n/a	https://water.weather.gov/ahps/about/about.php
6	CICS High-Resolution Optimally Interpolated Microwave Precipitation from Satellites (CHOMPS)	Y	Satellite data	1998 - 2007	0.25° x 0.25° Global	Daily	https://climatedataguide.ucar.edu/climate-data/chomps-cics-high-resolution-optimally-interpolated-microwave-precipitation-satellites
7	Global Historical Climatology Network (GHCN)	Y	Station-based	Varies by station	Global	Daily	https://www.ncdc.noaa.gov/ghcn-daily-description
8	Tropical Rainfall Measuring Mission (TRMM)	Y	Satellite data	1997 - 2015	n/a	n/a	https://gpm.nasa.gov/trmm
9	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN)	Y	Remotely Sensed Information using Artificial Neural Networks	1982 - present	60° S - 60°N and 0° to 360°	Daily	https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00854
10	CPC Unified Gauge-Based Analysis of Daily Precipitation over CONUS	Y	Gauged-based analysis	1948 - 2006	0.25° x 0.25° CONUS	Daily	https://psl.noaa.gov/data/gridded/data.unified.daily.conus.html
11	scPDSI for Global Land Climate Research Unit (CRU)	Y	Rainfall and temperature observations	1901 - 2019	0.5° x 0.5° Global (~50km)	Monthly	https://crudata.uea.ac.uk/cru/data/drought/#global
12	Global Precipitation Climatology Centre (GPCC)	Y	Gauged-based analysis	1951 - 2000	1° x 1° Global	Monthly	http://www.cgd.ucar.edu/cas/catalog/surface/precip/gpcc.html

Table 3: Rainfall product evaluation.

The criteria evaluated for selection were that the product must have precipitation data at a daily timescale (to allow for dry day analysis); high resolution (to account for wide variation in island rainfall); station-based data (for accuracy and to match Larsen data as closely as possible); and at least 31 years of available data (to establish the long-term average). I found that two rainfall product sources met the criteria: the Daymet Daily Surface Weather Data on a 1-km Grid for North America, Version 3 and the Global Precipitation Climatology Project (GPCP) data.

I selected the Daymet Data on a 1-km Grid for North America, Version 3, Puerto Rico Tile Mosaic, because it has higher resolution. The Daymet data are available from the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC), a NASA Earth Observing System Data and Information System (EOSDIS) data center managed by the Earth Science Data and Information System Project (ORNL DAAC 2019). The Daymet dataset consists of gridded estimates of daily parameters including precipitation (Table 3). The dataset is derived using several inputs, including ground observations of daily maximum and minimum temperatures and precipitation from NOAA's National Centers for Environmental Information's Global Historical Climatology Network (GHCN). Eight of the twelve stations used in Larsen's analysis are listed under the NCEI network, assuring that data in the two studies have some overlap, as both use data derived from land-based stations in the NCEI GHN network. In addition to the station data, the Daymet gridded dataset algorithm uses a digital elevation model, land mask, and sun-slope geometry (Daymet 2020). Daily data is available for the 40-year period from 1980 to 2019. The average absolute error for predicted annual total rainfall is 19.3%, while the success rate for daily rainfall was 83.3.% (Thorton et al. 1997).

Downloading rainfall data from the data grid

The next step in the rainfall analysis was to download the rainfall data using the Daymet Single Pixel Extraction Tool API. The Daymet Single Pixel Extraction Tool allows users to download single pixels

instead of downloading the entire data grid. In an effort to mimic the data locations from Larsen (2000), I extracted the pixes from the same coordinates where the rainfall stations analyzed by Larsen were located. Using the extraction tool, I successfully downloaded 12 individual 1km x 1km pixels containing the coordinates from the 12 rainfall stations in Larsen (2000).

Establishing long-term averages

Gridded rainfall data was then analyzed to determine the timing and severity of meteorological drought from 2000 to 2019. First, to establish the long term average for each location, average annual rainfall accumulation from 1980 to 2019 was calculated for each of the 12 locations. Second, to get a closer look at the severity of the most recent period of extreme drought, average rainfall for the drought period of 2014 to 2016 will also be calculated for each location. Next, the departure from the long term average will be expressed using a rainfall index derived from the following equation:

$$Rainfall\ index\ =\ 1\ -\ (location\ annual\ rainfall\ \div\ average\ rainfall\ for\ period\ of\ record)$$

Evaluation of region variation

Regional variation in rainfall was evaluated by coupling locations from each region into the following: Canóvanas and Corozal (North), Fajardo and Humacao (East), Aguirre and Ponce (South), Coloso and Mayagüez (West). To calculate the timing and intensity of regional drought conditions, monthly rainfall data will then be organized into deciles of rainfall distribution by region.

Rainfall deciles

Deciles, sometimes referred to as Deciles Index, is a meteorological drought index that ranks the rainfall of a specified period by dividing data into ten sections of equal value in the context of the period

of record. Deciles are used to place recent rainfall data into historical context by determining the distribution of rainfall level occurrence over a chosen period of time. Of the many available drought indexes, deciles are considered one of the most simple to use. First, deciles only require one variable; rainfall. Second, deciles use simple mathematics and are flexible because they can be calculated at different timescales. This timescale flexibility makes deciles useful for application in meteorological, agricultural, and hydrological drought analyses (World Meteorological Organization and Global Water Partnership, 2016).

By comparing rainfall deciles in locations in the North, East, South and West regions, the severity of rainfall deficiency can be evaluated in terms of its regional occurrence in Puerto Rico. To calculate deciles, monthly rainfall totals for the entire period will first be organized in ascending order. Next, the data is divided into ten equal sections. The first decile represents the driest months with the lowest rainfall totals for the period, while the tenth decile contains the wettest months. A common practice is to then couple the data into pairs of deciles (as seen in Table 8). In this arrangement, the middle deciles, five and six, represent near normal rainfall values. Below normal precipitation values are considered deciles three and four, while much below normal rainfall are in the lowest deciles, one and two.

Trends in annual dry days (TDD and MCDD)

I used total annual dry days (TDD) as one measure of an increase or decrease in drying trends island-wide and in the four regions. If TDD are increasing, it may suggest an overall drying of the climate and/or a shift in rainfall patterns toward dry conditions between rainfall events. On the other hand, a decreasing trend of TDD could suggest that the climate is shifting toward wetter conditions, and/or that rainfall patterns have shifted to more frequent rainfall events.

By analyzing maximum consecutive dry days (MCDD) over the 40 year study period, I can identify whether there is an overall trend in how periods of dry days might be changing over time. An increase in

MCDD would indicate a lengthening of dry periods from 1980 to 2019, whereas a decrease in MCDD would indicate shortening dry periods or a shift in rainfall patterns toward more frequent rainfall events. First I will calculate the number of TDD and MCDD for each location, and then I will analyze the statistical significance of island-wide dry days using the Mann-Kendall trend test. The Mann-Kendall trend test is a non-parametric statistical analysis used to identify a trend in a series. The test can also identify trends in data series that may have seasonal variation (Addinsoft 2020). Using Microsoft Excel add-in called XLSTAT, I will first carry out the Mann-Kendall trend test to determine whether there is a statistically significant trend in monthly rainfall island-wide from 1980 to 2019. I will then use the island-wide total annual dry day data to determine whether there is a statistically significant trend in total dry days from 1980 to 2019. The results show whether there is a trend not due to seasonality. If the p-value shows the null hypothesis is rejected, then there is a significant trend even when taking into account seasonality. The Sen-slope value indicates the magnitude of the trend.

Streamflow analysis

The United States Geological Survey (USGS) describes streamflow as the volume of water flowing past a certain point in a given time period (USGS 2018). The USGS has provided streamflow data in Puerto Rico since 1959 (Quiñones et al. 1984). Today, real-time data on streamflow is available for over one hundred sites on the island. In drought analysis, streamflow data provides useful information about the manner in which the effects of deficient rainfall are reflected in surface water. Low streamflow is an indicator for hydrological drought, and since streams and rivers transport water to public supply reservoirs, prolonged low flow values will precede a reduction in reservoir levels. By studying streamflow, we can gain a greater sense of the timing, intensity, and duration of hydrological drought.

Rivers to be analyzed

The four rivers included in this analysis are Río de la Plata, Río Grande de Loíza, Río Gurabo, and Río Tanamá. The first three rivers were selected because they drain into two of the main public supply reservoirs in Puerto Rico's metropolitan area (Loíza and La Plata Reservoirs). The Río Tanamá was selected as a substitute for Río Guajataca, a river that drains into the reservoir that supplies water to northwest Puerto Rico, but for which data was not available until 2017, making it unsuitable for this analysis. Therefore, Río Tanamá, a river with similar characteristics to Río Guajataca, will be used. Río Tanamá was also used to represent Río Guajataca in Larsen's (2000) paper and thus ensures comparability between the two periods of analysis.

Streamflow frequency analysis

To explore the hydrologic response to reduced rainfall during the major drought of 2014 to 2016, 'normal' conditions can be determined by calculating streamflow duration for the four rivers. Flow duration is a measure of the frequency of streamflow magnitudes over a specified period. I use streamflow duration from Atkins 1999 for the selected rivers. A frequency analysis of streamflow determines the probability of a certain magnitude of streamflow over a selected period. When studying drought, the streamflow frequency analysis is particularly useful because it helps to determine the frequency and probability of low-streamflow events.

Flow percentiles

Next, the cumulative percentage of days with discharge at or below flow percentiles will be calculated. A frequency distribution will be created with daily discharge during the period and then the entire period of record, to then aggregate into flow percentiles. The comparison of average daily

discharge in drought to low flows for the entire period will provide more insight into the severity of dry periods.

Reservoir level analysis

Reservoir levels will be compared to 1994 levels to enable comparison of the two most recent severe drought periods. To evaluate the relationship of the meteorological and hydrological droughts in the study period, daily reservoir levels will also be compared to precipitation and streamflow data. Three reservoirs have been selected for analysis: the Loiza, La Plata, and Guajataca reservoirs.

The Loíza reservoir supplies about 30% (100 MGD) of the San Juan metropolitan area's public water (Ortíz-Zayas et al. 2004). About 70% of the Loíza Reservoir's water is supplied by the Río Grande de Loíza and the Río Gurabo (Webb and Soler 1997). Like the Loiza reservoir, La Plata reservoir also supplies about 30% of the metro area's water. La Plata receives its water supply from Río de la Plata. As previously mentioned, the Guajataca reservoir was selected because it is the main source of water supply for the northwest of Puerto Rico (Ortíz-Zayas et al. 2004).

Results

Rainfall from 1980 - 2019

According to Daymet data, annual rainfall in Puerto Rico shows a general increasing trend during the 40 year period of 1980 to 2019. In Figure 14, the blue trendline is just above 1600 mm annual rainfall in 1980. By 2019, the trendline shows the average annual rainfall at 1800 mm. However, the trendline's R^2 value is only 0.039, indicating the rainfall data does not closely fit with the trendline because it is spread quite widely across the y axis. To better determine the trend in rainfall from 1980 to 2019, a Mann-Kendall trend test was performed.

The Mann-Kendall trend analysis yielded a p-value of 0.048, indicating we reject the null hypothesis that there is no trend in annual rainfall from 1980 to 2019. Therefore, there is a statistically significant positive trend in the average annual rainfall of the 12 locations from 1980 to 2019. Sen's slope results indicate a 5 mm increase in rainfall per year.

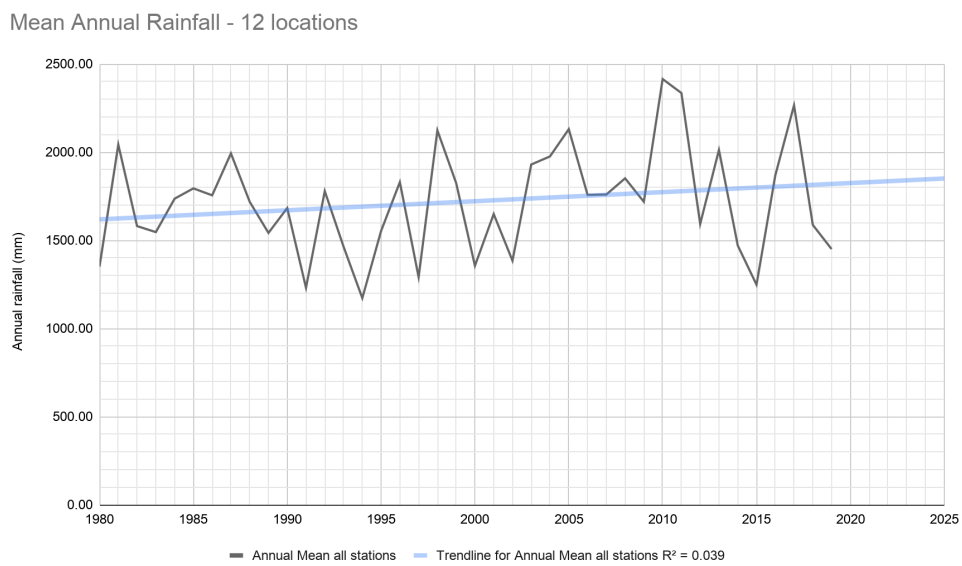


Figure 14: Mean annual rainfall averaged from 12 locations from 1980 to 2019 using Daymet data. Linear trendline in blue.

According to Daymet data, the average annual rainfall accumulation across all 12 locations from 1980 to 2019 was 1719 mm per year, with individual locations ranging from an average of 1086 mm in Ponce to 2249 mm in Humacao (Table 4). Annual rainfall was graphed for the twelve individual locations examined in this study (Appendices I to XII). Eleven of the twelve locations display trendlines that indicate an increase in annual rainfall from 1980 to 2019. The ranges of the R^2 values of the respective trendlines of the 12 locations were quite low, from 0.002 to 0.127, indicating that the data was a not a strong fit to the trendlines. Seven of the twelve locations increased their annual average rainfall when comparing 20th century averages from Larsen 2000 to the 1980 to 2019 Daymet averages.

During the drought period of 2014 to 2016, the average annual rainfall for ten of the twelve locations was less than their 1980 to 2019 average. In contrast, from 2014 to 2016 the Mayagüez and Coloso locations registered an average annual rainfall higher than their respective long-term averages. Meanwhile, the annual averages for the drought periods at the Fajardo, Guayama and Dorado locations were lowest when compared to the 1980 to 2019 average at 82, 83, and 84 percent of their long term averages, respectively (Table 4).

Name	Coordinates	Elevation	Mean/median	Mean, 1980 - 2019	Mean 2014 - 2016	2014 – 2016 mean/ 1980 – 2019 mean
Aguirre	17.95556, -66.22222	14.9	1.02	1278.78	1108.67	0.87
Arecibo	18.45333, -66.67472	3	1.03	1659.40	1333.33	0.80
Canóvanas	18.37861, -65.89417	3	1.01	2045.00	1777.67	0.87
Coloso	18.38306, -67.16083	12.2	1.03	1629.80	1688.67	1.04
Corozal	18.32667, -66.35917	198.1	1.02	1875.63	1677.67	0.89
Dorado	18.47222, -66.30556	1.5	0.97	1641.68	1384.00	0.84
Fajardo	18.31472, -65.65222	9.1	1.03	2241.83	1844.33	0.82
Guayama	17.97861, -66.08722	21.9	1.00	1508.95	1254.67	0.83
Humacao	18.13333, -65.81667	39.9	1.03	2249.00	1973.67	0.88
Mayagüez	18.18778, -67.13778	22.6	1.00	1578.25	1586.00	1.00
Ponce	18.02583, -66.52528	21.3	0.96	1086.00	1039.67	0.96
Río Piedras	n/a	29.9	1.02	1834.40	1675.67	0.91
Mean, all			1.02	1719.06	1528.67	0.89

Table 4. Mean rainfall accumulation, in mm, at 12 locations.

Regional variation of drought periods

Regional rainfall variation was evaluated by coupling locations to represent average rainfall for the four regions in Puerto Rico. The north region was represented by the average rainfall of the Canóvanas and Corozal locations. The east region was represented by the Fajardo and Humacao locations. The south was represented by Aguirre and Ponce locations, and the west represented by the Coloso and Mayagüez locations. When I reference the rainfall average in a region, I am referring to the average of the two aforementioned locations that represent the region.

Figure 15 shows annual rainfall index for the west, east, north and south regions and the average of the regions from 1980 to 2019. According to Daymet data, the longest dry period that affected all four regions was the three-year period of 1993 to 1995 when dry conditions maintained 10% below normal rainfall for all regions (Figure 15A). The same period was also the most severe meteorological drought in the study period because it was the the longest sustained drought that caused below or well-below rainfall for three consecutive years. In 1994, the driest year of the period, rainfall was 22, 25, 41, and 20% below normal in the west, east, north, and south, respectively. The entire island went through a dry period from 1989 to 1997, though severity of dryness varied among regions.

The driest year from 1980 to 2019 varied by region. For example, 1991 was the driest year of the 1990s for the west, east and south while the north's driest year of the 1990s was 1994. In 2014 and 2015, the average annual rainfall for all four regions combined was 14 and 23% below normal, respectively (Figure 15A). From 1980 to 2019, the driest year across the 8 locations was 1991 when rainfall was 30% below normal (Figure 15A).

West - In the western region (average of Coloso and Mayaguez locations), the longest sustained dry period was from 1993 to 1997. The five-year dry period had average annual rainfall values that hovered around 20% below normal (16, 22, 26, 19, and 22%) (Figure 15B). The 2015 drought did not affect the west as severely as other regions. In 2014 and 2015, average annual rainfall in the west was 11 and 4% below normal, respectively. The average annual rainfall in the west was 1604 mm. Between 1980 to 2019, the west's driest year occurred in 1991 when the average annual rainfall was 38% below normal at 1001 mm.

East - In the eastern region (average of Fajardo and Humacao locations), the longest sustained period of drought was from 1989 to 1995 when rainfall was below average each year, dipping down to 25% below average annual rainfall in 1991 and 1994 (Figure 15C). For 1993, 1994, and 1995, average annual rainfall was 8, 25, and 11% below normal, respectively. The period of 2000, 2001, 2002 was

another three-year dry period, with 27, 12, and 25% below normal annual rainfall. In 2014 and 2015, annual rainfall was 15 and 31% below normal, respectively. (Figure 15C). The long-term average annual rainfall in the east was 2245 mm. The driest year in the east between 1980 and 2019 was 2015 when average annual rainfall was 1558 mm.

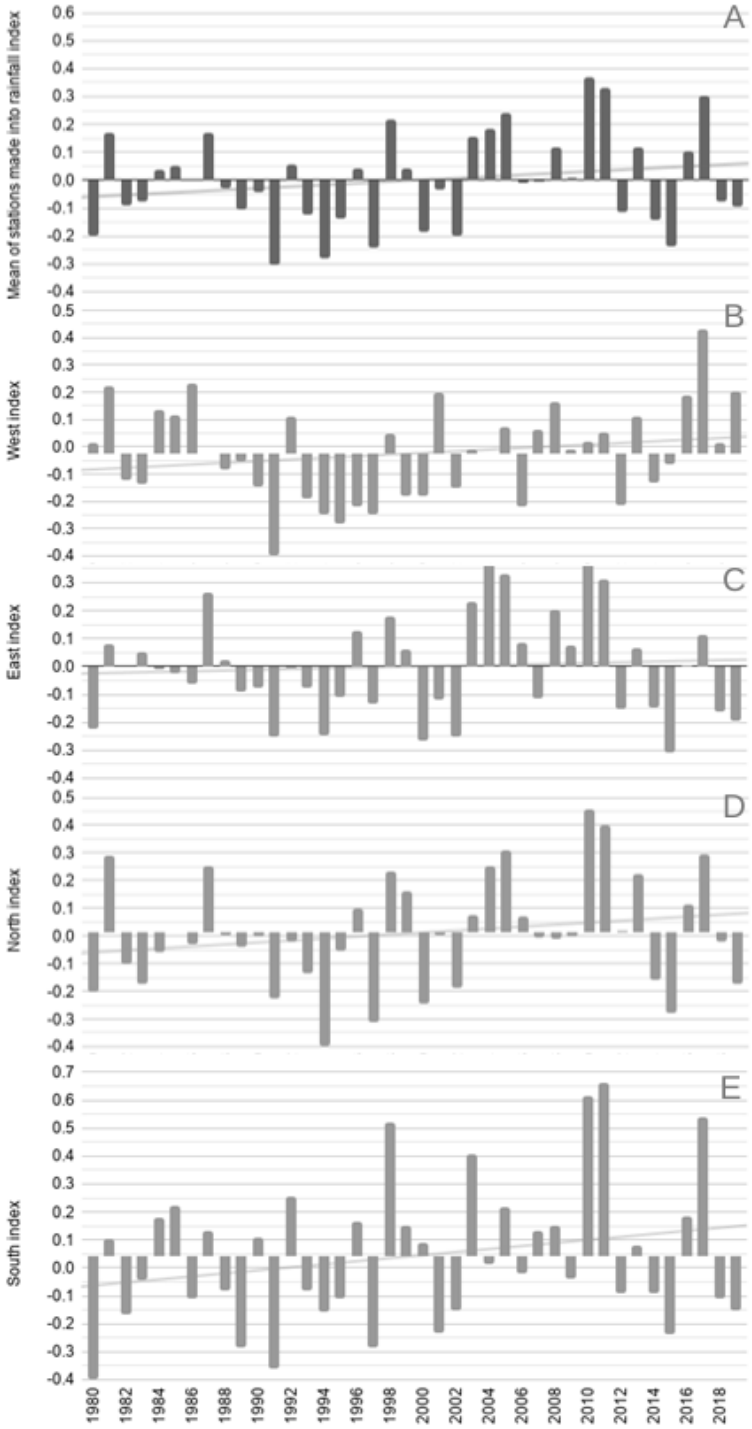


Figure 15: Annual rainfall departure from the long term average (1980 to 2019) for pairs of locations representing regions of Puerto Rico. (A) Mean of 8 stations, (B) West: Coloso and Mayaguez, (C) East: Fajardo and Humacao, (D) North: Canóvanas and Corozal, (E) South: Ponce and Aquirre. Rainfall index = (annual rainfall / average rainfall) -1. Data source: Daymet gridded rainfall, single pixel extraction for rainfall stations.

North - In the northern region (average of Canóvanas and Corozal locations) the longest dry period was the eight year period of 1988 to 1995 when rainfall maintained levels below normal, reaching a low point of 41% below normal rainfall in 1994 (Figure 15D). There were several two-year dry periods from 1980 to 2019: 1982-1983, 1993-1994, and

2014-2015. In 1982 and 1983, average rainfall was 11 and 19% below normal, respectively. In 1993 and 1994, average annual rainfall was 15 and 41% below normal, respectively. In 2014 and 2015, the average annual rainfall was 17 and 29% below normal, respectively. The long-term average rainfall for the north was 1960 mm and the north's driest year in the study period was 1994 at 1156 mm.

South - In the southern region (Ponce and Aguirre locations), the longest continuous dry period was the three year period of 1993, 1994, and 1995 when rainfall was 12%, 20%, and 15% below normal, respectively (Figure 15E). Notable noncontinuous dry years included 1989, 1991, and 1997 when average annual rainfalls were 33, 40 and 33% below normal, respectively. In the years 2014 and 2015, average annual rainfall was 14 and 28% below normal, respectively. In the south, the long-term average annual rainfall was 1182 mm. The driest year in the south from 1980 to 2019 was 1980 when the average annual rainfall was 44% below normal at 658 mm.

Dry years and dry day trends

To determine the driest years from 1900 to 2019, I used two data sets. Given that Daymet data is not available prior to 1980, for years between 1900 and 1980, I referenced average annual rainfall data from Larsen's paper derived from twelve NOAA stations. For years between 1980 to 2019, Daymet data was used to calculate the average annual data among the twelve rainfall locations. As previously mentioned, the Daymet rainfall data was extracted and downloaded at the same coordinates of the twelve NOAA rainfall stations used in Larsen 2000.

In Table 5, combined NOAA and Daymet data are listed to show the driest years since 1900. Nine of the top ten driest years occurred in the 20th century (Table 5, Figure 16). The driest year in the 21st century was 2015. The driest year since 1900 continues to be 1967 (Table 5). In the last 120 years, 2015 ranks as the fourth driest year. In the last 40 years, my main period of study, 2015 ranks as the third driest year, following 1994 and 1991.

Table 6 shows a comparison of the Larsen 2000 ranking of driest years versus the updated ranking with Daymet data. Differences in annual rainfall are noted for driest years between 1980 and 2000 that are available in both datasets, providing insight into the variation in rainfall observations versus rainfall product data: 1980 (Daymet 32 mm more), 1991 (Daymet 32mm less), 1994 (Daymet 1mm more), and 1997 (Daymet 151 mm more). Daymet values for annual rainfall are higher than NOAA data used by Larsen 2000 for three of the four overlapping years. Table 7 shows the top ten driest years according to Daymet data during the period of study, 1980 to 2019.

Year	Mean annual rainfall, mm	Rank
1967	1065*	1
1994	1172	2
1991	1230	3
2015	1249	4
1964	1255*	5
1976	1259*	6
1997	1292	7
1930	1308*	8
1947	1342*	9
1980	1351	10

Table 5: Rank of ten driest years since 1900. The average annual rainfall is the average of twelve locations in Puerto Rico from 1980 according to Daymet data. Years before 1980 are listed with values from Larsen 2000 (rainfall data from twelve NOAA stations, denoted with an asterisk).

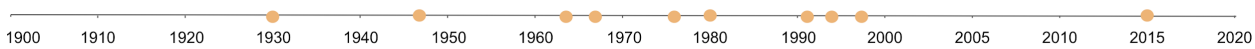


Figure 16: Temporal distribution of top ten driest years among 12 locations from 1900 to 2019 according to NOAA data (1900 to 1980) and Daymet data (1980 to 2019).

Rank	2020 (this study)	Mean annual rainfall (mm)	2000 (Larsen's study)	Mean annual rainfall (mm)
1	**1967**	1065*	**1967**	1065
2	**1994**	1172	**1997**	1141
3	**1991**	1230	**1994**	1171
4	**1964**	1255*	**1964**	1255
5	**1976**	1259*	**1976**	1259
6	**2015**	1249	**1991**	1261
7	**1997**	1292	**1930**	1308
8	**1930**	1308*	**1980**	1319
9	**1947**	1342*	**1947**	1342
10	**1980**	1351	**1957**	1352

Table 6: Comparison of ranking top ten driest years from this study versus Larsen 2000. The annual rainfall for years prior to 1980 uses the rainfall data from the twelve rainfall stations used in Larsen 2000, denoted with an asterisk.

Rank	Year	Annual rainfall (mm)
1	1994	**1172**
2	1991	**1230**
3	2015	**1249**
4	1997	**1292**
5	1980	**1351**
6	2000	**1356**
7	2002	**1385**
8	2019	**1450**
9	1993	**1464**
10	2014	**1471**

Table 7: Ranking of top ten driest years since 1980 with annual rainfall averaged among twelve locations. Data: Daymet.

Annual dry days

According to Daymet data, dry days are not becoming more frequent. Rather, total annual dry days are decreasing. Prior to 1996, the TDD for all 12 locations was consistently over 200 days per year

(Figure 17). After 1996, the TDD was frequently less than 200. The average number of total annual dry days (TDD) of the 12 locations from 1980 to 2019 is 206 days. The maximum number of TDD throughout the period was 241 days in 1983, while the minimum was 155 days in 2013.

The linear trendline (Figure 17) shows a 44 day decrease in total annual dry days through the 40 year period, or about one less dry day per year. The average total annual number of dry days at the beginning of the period in 1980 was about 228 days. By 2019, the average TDD was about 184 days. The years with the highest TDD across the 12 locations between 1980 to 2019 were 1983 (241.8 days), 1994 (235.8 days), 1991 (230.9 days), 1993 (230.7 days), and 1980 (228.8 days) (Figure 17). The results from the Mann-Kendall trend test on the sum of the total annual dry days of all 12 locations confirmed the downward trend of the total annual dry days to be statistically significant. The test yielded a p-value of 0.0001 which is significantly lower than the alpha 0.05, indicating we reject the null hypothesis and accept the alternative hypothesis that there is a downward trend in TDD for Puerto Rico.

Furthermore, the total annual number of dry days shows a decreasing trend for all 12 locations from 1980 to 2019 (Figure 17). Among the twelve locations, the average number of TDD during the first 20 years of the study period (1980 to 1999) was about 217 TDD. From 2000 to 2019, the average TDD between the 12 locations was about 195 dry days. All twelve locations show a decreasing trend in TDD (Appendices XIII-XXIIII). No locations show an increasing trend in total annual dry days. The highest average TDD occurred at the Ponce, Mayagüez, and Aguirre locations, with about 280, 260, and 249 average total dry days from 1980 to 2019, respectively. The lowest average TDDs occurred at the Humacao, Fajardo and Canóvanas locations with about 139, 142 and 145 average TDD from 1980 to 2019, respectively. According to the trendlines, the locations with the greatest decrease in TDDs trends were Coloso, Arecibo and Aguirre with decreases of about 64, 61 and 60 TDDs over the 40-year period. The locations with the least decrease in TDDs were Canóvanas, Fajardo and Guayama with decreases of about 22, 29 and 29 TDDs from 1980 to 2019.

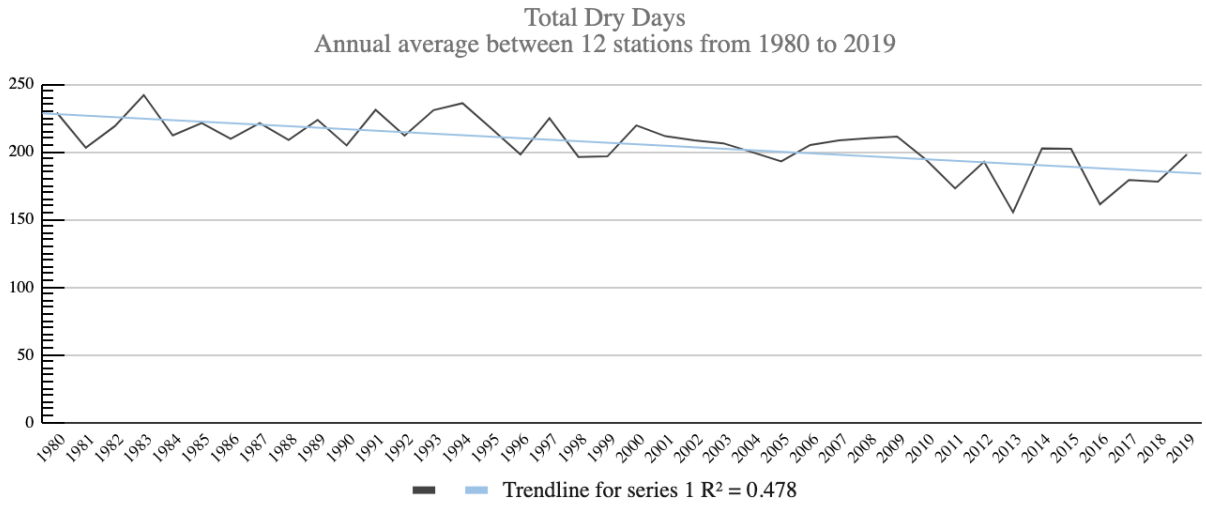


Figure 17: Annual average of total dry days (rainfall less than 1 mm) for the 12 locations. Trendline in blue.

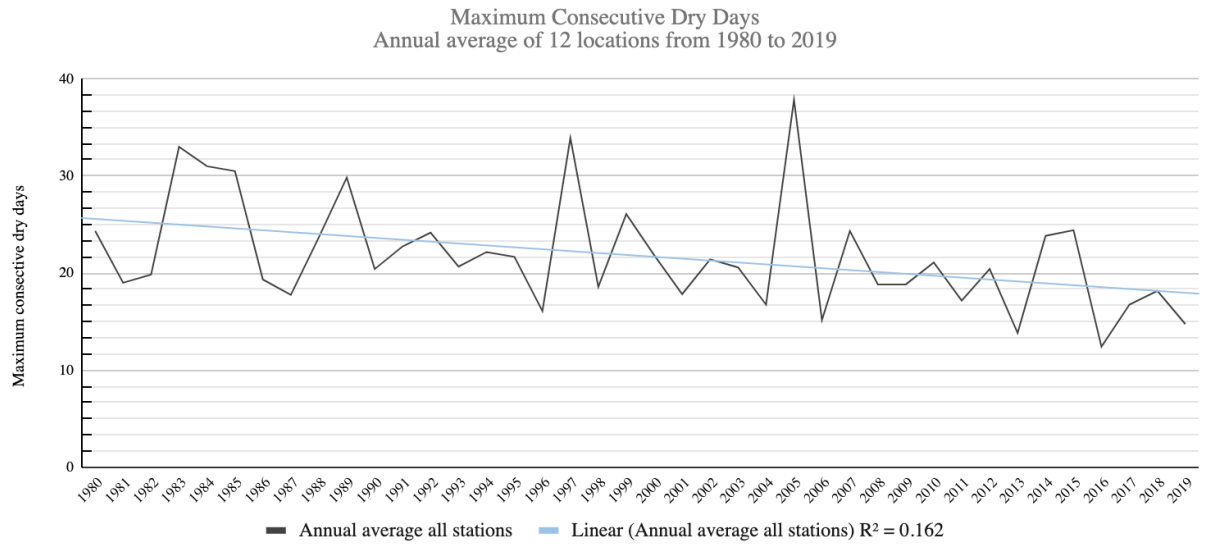


Figure 18: Annual average of maximum consecutive dry days (rainfall less than 1 mm) for the 12 locations.

The average number of maximum annual consecutive dry days (MCDD), or the longest period of consecutive days with rainfall less than one mm per day, for all twelve locations combined was 22 days. For the individual locations, the number of MCDD shows a decreasing trend from 1980 to 2019 for eleven of the twelve locations (Figure 18). Among the twelve locations, the average decreasing trend is

about 8 days across forty years, starting at an average of 26 MCDD in 1980 and ending with an average of 18 MCDD in 2019. The overall decrease in MCDD indicates that the longest dry periods show a shortening trend in the last 40 years. In other words, from 1980 to 2019, the longest dry periods became shorter. The years with the highest MCDD across the 12 locations between 1980 to 2019 were 2005 (37.8), 1997 (33.9), 1983 (33), 1984 (31), and 1985 (30.5) (Figure 18). The longest period of elevated maximum consecutive dry days was 1983 to 1985 (Figure 18).

The Mann-Kendall trend test for MCDD of the combined 12 locations confirmed that the downward trend in maximum consecutive dry days is statistically significant. The test yielded a p-value of 0.005 which is lower than the alpha 0.05, indicating we reject the null hypothesis and accept the alternative hypothesis that there is a statistically significant downward trend in MCDD for the average of all locations.

Unlike the other locations, the number of MCDD for the Humacao location remained steady from 1980 to 2019, showing no upward or downward trend (Appendices XXV-XXXVI). The locations with the least change in MCDD were Humacao, Corozal and Fajardo with a 0, 2 and 4 day decrease in MCDD from 1980 to 2019. The Mayaguez, Aguirre and Coloso locations show the most significant decrease in MCDD, with a decrease of about 17, 16 and 16 MCDD respectively from 1980 to 2019. In other words, their longest dry periods have shortened by 16 to 17 days in the last 40 years.

Deciles

Decile distribution shows the severity of rainfall deficiency at four locations in Puerto Rico from 1980 to 2019 (Table 8). The most intense droughts varied by location. Deciles show that the period of October 1996 to March 1998 was the worst drought for the Mayaguez and Ponce locations, where rainfall was below normal 61% of the time for both locations. According to the Daymet data, the

Mayaguez location had much below normal rainfall 44% of the time, while the Ponce location rainfall was much below normal 39% of the time.

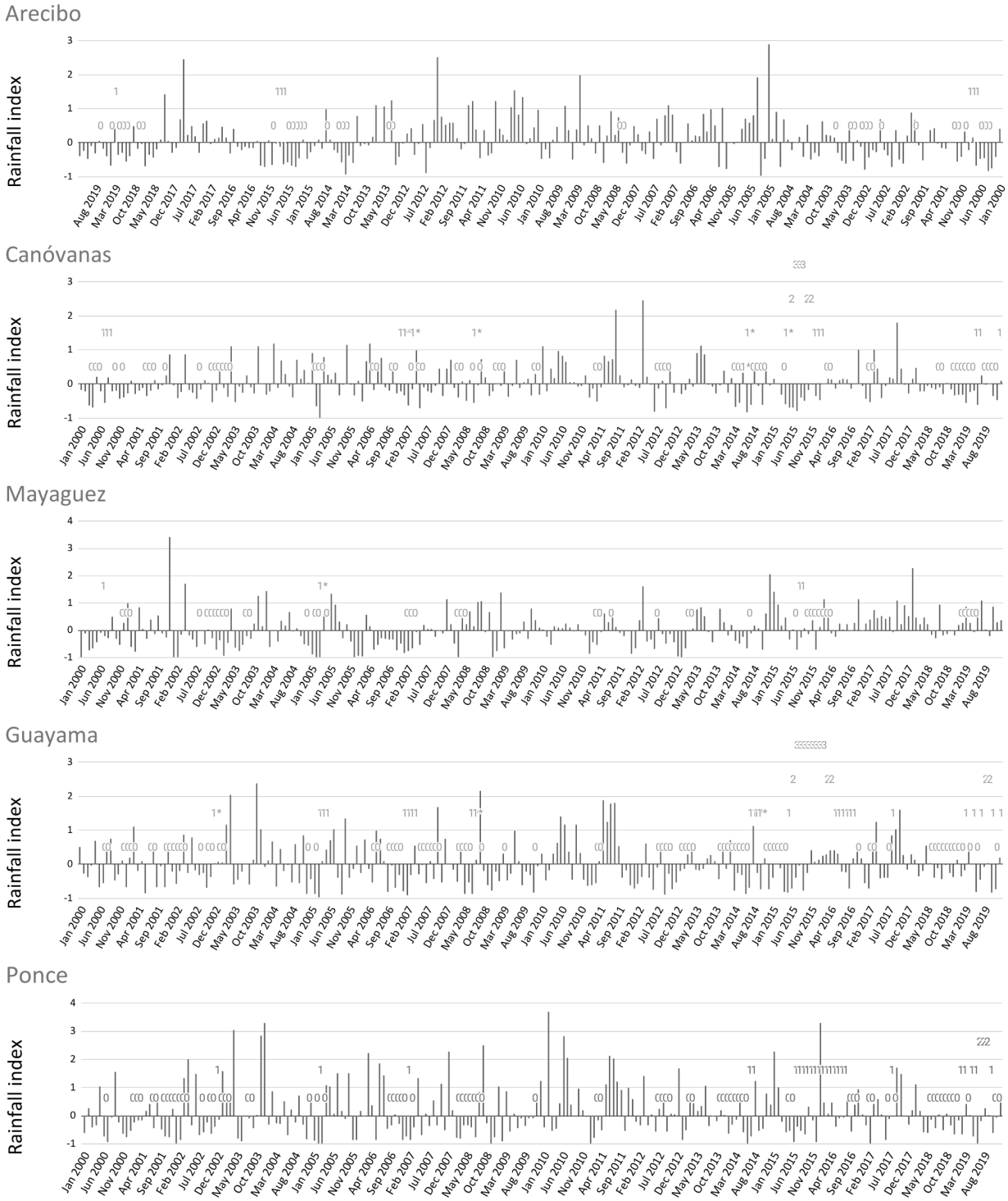
At the Arecibo location, the worst drought year was 2015, where rainfall was much below normal for 58% of the year, and below normal for a combined 75% of the year (58% much below normal plus 17% below normal). The worst drought years for the Canóvanas location were 2014 and 2015, with much below normal rainfall 42% of the time for each year and below normal rainfall for 17 and 33% of the time for 2014 and 2015, respectively.

For the average of the four locations, the worst droughts were from October 1996 to March 1998 and the year 2000, where rainfall was much below normal 33% of the time for both years, and below normal 22 and 23% of the time, respectively for a combined 55 and 56% below normal (Table 8). In 2015, the rainfall was much below normal 31% of the time and below normal 25% of the time, for a combined 56% below normal.

		Cumulative distribution of monthly rainfall by deciles				
	Monthly rainfall	Much below normal	Below normal	Near normal	Above normal	Much above normal
	Deciles	1, 2	3, 4	5, 6	7, 8	9, 10
	Classification	Lowest 20%	Next lowest 20%	Middle 20%	Next highest 20%	Highest 20%
Arecibo	Jan 1993 - Dec 1995	0.28	0.25	0.17	0.19	0.11
	Oct 1996 - Mar 1998	0.28	0.28	0.28	0.11	0.06
	Jan 2000 - Dec 2000	0.50	0.08	0.17	0.17	0.08
	Jan 2005 - Dec 2005	0.25	0.00	0.00	0.42	0.33
	Jan 2007 - Dec 2007	0.08	0.08	0.17	0.33	0.33
	Jan 2008 - Dec 2008	0.17	0.17	0.17	0.17	0.33
	Jan 2014 - Dec 2014	0.33	0.17	0.17	0.25	0.08
	Jan 2015 - Dec 2015	0.58	0.17	0.08	0.17	0.00
	Jan 2017 – Dec 2017	0.00	0.17	0.17	0.42	025
	Jan 2019 – Dec 2019	0.17	0.33	-.33	0.17	0.00
Canóvanas	Jan 1993 - Dec 1995	0.25	0.28	0.25	0.14	0.08
	Oct 1996 - Mar 1998	0.22	0.22	0.22	0.22	0.11
	Jan 2000 - Dec 2000	0.33	0.25	0.25	0.00	0.17
	Jan 2005 - Dec 2005	0.17	0.08	0.17	0.17	0.42
	Jan 2007 - Dec 2007	0.33	0.08	0.25	0.08	0.25
	Jan 2008 - Dec 2008	0.25	0.08	0.33	0.25	0.08
	Jan 2014 - Dec 2014	0.42	0.17	0.08	0.08	0.25
	Jan 2015 - Dec 2015	0.42	0.33	0.17	0.08	0.00
	Jan 2017 – Dec 2017	0.17	0.25	0.00	0.33	0.25
	Jan 2019 – Dec 2019	0.33	0.25	0.08	0.25	0.08
Mayaguez	Jan 1993 - Dec 1995	0.22	0.22	0.25	0.14	0.17
	Oct 1996 - Mar 1998	0.44	0.17	0.22	0.11	0.06
	Jan 2000 - Dec 2000	0.33	0.25	0.08	0.17	0.17
	Jan 2005 - Dec 2005	0.42	0.00	0.08	0.08	0.42
	Jan 2007 - Dec 2007	0.17	0.25	0.17	0.17	0.25
	Jan 2008 - Dec 2008	0.42	0.17	0.08	0.17	0.17
	Jan 2014 - Dec 2014	0.25	0.17	0.17	0.25	0.17
	Jan 2015 - Dec 2015	0.17	0.25	0.33	0.17	0.08
	Jan 2017 – Dec 2017	0.00	0.25	0.08	0.25	0.42
	Jan 2019 – Dec 2019	0.00	0.25	0.08	0.42	0.25
Ponce	Jan 1993 - Dec 1995	0.25	0.28	0.19	0.19	0.08
	Oct 1996 - Mar 1998	0.39	0.22	0.28	0.11	0.00
	Jan 2000 - Dec 2000	0.17	0.33	0.42	0.00	0.08
	Jan 2005 - Dec 2005	0.33	0.08	0.00	0.25	0.33
	Jan 2007 - Dec 2007	0.25	0.08	0.25	0.33	0.08
	Jan 2008 - Dec 2008	0.25	0.08	0.00	0.33	0.33
	Jan 2014 - Dec 2014	0.08	0.42	0.17	0.17	0.17
	Jan 2015 - Dec 2015	0.08	0.25	0.25	0.33	0.08
	Jan 2017 – Dec 2017	0.17	0.17	0.17	0.33	0.17
	Jan 2019 – Dec 2019	0.17	0.17	0.42	0.08	0.17
Mean of four locations	Jan 1993 - Dec 1995	0.25	0.26	0.22	0.17	0.11
	Oct 1996 - Mar 1998	0.33	0.22	0.25	0.14	0.06
	Jan 2000 - Dec 2000	0.33	0.23	0.23	0.08	0.13
	Jan 2005 - Dec 2005	0.29	0.04	0.06	0.23	0.38
	Jan 2007 - Dec 2007	0.21	0.13	0.21	0.23	0.23
	Jan 2008 - Dec 2008	0.27	0.13	0.15	0.23	0.23
	Jan 2014 - Dec 2014	0.27	0.23	0.15	0.19	0.17
	Jan 2015 - Dec 2015	0.31	0.25	0.21	0.19	0.04
	Jan 2017 – Dec 2017	0.08	0.21	0.10	0.33	0.27
	Jan 2019 – Dec 2019	0.17	0.25	0.23	0.23	0.13

Table 8: Classification of monthly rainfall by deciles during drought periods from 1980 to 2019. Source: Daymet.

Figure 19: Departure from long-term annual rainfall average at Arecibo, Canóvanas, Mayagüez, Guayama and Ponce. Rainfall index = (annual rainfall / average rainfall) -1. Data from Daymet gridded rainfall, single pixel extraction. Data labels show US Drought Monitor drought category (D Abnormally dry: 0, Moderate: 1, Severe: 2, Extreme: 3).



Monthly rainfall

To characterize drought periods since 2000 when the US Drought Monitor began, I will take a more detailed look at rainfall by examining monthly rainfall in various regions of the island: Arecibo, Canóvanas, Mayaguez, Ponce, and Guayama (Figure 19). USDM drought categories displayed in the figure indicate the months where the corresponding municipality registered drought conditions. Months with USDM drought conditions do not necessarily include the 1km x 1km pixel where the rainfall data was extracted. On several occasions, the shapefile of drought conditions published by USDM did not cover the coordinate locations where data was extracted from the Daymet rainfall grid. While drought conditions may have affected other municipalities included in other areas of this study, the following discussion solely focuses on Arecibo, Canóvanas, Mayaguez, Ponce, and Guayama. It is important to remember that the US Drought Monitor considers several variables and metrics and is not solely dependent on rainfall. US Drought Monitor considers variables that are influenced by factors other than meteorological drought, such as reservoir levels that are not only dependent on rainfall but also on water consumption, population, and water loss in the distribution system. Detailed information on the data used by the US Drought Monitor can be found in chapter two. In the following paragraphs, I will detail how each drought registered in Puerto Rico effected the aforementioned municipalities.

Streamflow

Mean daily discharge for the period June 24, 2014 to November 15, 2016 are shown along with the 10th, 20th, and 30th flow percentiles for each of the four USGS streamflow stations at the Río Tanamá, Río de la Plata, Río Grande de Loíza, and Río Gurabo (Table 9, Figure 20). The specific date range was selected because June 24, 2014 is two weeks before moderate drought was registered in Puerto Rico by the United States Drought Monitor, and November 15, 2016 is one week after moderate drought was no

longer detected on the island. According to the USDM, abnormally dry conditions had been present for between 21 to 45% of Puerto Rico since November of 2013.

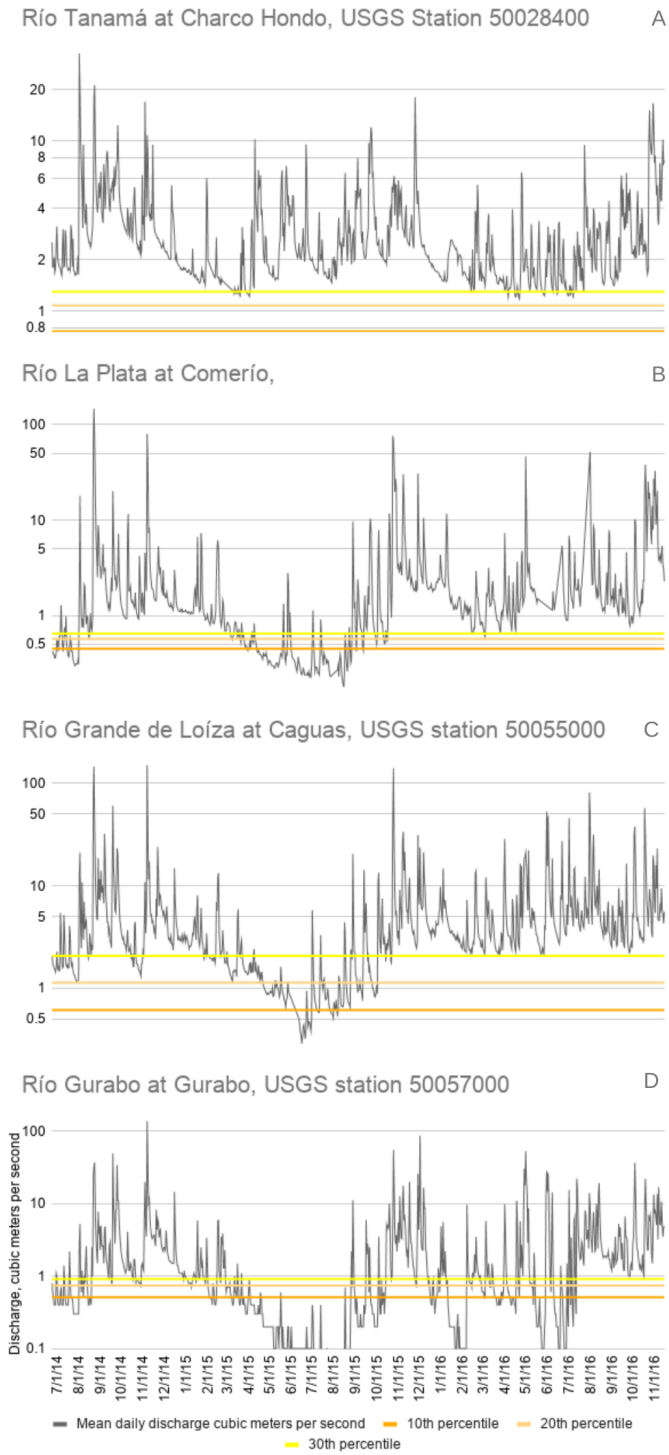


Figure 20. Mean daily discharge at four USGS streamflow gaging stations in Puerto Rico from June 24, 2014 to November 15, 2016. Station locations shown in Figure 13. The 10th, 20th and 30th percentiles are shown in orange, light orange and yellow lines, respectively. Streamflow and flow percentiles include effects of withdrawals and additions by filtration and sewage treatment plants.

Table 9 shows the cumulative percentage of days between June 24, 2014 to November 15, 2016 with discharge at or below flow percentiles 1 through 99. Discharge in the first percentile indicates extreme hydrological drought. Between June 24, 2014 to November 15, 2016, discharge was in the first percentile for 20% of the time for the Río Gurabo and 3% of the time for the Río Grande de Loíza. Discharge did not reach extreme hydrological drought for the Río Tanamá or Río de la Plata. Discharge in the 1st to 10th percentile indicates severe hydrological drought. Discharge was in the 1st to 10th percentiles for a cumulative 17% of the time for the Río de la Plata, 12% for the

Río Grande de Loíza and 36% of the time for the Río Gurabo, while the Rió Tanama did not reached severe hydrological drought.

Discharge in the 10th to 20th percentiles indicates moderate drought. Discharge was in the 20th percentiles 21 to 44% of the time for the Río de la Plata, Río Grande de Loíza, and Río Gurabo. Discharge in the Río Tanamá did not reach moderate drought conditions during the drought of 2015.

Mean daily discharge with 10th, 20th and 30th percentiles in orange, light orange and yellow are shown for the four rivers from June 24, 2014 to November 15, 2016 (Figure 20). In 2014, two of the four rivers, the Río la Plata and Río Gurabo, maintained moderate to severe drought conditions for multiple weeks (Figure 20B and D). Discharge in the Río Grande de Loíza reached abnormally dry conditions, and neared moderate drought conditions on two occasions in 2014, otherwise maintaining abnormally dry conditions or above (Figure 20C). Meanwhile, Río Tanamá did not reach abnormally dry conditions in 2014 (Figure 20A). While conditions were dry in the summer of 2014, there was a slight increase in discharge in August and September. By December of 2014 and January of 2015, discharge at all four rivers was declining toward abnormally dry conditions once again (Figure 20).

Cumulative percentage of days with discharge at or below listed flow percentiles

	Río Tanamá	Río de la Plata	Río Grande de Loíza	Río Gurabo
Percentile	June 24, 2014 through Nov 15, 2016			
1	0	0	3	20
2	0	2	4	22
5	0	11	8	28
10	0	17	12	36
20	0	21	21	44
30	4	24	29	50
50	34	37	49	63
70	62	61	70	75
80	76	74	81	80
90	88	87	90	90
95	95	94	95	95
98	98	97	98	98
99	100	100	100	100

Table 9. Cumulative percentage of days with discharge at or below flow percentiles for four rivers in Puerto Rico from June 24, 2014 to Nov 15, 2016. Source data from USGS.

Between February and June of 2015, discharge at the Río Gurabo, Río de la Plata and Río Grande de Loíza rivers reached the 10th percentile, indicating severe drought conditions (Figure 20, Table 9). From April to August of 2015, discharge in the Río Gurabo and Río de la Plata primarily remained at levels below the 10th percentile (indicating severe drought conditions) for about five months. Meanwhile, discharge at the Río Grande de Loíza intermittently reached the 10th percentile between June to August of 2015.

By October of 2015, though discharges in the Río Grande de Loíza, Río de la Plata, and Río Tanamá hovered around the 30th percentile, occasionally indicating abnormally dry conditions, the three rivers were no longer exhibiting drought conditions. On the other hand, the Río Gurabo continued exhibiting drought conditions for another 9 months until July of 2016. Discharge at the Río Tanamá primarily maintained levels above abnormally dry conditions apart from spring in 2015 and the spring and summer of 2016. Of the four rivers examined in this study, USGS streamflow data indicates that the 2015 drought most affected the Río Gurabo.

Discharge at the the Río Gurabo was at or below the 10-day / 30-day and 10-year / 7-day recurrence intervals for low flow (Santiago Rivera 1992 and 1998) from May to September of 2015 (Appendix 39). In September 2015, discharge improved until January to February of 2016 when levels once again were maintained below the 10-day / 30-day and 10-year / 7-day recurrence intervals for low flow. From May to July 2016, discharge at the the Río Gurabo intermittently dipped below the 10-day / 30-day many times, though it was not maintained as it was during the aforementioned periods.

At the the Río Grande de Loíza, discharge was at or below 10-day / 30-day and 10-year / 7-day recurrence intervals for low flow (Santiago Rivera 1992, 1998) from late June to mid July of 2015 (Appendix 37). Discharge dipped below the 10-day / 30-day intermittently until September of 2015.

Meanwhile, discharge at the Río Tanamá maintained levels above low flows for the entirety of the 2014 to 2016 drought. Unfortunately, low flows were not available for the Río de La Plata.

Reservoir levels

Comparing droughts from 1994 to 1995 to 2014 to 2016

In January of 1994, the water level of La Plata reservoir began to steadily decline from 49 meters, until reaching its low point of 33 meters in August of the same year. Water levels increased to 41 meters elevation by November 1994, but began to decline to 33 meters by February of 1995. La Plata's water levels increased and decreased several times before recovering to 50 meters elevation by November of 1995. Since 1980, La Plata Reservoir reached its lowest levels from 1994 to 1995. The 2015 drought was also quite severe for the reservoir, reaching a low point of 34.5 meters in August 2015.

Meanwhile, the water level in Loíza Reservoir began declining from 39 meters in April to 33 meters in August of 1994. From August to October 1994, the water elevation in the Loíza reservoir recovered to 40 meters. Loíza's water level declined from January to February of 1995, maintained normal levels in March before declining rapidly in April and May of 1995 until it reached 35.5 meter elevation. Between June and early July of 1995, Loíza levels increased to 39 meters, then dipped down again a couple times before reaching 40 meters again by October 1995. Since 1980, the worst drought years for the Loíza Reservoir were 1994 and 2015. The 1994 drought lasted until September 1994, and returned shortly in 1995 before subsiding once again by July 1995. The 2015 drought lasted until October 2015.

Unfortunately, data for the Guajataca Reservoir is not available prior to April of 1995. Normal levels for Guajataca hover around 195 m. In early May of 1995, levels reached 189 m before increasing rapidly mid-May when levels maintained about 194 m until increasing to 196 m in October before steadily declining from 196 to 191 m by May of 1996. Since 1980, the drought periods that most affected

the Guajataca reservoir occurred in 1997 and 1998, lasting from early 1997 to around August 1998 (Figures 21 and 23). While water levels were affected by the 2014 to 2016 drought, the Guajataca Reservoir was not affected as severely as the Loíza and La Plata Reservoirs. The 2019 drought affected the Guajataca Reservoir until the rains of May 2019.

Fig 21. Daily pool elevation for La Plata, Guajataca, Loíza reservoirs

Drought 1997 to 1998

In January of 1997, Guajataca Reservoir levels decreased until August when it reached 186 m. Levels remained low until in increased briefly to 190 m at the end of 1997 (Figures 21 and 23). However, the reservoir level decreased again to the low point of 185 m in May of 1998. Levels steadily increased to

196 m by the end of the year. From 1995, when data is available for download via USGS, to 2019, the worst hydrological drought for Guajataca reservoir was from 1997 to 1998. Water levels of Loíza and La Plata reservoirs began to decline in Spring of 1997. The Loíza reservoir reached 34.3 m, lower than its lowest point in the 1994 to 1995 drought, though levels recovered more quickly, reaching by 41 m by the summer of 1997. For La Plata reservoir, levels decreased to a low point of 38 m in October of 1997, thought water levels quickly recovered thanks to a storm on October 14, 1997. In 1998, both La Plata and Loíza reservoirs decreased in the August, though conditions were not severe (Figures 21, 22, 24).

Drought 2014 to 2016

In August of 2013, water levels at Guajataca reservoir began to decline, reaching 189 m by April 2014. Levels remained low until November 2014 when levels increased to 195 m. For Guajataca, the worst of the 2014 to 2015 occurred in 2014.

In the summer of 2014, water levels in the Loíza reservoir declined to just under the operation adjustment level in late July and early August, while levels at La Plata decreased until reaching 41 m by August of 2014. By November 2014, conditions were near normal water levels at Loíza and La Plata until early 2015 when dry conditions continued. For La Plata and Loíza reservoirs, the low points of the 2015 drought occurred in August when levels reached 34.6 and 33.3, respectively. While the 2015 drought reached their low points in August for La Plata and Loíza reservoirs, water levels were back to normal for Guajataca. While levels at La Plata reservoir reached a low point that was similar to that of the drought of 1994 to 1995, the 2014 to 2015 was less severe as low conditions were maintained for merely three months, compared to the 10 month sustained dry period in 1994 to 1995 (Figures 21 and 22).

Drought 2017

In July and August of 2017, a brief period of moderate drought developed on the southern coastal region of Puerto Rico, though conditions returned to normal prior to Hurricanes Irma and María in September 2017. The water level at Guajataca reservoir shows a significant decrease as well, though it was not due to the drought (Figure 21). Drought conditions did not affect the northern area where Guajataca's watershed is located. The decrease in Guajataca's water level was due to infrastructural damage caused by Hurricane María rather than drought conditions. According to the Army Corps of Engineers, the spillway was damaged during the hurricane, putting the downstream populace in danger of a potential flood (Carrasco 2019). While the structure was repaired, water levels were maintained at 193 meters for safety purposes. In December of 2018, the reservoir was repaired to the point that water levels could be safely increased (Carrasco 2019).

Drought 2019

Just after the infrastructural repairs in the Guajataca reservoir allowed water levels to be re-established, conditions appear to dry even prior to the start of 2019. Water levels in Guajataca reservoir decreased to 187.8 m, with levels hovering around 188 m from February to May of 2019. Conditions returned to normal in early June 2019 when the water level reached 195 m.

La Plata reservoir water levels declined steadily since the beginning of 2019, finally reaching a low point of 46.9 m by August. By the end of the year, levels had increased to 49.5 m. At Loíza reservoir, drought conditions did not reflect nearly as much as in Guajataca and La Plata, only decreasing slightly to a low point of 39.4 m briefly in July of 2019.

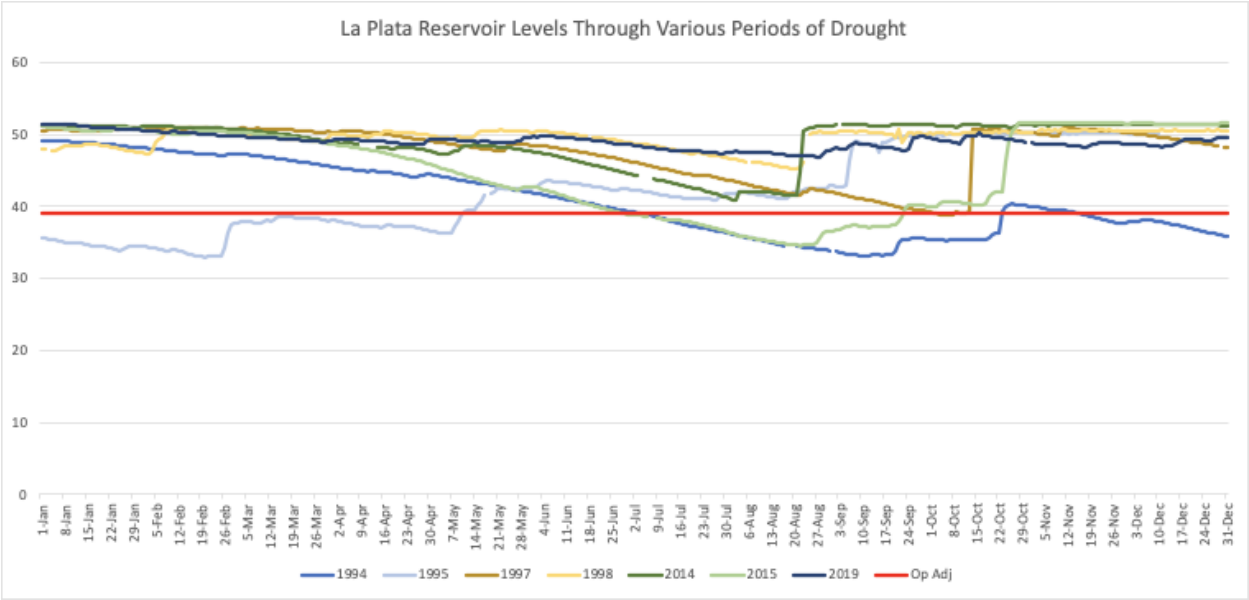


Fig 22. La Plata reservoir levels for select drought years. Data: USGS. Red line indicates the operational adjustment level when rationing may be considered by management officials.

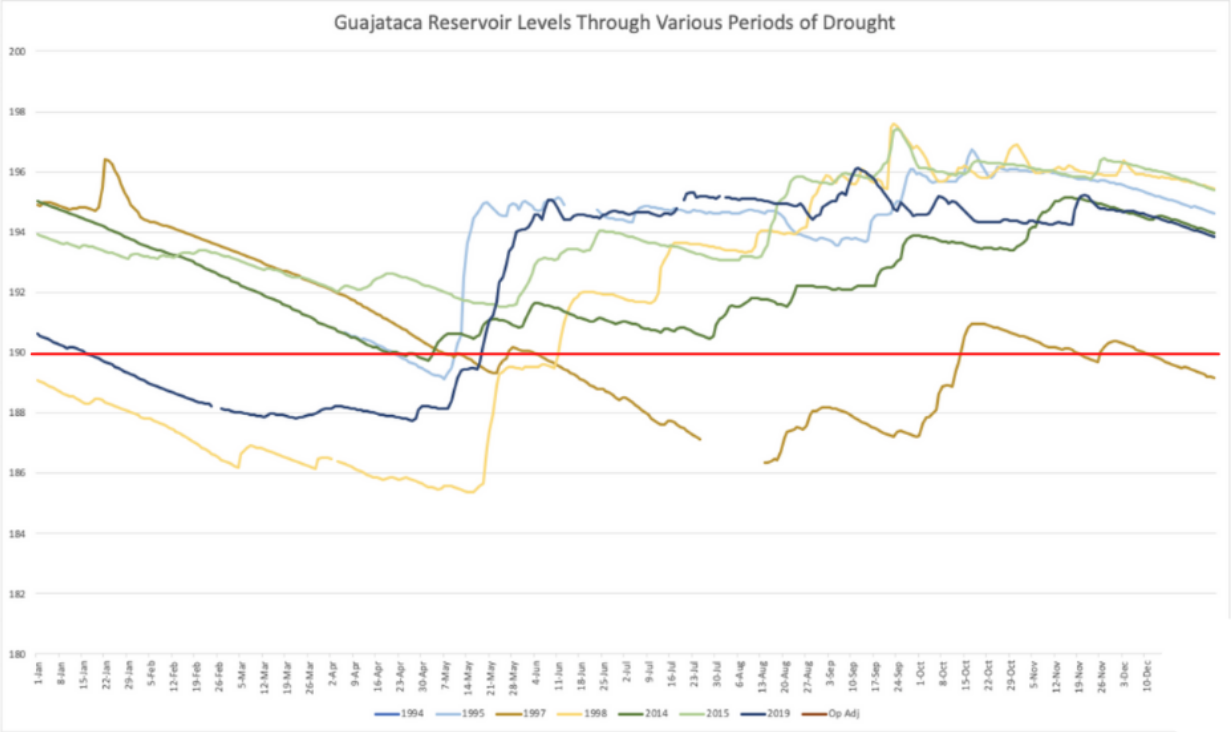


Fig 23. Guajataca reservoir levels for select drought years. Data: USGS. Red line indicates the operational adjustment level when rationing may be considered by management officials.

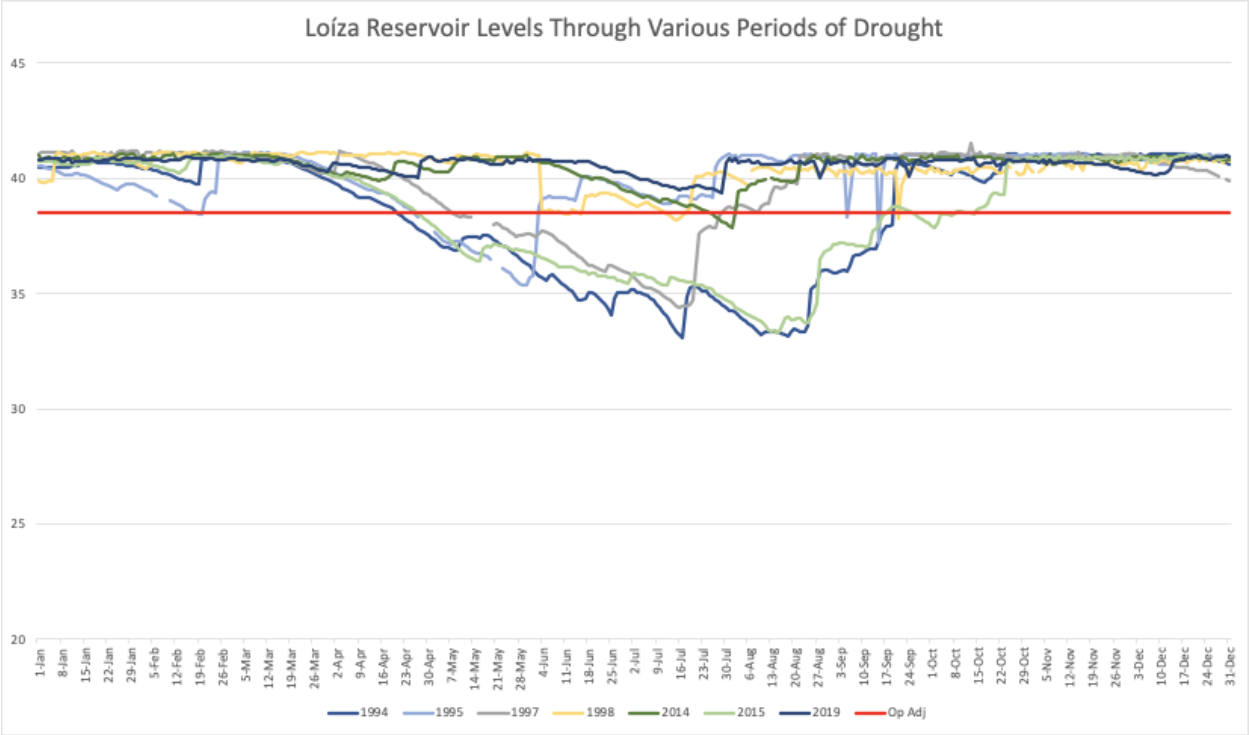


Fig 24. Loíza reservoir levels for select drought years. Data: USGS. Red line indicates the operational adjustment level when rationing may be considered by management officials.

Conclusion

The findings in this study indicate that Puerto Rico is not getting drier when it comes to annual rainfall or annual dry days. Daymet data indicate that average annual rainfall is increasing across the island. This trend in rainfall aligns with other recent analyses in the region that rainfall is increasing across the island (Van Beusekom et al. 2015, Méndez-Lázaro et al. 2014, Méndez Lázaro and Martínez 2012, Peterson et al. 2002). The average annual rainfall has increased overall since Larsen 2000's characterization of meteorological drought in 2000 using observational data from NOAA weather stations. When comparing the average annual rainfall from 1900 to 1999 from NOAA weather stations (Larsen 2000) to Daymet estimated data from 1980 to 2019, seven of the twelve stations had a higher annual rainfall average.

In Larsen's 2000 paper, the annual average rainfall from 1900 to 1999 of all locations was 1654 mm, ranging from 910 mm in Ponce to 2159 mm in Humacao. According to Daymet data, the average annual rainfall accumulation across all 12 locations from 1980 to 2019 was an average of 1719 mm, ranging from an average of 1086 mm in Ponce to 2249 mm in Humacao (Table 3). The Mann-Kendall test confirmed that the increasing trend in annual rainfall is statistically significant. The increased wetness of Puerto Rico is further evidenced by the decrease in total annual dry days. Since 1980, the average number of annual dry days island-wide has decreased by 44 days, indicating more frequent rainfall. These findings echo those of Méndez-Lázaro et al. 2014 that total annual dry days are decreasing.

However, my study did not examine the seasonal distribution of rainfall. Though annual rainfall is increasing, a shift in the seasonal distribution of rainfall could cause more frequent and intense droughts as less rainfall is received in months that were previously wetter. Nevertheless, meteorological droughts do not appear to be worsening. Though the recent meteorological drought of 2015 may not have been as severe as the 1990s drought, domestic access to water may have been compromised earlier than it may be have been previously necessary due to further deterioration of water infrastructure in the last 30

years. Since water lost by the public water utility company PRASA has increased between 10 and 20% since the 1990s drought and is now triple the average rate in the United States (PRASA 2015, Larsen 2000, EPA 2015), rainfall deficiency would become a problem sooner than if water losses were more modest. Furthermore, the accumulation of sediment in the island's in-stream reservoirs further limits the capacity to effectively capture and store water for use during periods of drought. Meanwhile, despite the decline in island population and decreased per capita water consumption, total water withdrawals have significantly increased since 1995, perhaps to compensate for water lost to damaged infrastructure. The lack of management plans for island reservoirs combined with the extremely high rate of water loss increases the likelihood of domestic water rationing. In the following final conclusion chapter, I review my results from chapters two and three, and discuss ideas for further research and policy needs.

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Chapter 4: Conclusion

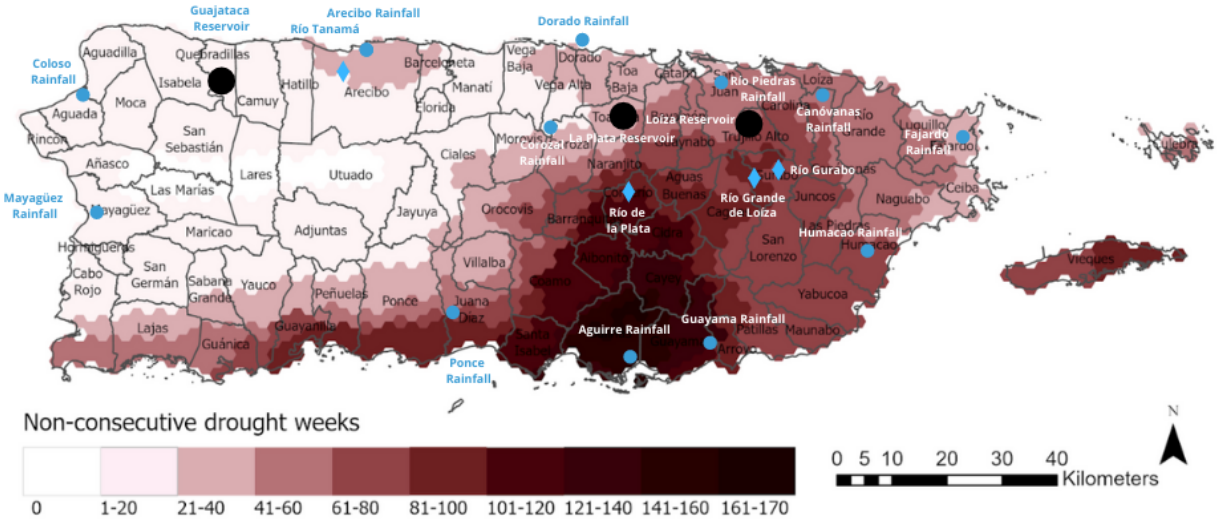

Figure 25: Non-consecutive drought weeks from 2000 to 2020 and the location of extracted pixels for Daymet rainfall data (blue circles), USGS streamflow gauging stations (blue diamonds) and USGS reservoir level gauging stations (black circles).

Introduction

My research aimed to determine where drought conditions in Puerto Rico occur most frequently, whether drought conditions are becoming more intense, and whether the local climate is exhibiting an overall drying trend. Based on my quantitative analyses of rainfall and drought using Daymet rainfall data, USGS streamflow and reservoir data, and US Drought Monitor drought data (Figure 25) , I conclude that 1) drought conditions occurred most frequently in the southeast region of Puerto Rico from 2000 to 2020, 2) meteorological drought has not become more intense from 1980 to 2019, and 3) the local climate is exhibiting an overall wetting trend with an increase in annual rainfall and a decrease in dry days. Based on the Daymet rainfall data alone, rainfall and dry day trends indicate that current trends appear to contradict downscaled climate projections for midcentury. However, the analysis of US Drought Monitor indicate a possible increasing trend in the duration, intensity and spatial extent of

droughts, aligning with climate projections for the region. My study offers a comprehensive update on meteorological drought in Puerto Rico and explores the accumulation of drought conditions since the establishment of the US Drought Monitor in 2000.

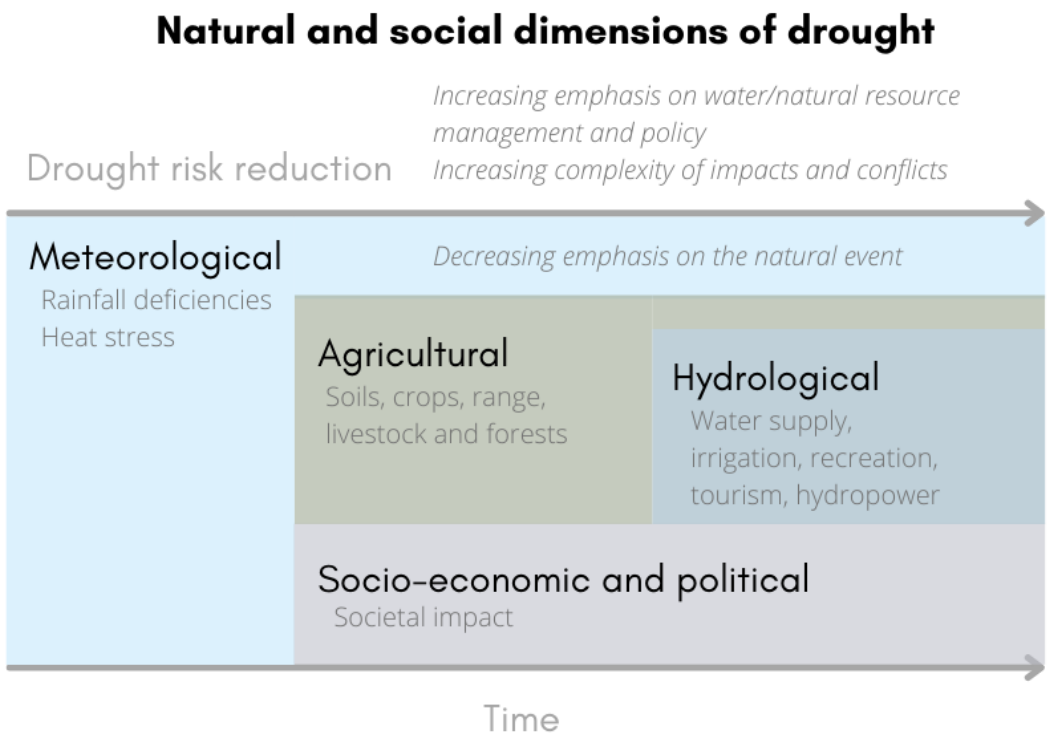

Figure 2: Sequence of the different types of drought and their impacts.

Meteorological drought

More specifically, the results of my study indicate that the recent meteorological droughts in the 21st century have not been more intense than Puerto Rico's most severe meteorological droughts in the nineties, seventies or sixties. Meanwhile, total annual dry days (TDD) show a statistically significant decreasing trend among the 12 locations across the island, having decreased by about one day per year since 1980 with a 44 day decrease in the last 40 years. The longest dry periods (MCDD) show a

shortening trend for eleven of the twelve locations. While the drought year of 2015 was the fourth driest year among 12 locations from 1900 to 2019 (after ‘67, ‘94 and ‘91), it was not among the years with the highest TDD or MCDD for the 12 locations combined from 1980 to 2019 (Figures 14 and 15). Furthermore, while rainfall is projected to decrease by midcentury, annual rainfall is currently increasing across the 12 locations around the island.

It is important to note that while my study concludes that annual rainfall is increasing despite seasonality, I did not examine trends in seasonal rainfall. Since I did not isolate seasons or months to determine whether rainfall is increasing or decreasing in smaller time scales, it is possible that rainfall is decreasing for some locations in certain seasons or months, though this dynamic was not detected in my study. According to my results that annual rainfall is increasing overall, any potential decrease in rainfall in one or more periods of the year is compensated by an increase in rainfall at other periods of the year. Although annual trends indicate an overall increasing in rainfall and decrease in dry days, seasonal rainfall patterns may be shifting so that historical wetter months are shifting to dry, and vice versa, as found by Méndez-Lázaro regarding the decrease of rainfall during summer months of June and August in the San Juan metro area.

Nevertheless, the US Caribbean is expected to experience a decline of more than 10% in annual rainfall by midcentury (Gould et al. 2018). In Puerto Rico, temperature, dry days and drought intensity are projected to increase in the future (Henareh et al. 2016, Gould et al. 2015), highlighting the importance of strategic management of water resources for domestic, industrial and agricultural purposes.

Agricultural drought

While my research did not examine agricultural drought, it is important to mention that about 95% of agriculture in Puerto Rico is rain-fed, making it particularly vulnerable to drought. Agricultural

production in the Caribbean is challenging due to the climatic challenges of drought, intense rainfall, and hurricanes; and climate change is posed to present new challenges, such as shifts in seasonal rainfall. As temperatures rise with climate change, agricultural water demand will likely grow with increased evapotranspiration and increased crop and livestock water demand (Harmsen 2019).

In the future when overall rainfall is projected to decline, it may be necessary to utilize groundwater to compensate for the reduction in rainfall. The regions that already rely on groundwater would likely need to use more, and some regions that currently use rainwater may need to shift to groundwater use (Harmsen 2019). A greater reliance on groundwater in the future could be problematic in coastal areas as increased groundwater extraction leads to increased salinization. At the present time, there is a moratorium on the construction of new groundwater wells in some areas of the southern coast due to dangerously low aquifer levels (Harmsen 2019). However, the projected increase in rainfall during the wet season would aide in regular groundwater recharge (Harmsen 2019). But increased rainfall in the wet season will lead to greater soil erosion, loss of soil fertility, and accelerated sedimentation of reservoirs (Harmsen et al. 2009).

The Puerto Rico Electric Power Authority (PREPA) is the agency responsible for the management of the irrigation districts in Puerto Rico. An estimated 63% of the PREPA water meant for irrigation districts is currently sold to AAA for non-agricultural purposes, limiting potential future growth for agricultural production (Harmsen 2019). Another challenge with water in this region is the lack of incentive for groundwater conservation in agricultural activities. While industrial and commercial entities are required to pay for groundwater, farmers and agroindustries are not. Large multinational seed companies (e.g. Monsanto) are also exempt from paying for groundwater, though they are limited by the Department of Natural and Environmental Resources in the amount of water extracted and they must submit annual reports on groundwater usage (Harmsen 2019). In a future with increased agricultural production and increased agricultural water demand, a greater portion of water used would need to

come from surface water and reservoirs due to the limitations on groundwater extraction. While increased production of local products would benefit the island's food security and economy, the rise agricultural water demand could pose new challenges for an already burdened water distribution system.

Hydrological drought

In terms of hydrological drought, I found that 2015 was not more intense than the severe droughts in the nineties. The rivers and reservoirs examined in my study showed a lesser response in 2015 when compared to the most severe droughts since 1980.

The drought in the early nineties (1993-1996) was the most intense hydrological drought for two rivers and two reservoirs in my study: Río de la Plata, Río Tanamá, La Plata Reservoir and Loíza Reservoir. The 1997 to 1998 drought was the most intense for the Guajataca Reservoir, and the 1967 drought was the worst for Rió Grande de Loíza. The 2015 drought was the most intense drought for Río Gurabo. In terms of the timing of the reservoir response to sustained changes in river levels, there was about a one month lag between river levels dropping and rising due to the onset and recovery of meteorological drought for the change to be apparent in the reservoir in the 2015 drought for the Loíza and La Plata Reservoirs.

While the meteorological drought of 2015 was less intense than the droughts in the nineties for most of the locations in my study, water rationing was still required for a large portion of the population in the San Juan metropolitan area. So, was water the rationing avoidable? Hydrologist Ferdinand Quiñones posed that the 2015 water rationing could have been largely avoided if it weren't for the roughly 50% loss of water by PRASA (Harmsen 2019). Along these lines, after the two severe droughts in the 1990s, Larsen stated that while the meteorological drought of '93 - '95 was not much more severe than those in '66 - '68, '71 -' 74 and '76 - '78, the need for mandatory water rationing was probably

influenced by factors such as water management and consumption. Larsen stated that significant increases in population, per capita water consumption, public water supply withdrawal coupled with further reduction in water losses and reservoir capacity made rationing much more likely under conditions that, in the past, might not have been required (Larsen 2000).

Today, while the island population and per capita consumption decreased significantly in the last 20 years, water withdrawals have significantly increased. In 2015, the population had decreased by about 1 million people since 1995. Per capita water consumption declined by about a third from 141 gal/pp/day in 1995 to 98 gal/pp/day in 2015. Meanwhile, combined surface and groundwater withdrawals has increased significantly from 431 MGD to 625 MGD. One possible explanation for increased withdrawals despite reduced population and per capita water use is the need to compensate for the high rate of water loss in the water distribution system.

Conclusion

In recent years, several droughts have resulted in agricultural losses, repercussions in ecosystems and interruptions in water availability for the population. In a scenario where annual rainfall is increasing, the ideal freshwater storage system would have the capacity to store excess water during intense rainfall events and wet seasons to store for dry periods and drought. Whether rainfall begins to decrease or continues increasing as climate change continues, it is important to plan for a future scenario where conditions are drier *and* more extreme. The majority of people and industry in Puerto Rico depend on surface water in reservoirs and rivers. Therefore, it is in the interest of the Puerto Rican government, land managers and landowners to prepare for a decline in annual rainfall anywhere from 312 to 916 mm and as a consequence, a decreased supply of freshwater resources. Considering the aging infrastructure that leaks over 50% of PRASA's managed water and the constantly declining capacity in the island's reservoirs due to sedimentation, an improved system for the maintenance of the island's

reservoirs and water distribution systems should be a high priority. Furthermore, considering that an increase in high intensity rainfall would cause high rates of soil erosion, resulting in an increased rate of sedimentation in reservoirs (Harmsen 2019), the regular dredging of the in-stream reservoirs must be prioritized.

While the analysis of annual rather than seasonal or monthly rainfall limits the specificity of the results, my approach provides new insight into current overall trends of the local climate by determining the locations most frequently affected by drought and the island's overall changes in rainfall. My research clearly illustrates that while rainfall is increasing rather than decreasing, water availability is still limited by lack of storage capacity, dilapidated infrastructure, and competing water uses. While meteorological drought is a part of a normal climate regime, climate change will likely shift the frequency and intensity of drought events. Although the results of my study indicate that current trends in rainfall and dry days contradict downscaled projections for the midcentury, it does not indicate that the climate projections are incorrect. Rainfall data is only one variable in the bigger picture of drought. Other contributing factors are very important, such as temperature and evapotranspiration. My analysis of US Drought Monitor data, which includes data additional data aside from rainfall, provides a more complete view of drought trends in Puerto Rico. The increasing trend in drought duration, severity and spatial extent are aligned with downscaled climate projections for the region. Based on these conclusions, practitioners should consider prioritizing improved maintenance of freshwater storage and distribution systems to maximize storage capacity and minimize losses.

Future studies could analyze seasonal and monthly rainfall around the island to first see whether rainfall is changing at smaller time scales than were evaluated in my research. Adding the variables of temperature, soil moisture and evapotranspiration into the analysis would be especially valuable to obtain a more complete view of drought conditions. Furthermore, it would be helpful to analyze Puerto Rico's water storage and distribution systems for domestic and agricultural use under varying future

scenarios of climate change. One idea is to create a model to explore future domestic, agricultural and industrial water availability in key regions based on different climate projections for rainfall, temperature, evapotranspiration, and the rates of reservoir sedimentation and water distribution losses. By analyzing the water storage, and distribution, sedimentation and loss rates under different climate change scenarios, we could evaluate potential scenarios for future water availability on the island, and potentially identify locations where water availability will be limited by future demands, such as increased agricultural production.

In terms of policy recommendations, the citizens of the neighboring US Virgin Islands are required by law to supply their own domestic water with rainwater catchment and cistern storage (Gould et al. 2018). In Puerto Rico, the Technical Scientific Drought Committee recommended that citizens collect rainwater, and that rainwater catchment systems are made mandatory for new housing (Gould et al. 2018). Such a reduced reliance on the public water company would be beneficial, though not a solution for all since the cost of the materials and installation may be prohibitive to some.

In the context of food insecurity, economic challenges, and aging water storage and distribution infrastructure, it is important to regularly evaluate trends in rainfall and drought; as well as the status of freshwater resources. Evaluating historical data helps us to understand how conditions are changing, and provides insight into where measures can be taken to reduce risk. My research suggests that despite an increase in annual rainfall, drought conditions may already be increasingly longer, more intense and more spatially extensive due to warmer temperatures and other changes in the climate. In a future where drought risk, drought intensity and climate extremes are expected to increase, we can only benefit from a deeper understanding of where drought conditions accumulate, how trends are changing, and what alternatives exist to improve resilience to climate variability and change.

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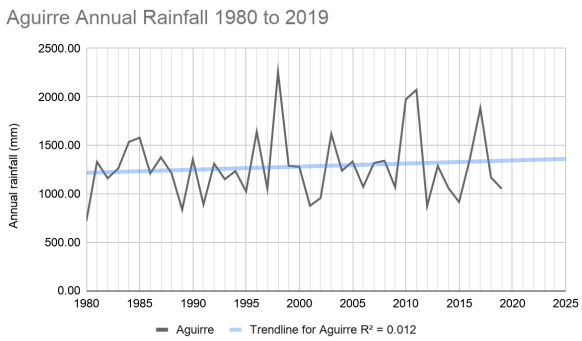
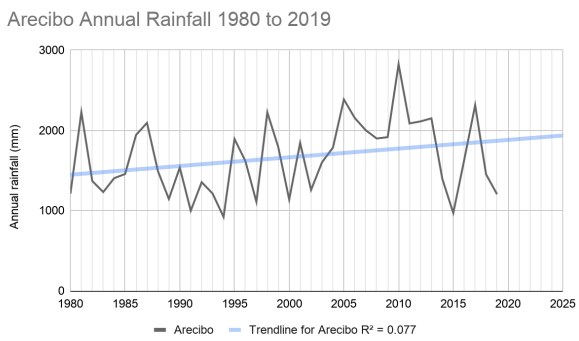
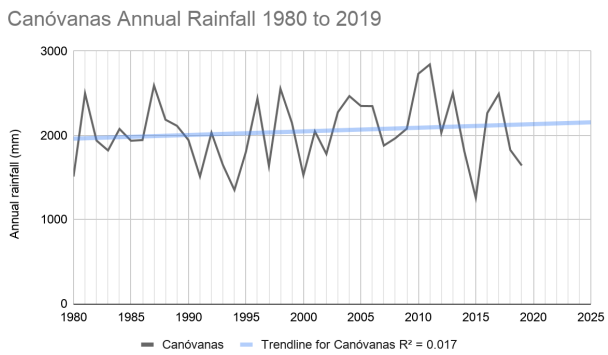
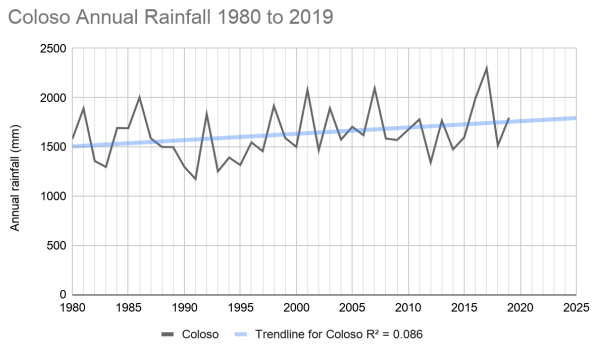
Appendices

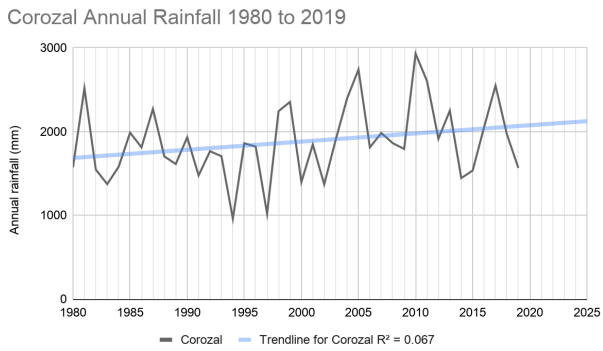
Appendices I - XII: Annual rainfall 1980 - 2019 at 12 locations according to Daymet data.

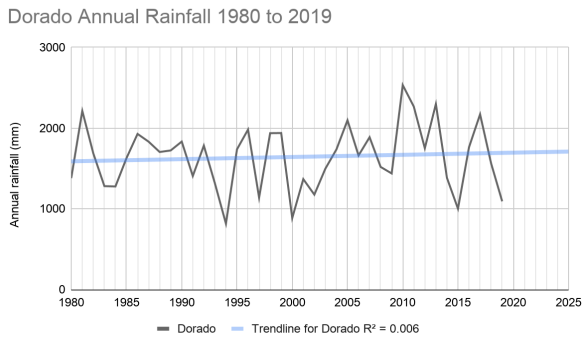


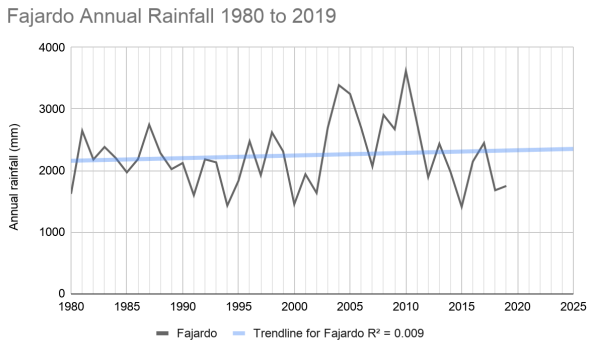


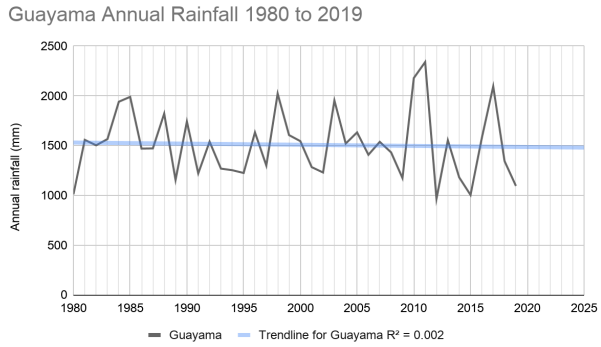


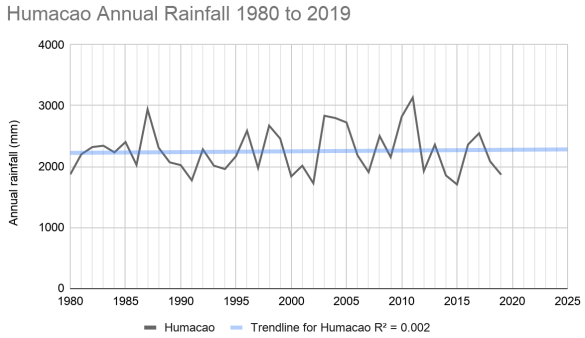


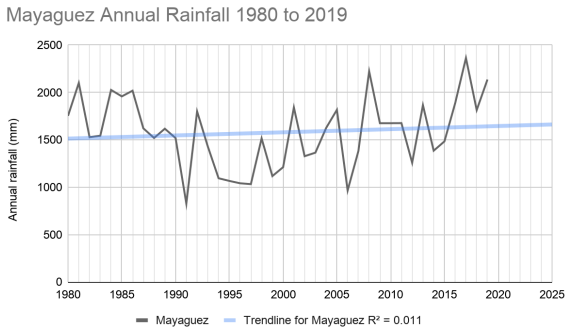


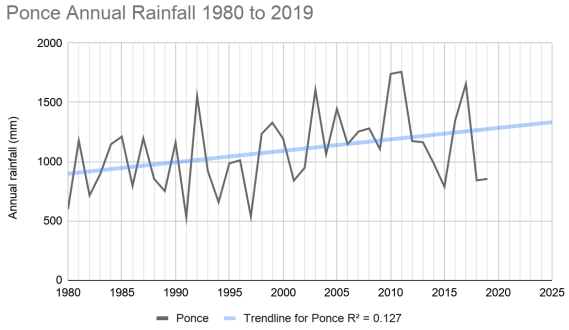


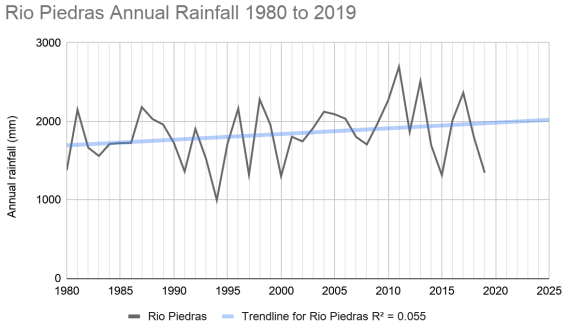

Fajardo Annual Rainfall 1980 to 2019
Annual rainfall (mm)
Fajardo
Trendline for Fajardo R² = 0.009


Guayama Annual Rainfall 1980 to 2019
Annual rainfall (mm)
Guayama
Trendline for Guayama R² = 0.002

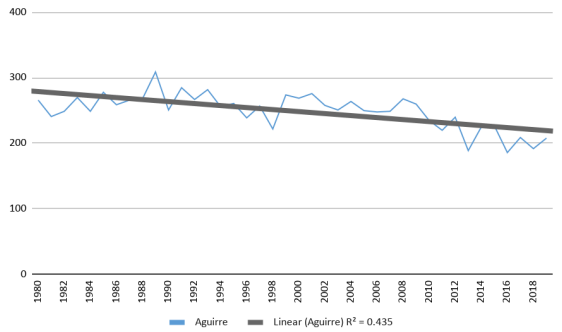

Humacao Annual Rainfall 1980 to 2019
Annual rainfall (mm)
Humacao
Trendline for Humacao R² = 0.002

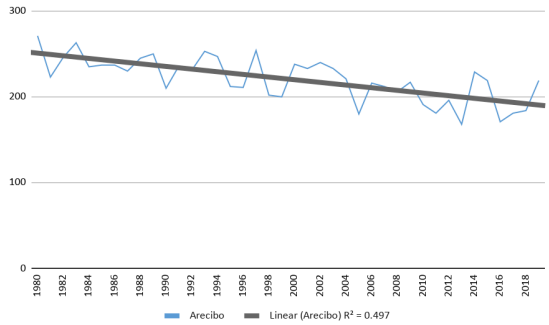

Mayaguez Annual Rainfall 1980 to 2019
Annual rainfall (mm)
Mayaguez
Trendline for Mayaguez R² = 0.011

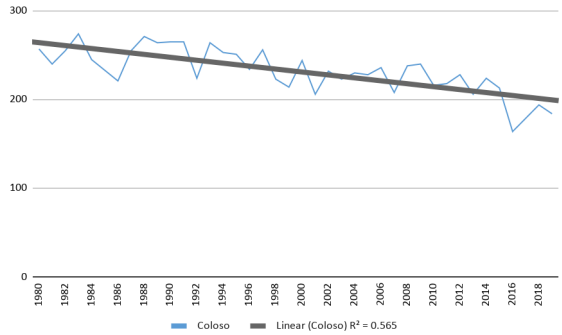

Ponce Annual Rainfall 1980 to 2019
Annual rainfall (mm)
Ponce
Trendline for Ponce R² = 0.127

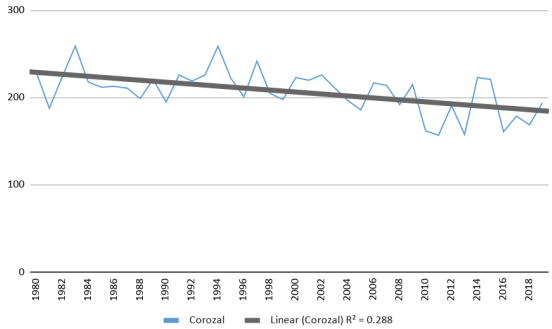

Rio Piedras Annual Rainfall 1980 to 2019
Annual rainfall (mm)
Rio Piedras
Trendline for Rio Piedras R² = 0.055

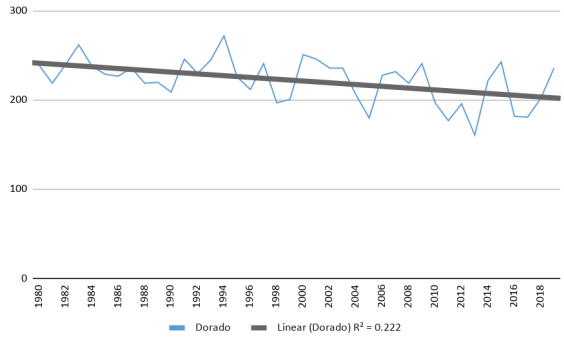
Appendices XIII - XIV: Total Annual Dry Days at 12 locations 1980 - 2019

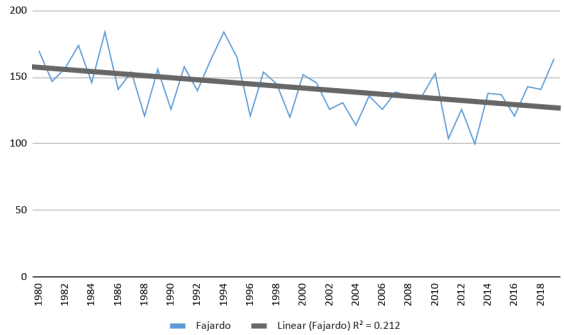


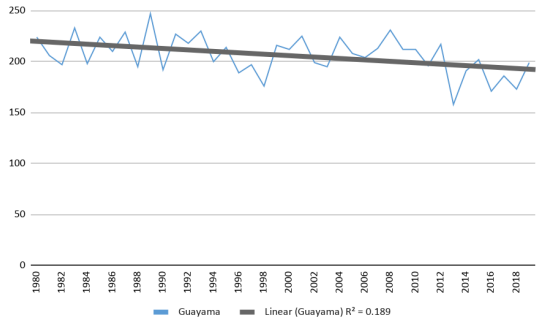


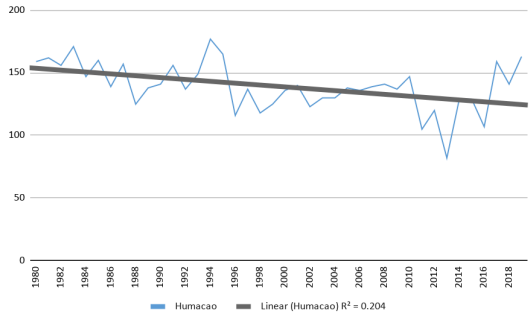


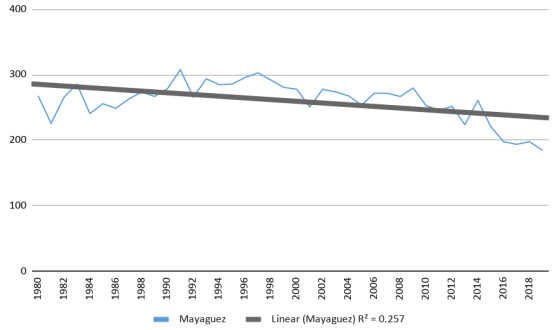


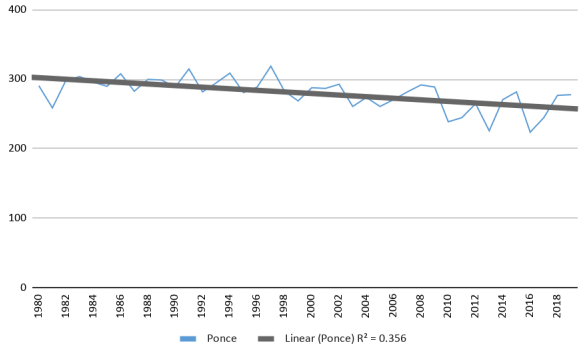


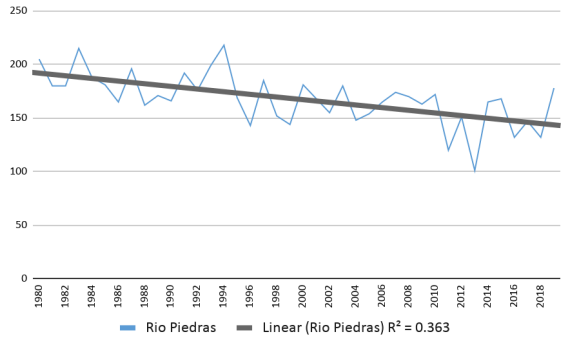




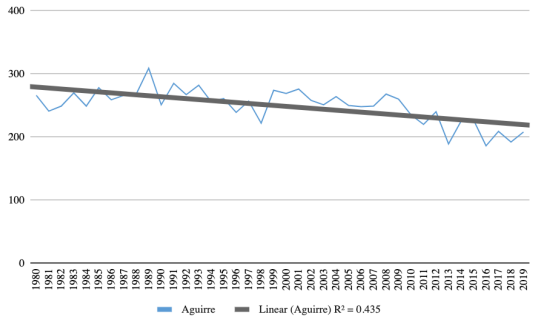


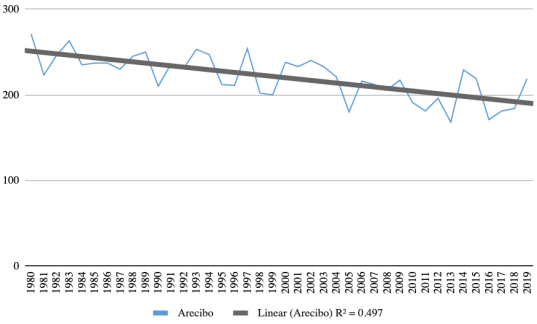


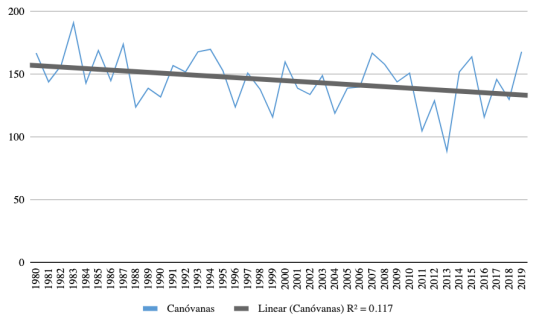


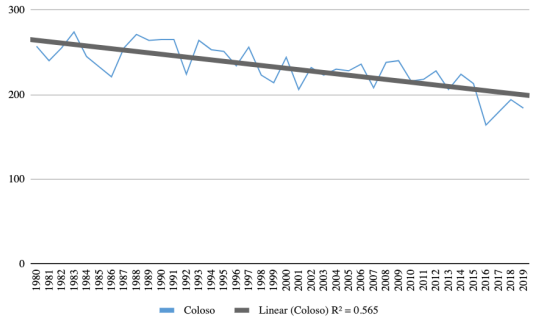


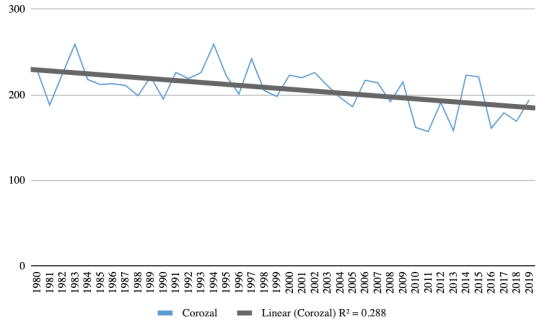
Appendices XIII - XXXIV: Maximum Consecutive Annual Dry Days at 12 locations 1980 - 2019

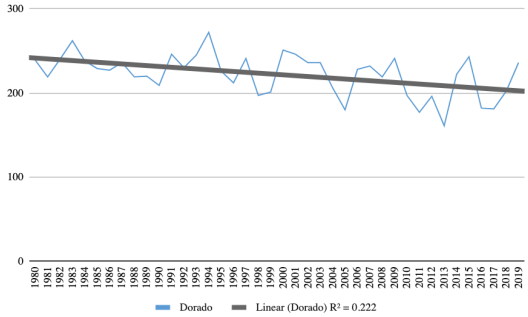


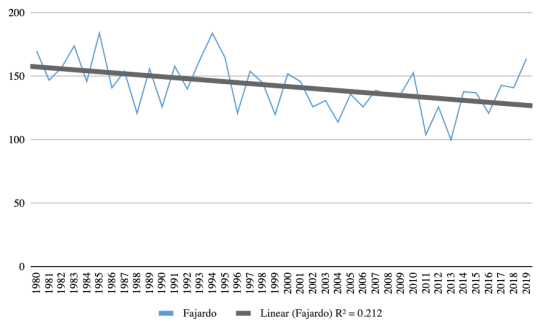


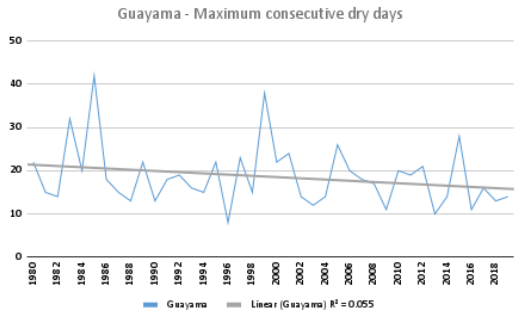

Canóvanas
Linear (Canóvanas) R² = 0.117

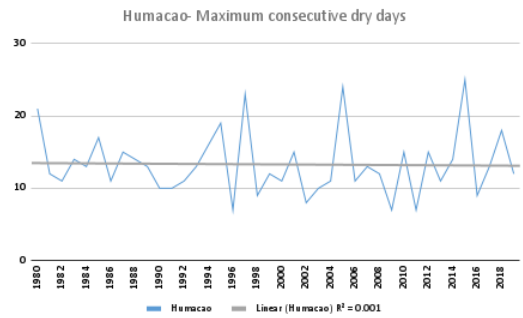

Coloso
Linear (Coloso) R² = 0.565

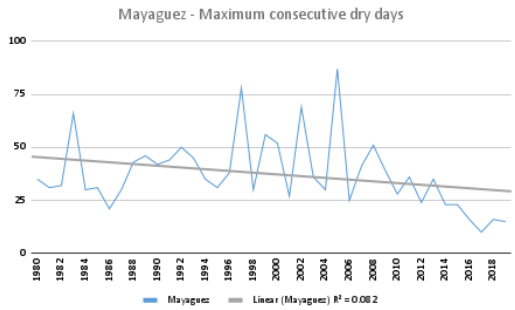

Corozal
Linear (Corozal) R² = 0.288

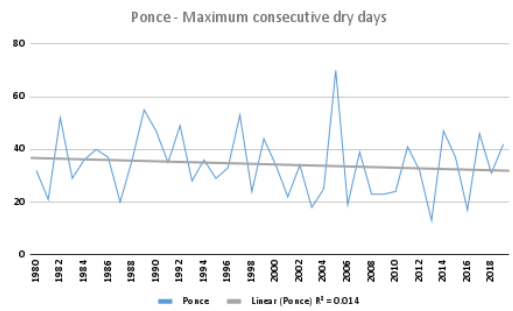

Dorado
Linear (Dorado) R² = 0.222

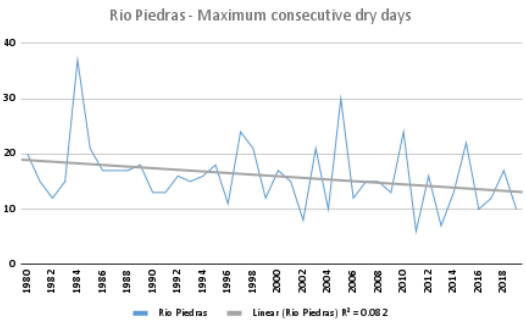






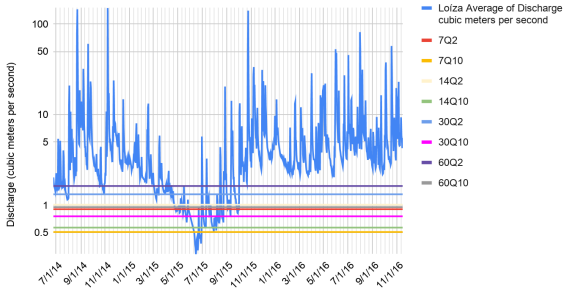




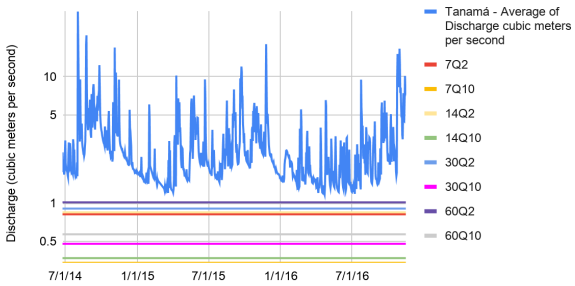


Appendices XXXVI - XXXVIII: Discharge in cubic meters from June 24, 2014 to November 15, 2016 and line indicating low-flows values (lowest average flow) for Río Grande, Río Tanamá and Río Gurabo based on Santiago-Rivera 1992 and 1998. The first number in the low-flow value indicates the number of consecutive days, while the second number indicates the number of years in which the low-flow is reached. For example, the red line (7Q2) indicates the lowest average flow in 7 consecutive days that occurs once every 2 years. 7Q10 indicates the lowest average flow in 7 consecutive days once every 10 years.

Río Grande de Loíza: Discharge and lowest average flow for indicated days and years



Río Tanamá: Discharge and lowest average flow for indicated days and years



Río Gurabo: Discharge and lowest average flow for indicated days and years