La Plata Nature Refuge

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Assessing Land Change

An Interactive Qualifying Project
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ABSTRACT

The La Plata Nature Refuge is a recreational area in Toa Alta, Puerto Rico, that includes a large reservoir and river. Over the last 5 years, this area and the greater La Plata watershed has been severely impacted by extreme weather events, caused by ongoing climate change. The organization that oversees this reservoir and refuge, the Department of Natural and Environmental Resources (DNER), has not been able to maintain accurate records of landscape change that allow for effective planning and mitigation efforts towards weather events and disasters. The goal of this project is to assess landscape changes of the La Plata Refuge and greater watershed area to provide data to inform future management plans for the DNER. To accomplish this goal, we assembled an event timeline for natural disasters in Puerto Rico from the years of 2003 to 2020 and combined this with satellite imagery of the area from Google Earth. This method created a comprehensive system to document and outline changes observed in the area over time, revealing that droughts and flooding leading to erosion and sedimentation were the greatest concern to the landscape and water levels. It was also apparent that extreme and intense events became significantly more prevalent in Puerto Rico over the past 5 years and may continue to do so. Deliverables for this project include a Google Earth file marking landscape changes throughout the watershed area, a user guide for Google Earth, an interactive Prezi timeline of natural disasters from 2003-2020, and a prototype ArcGIS file for future project development.

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INTRODUCTION

Although physical landscapes throughout the world seem permanent, they are undergoing a constant natural process of change and reformation. Climate change brought on by human activity has accelerated that process, contributing to droughts, flooding, and increased storm severity, reshaping the land. These changes impact wildlife, agriculture, ecosystems, energy, and water sources often in negative ways.

The area our team studied for this project is no exception to these changes. Our team studied changes in the La Plata Watershed in Figure 1 (outlined in red). The watershed includes La Plata Nature Refuge (El Refugio de Vida Silvestre Embalse la Plata), a park and refuge in Toa Alta, Puerto Rico, located south of San Juan. The refuge serves as a recreational and community space for residents. It also contains a reservoir that serves as a source of drinking water for communities in the Toa Alta and San Juan region. La Plata is susceptible to constant land change arising from an influx of stronger hurricanes, earthquakes, and droughts.

Figure 1. La Plata Location.
(Adapted from Cai, 2007)

The goal of this project is to assess landscape changes of the La Plata Refuge and greater watershed area to provide data to inform future management plans for the DNER.

The project objectives are:

1) Understand how natural disasters and climate change impact land change and resource management.

2) Create a timeline of natural disasters that have impacted Puerto Rico from 2003-2020.

3) Compare disaster timeline events and satellite images to identify observable impacts on La Plata river and reservoir.

4) Document human impact on landscape features within La Plata watershed.

These objectives helped us achieve our goal of offering recommendations to the El Departamento de Recursos Naturales y Ambientales or the Department of Natural and Environmental Resources (DNER) on how to assess and document land change specific to La Plata. A great number of studies outline various effects of natural disasters both broad and specific to Puerto Rico. At the time of this project, none offered documented information regarding the state of La Plata and how the refuge and reservoir have been specifically impacted by climate change events and human developments. We created a research-based plan to introduce a system of tracking land change at La Plata, and we provided suggested next steps the DNER might take to help maintain the land and reservoir.

We found that focusing on specific severe weather events from 2003-2020 in Puerto Rico helped us pinpoint patterns of land change. The most essential and effective tools for assessing these changes are the use of satellite images which can locate specific areas of change and offer comparisons between time periods. With these tools, we investigated indicators and secondary effects brought about by climate change and natural disasters. From satellite images, we observed changes in water level, erosion, and sedimentation in the river. Human development was tracked with broad observation of the watershed from 2003-2020.

Background

The surface and atmosphere of the Earth is constantly changing due to a multitude of factors caused naturally, by ongoing forces, and indirectly, due to cumulative and ongoing human interference. Natural forces from tectonic plates create earthquakes, often resulting in land change. Depending on the size of the earthquake this land change may or may not be noticeable. Human activity from production of fossil fuels and urbanization has resulted in global effects on the biotic community, causing pollution and ecological destruction. Unchecked human activity has resulted in rapid climate change, causing severe weather events such as droughts, heat waves, dangerous tropical storms, and heavy precipitation. These events can impact vegetation and increase erosion around waterways. A broad summary of effects can be seen in Figure 2.

In recent years land change and climate change events have threatened to disrupt the waterways and reservoirs in Puerto Rico, jeopardizing a source of drinking water and ecosystems. In this project, we looked at these threats to the La Plata reservoir and the river feeding into it.

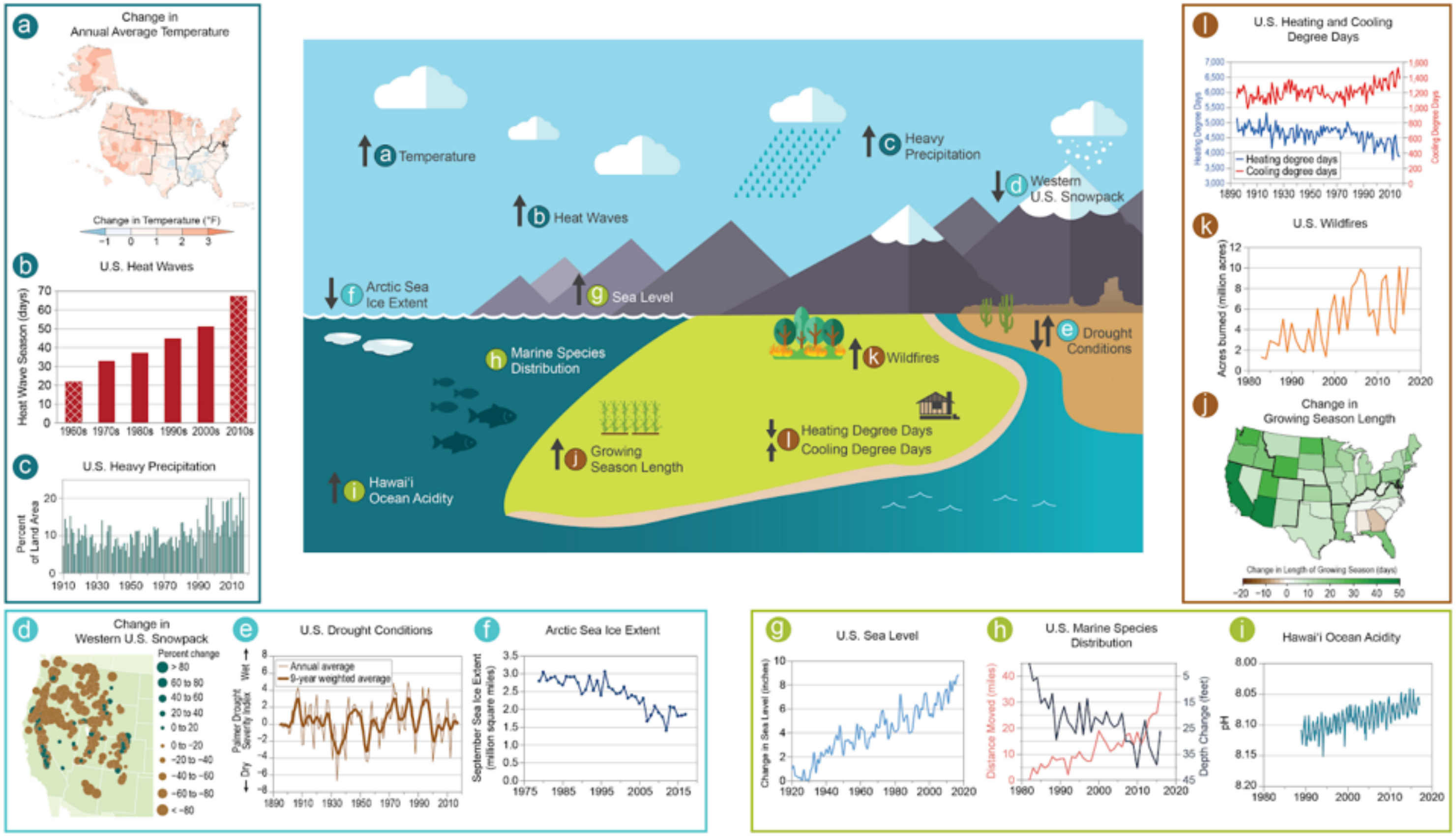


Figure 2. Climate Change Effects.

The various effects of climate change are graphed along the edges of the figure. The letter label on each graph corresponds with the impact shown in the center image (Adapted from Usgcrp, 2017).

La Plata Nature Refuge

La Plata Nature Refuge, located in the Toa Alta region is an important resource for the people of Puerto Rico. The refuge contains a reservoir that serves as a source of drinking water and a place of recreation for the surrounding communities. The area supports ecosystems including local flora and fauna. Destruction or loss of this area would be a significant loss for the people of Puerto Rico. Figure 3 shows our specific area of study within the La Plata watershed.

Within La Plata Nature Refuge is La Plata Reservoir and dam, built in 1973 as a source of drinking water for the surrounding municipalities. The reservoir supplies 36% of the population, or eight hundred thousand people, of San Juan with clean drinking water (López, 1998). The Department of Natural and Environmental Resources (DNER) manages the land of La Plata. The DNER is a branch of the Puerto Rican government founded in 1972 to manage environmental resources and ecosystems. They create conservation and protection programs designed to ensure the environment's longevity for use by future generations (Ortiz, 2019). Along with maintaining La Plata Nature Refuge, they provide education programs for the public on topics like aquatic resources, climate change, and natural resources (Imflores, 2021). In preserving the land at La Plata, it is important to understand the causes and effects of land change specific to the region. Figure 4 shows the specific region of La Plata that the DNER has control over. This region is the main focus of our study area within the watershed.

Figure 3. La Plata Watershed.
This image displays the La Plata watershed outlined with the dotted black line. The red box outlines the main focus of the study, La Plata Reservoir and River. (Adapted from Gómez-Fragoso, 2016)

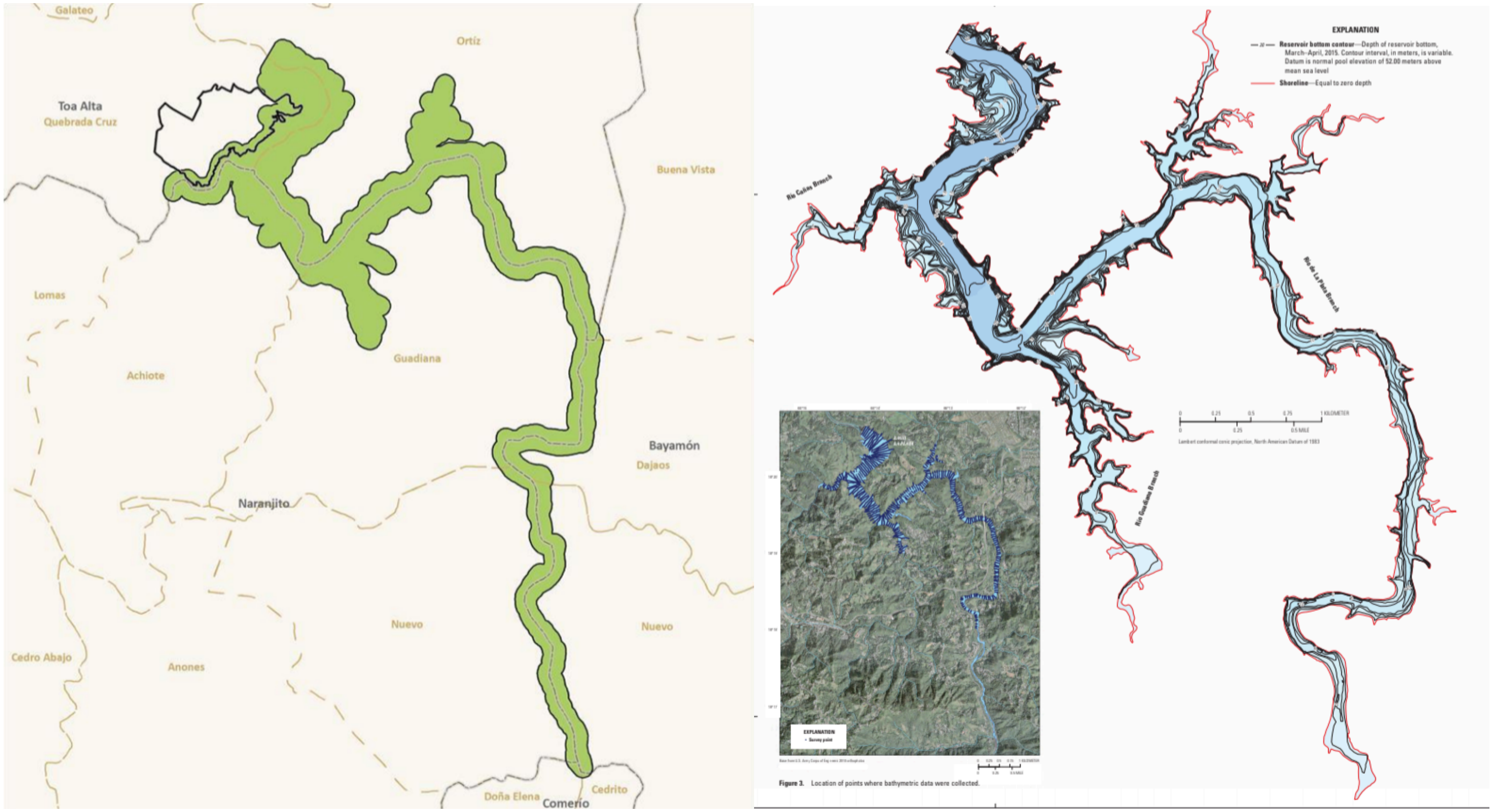


Figure 4. La Plata.

This area is outlined in red in Figure 3. In this figure, the area outlined in green (left) shows the general land area around the river. Outlined in black is the Refuge area next to the reservoir. The image (right) shows the specifics of the streams feeding into the La Plata River. (Adapted from Department of Natural and Environmental Resources & Estudios Técnicos Inc., 2013, 13 (left) and Gómez-Fragoso, 2016 (right))

Climate Change as a Threat to Land Change

Causes of climate change can be attributed to multiple factors that compound on each other to create drastic differences in weather patterns and ecosystem behaviors over time. The consequences of humanity's actions through anthropocentric beliefs are creating a world under destruction. Temperatures are rising, pollution is increasing, and storms are surging.

Human Influence on the Climate and Land

Climate change has been an issue that has slowly developed over years of natural environmental change and human impact on environmental ecosystems. As humanity chooses to modernize, more consumerism and production have caused an increase in CO_2 emissions. Many profit-motivated industries have not been driven by environmental concerns and their destructive actions have gone unchecked. As a result, CO_2 emissions are up to 395 parts per million in the atmosphere and rising (Jacobs et al., n.d.). Such pollution continues to feed the problem of greenhouse gases. As seen in Figure 5, CO_2 is the most prevalent gas being pumped into the atmosphere. More energy is pushed into the atmosphere with the rise in carbon emissions (Jacobs et al., n.d.). These changes have serious compounding effects on small communities that lack proper infrastructure or health and safety measures.

Political groups, institutions, and societal values all play a role in altering our natural landscape (Turner et al., 1993). Land is critical to the economy, as it is necessary for housing and food production (Wu, J., 2008). Political entities create policies that will ultimately influence how land is used and protected, shaping a community's proximity to and physical relationship with land, especially in terms of urban development, suburbanization, and agricultural use (Turner et al., 1993). Human activity such as urbanization, transportation, residential and business-related energy consumption have altered the climate and land at a higher rate than any other time in history, causing irreversible change in the land and climate (Bürgi et al., 2005; Turner et al., 1993).

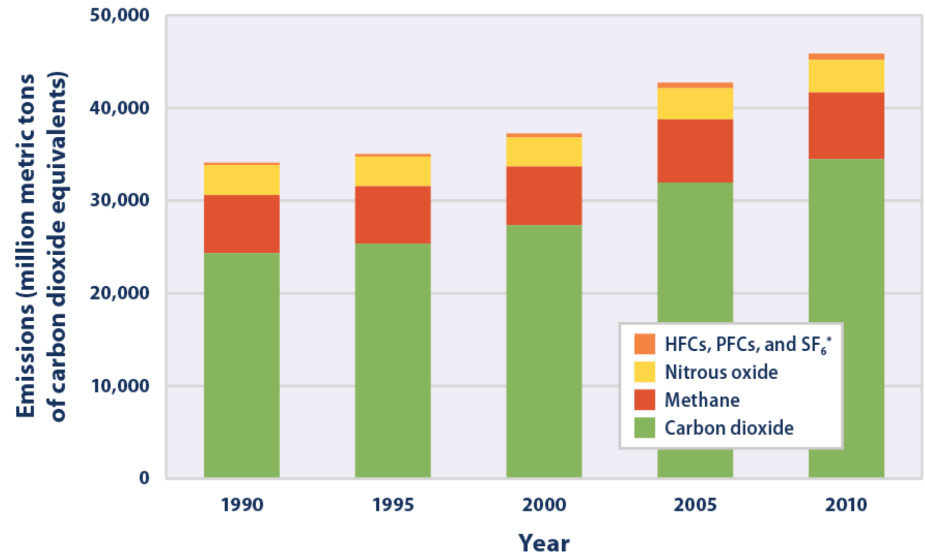


Figure 5. Global Greenhouse Gas emissions 1990-2010.
In the key, HFCs represent hydrofluorocarbons, PFCs are perfluorocarbons, and SF_6 is sulfur hexafluoride. Emissions are displayed in million metric tons. (Adapted from the United States Environmental Protection Agency, 2021)

How Climate Change Affects Land Change

Land change is a natural occurrence. The earth's topography, climate, soil characteristics, and weather are always evolving (Bürgi et al., 2005). Natural disturbances in land can be categorized as slow or fast-acting. Global climate change is categorized as slow-acting change, taking time to have visible impacts. Meanwhile fast-acting disturbances are viewed generally as small or large disasters such as avalanches, hurricanes, earthquakes, and mudslides. Such disasters can completely alter landscapes in an extremely short timeframe. With temperature increases, events such as heatwaves and droughts will likely become more frequent in all areas of the globe. Figure 6 shows the increase in temperature over the last century with a very strong increase in the late 20th century to present day.

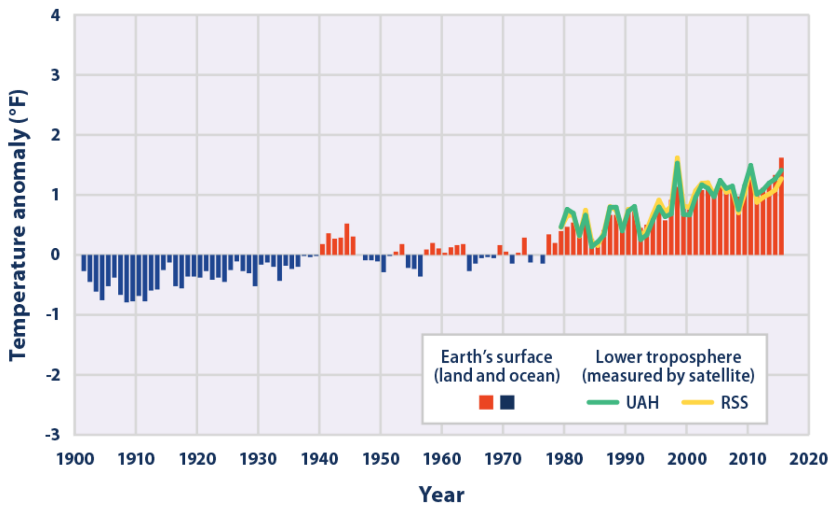


Figure 6. Global Temperatures 1901-2015.
(Adapted from the United States Environmental Protection Agency, 2021)

Effects of Climate Change on Puerto Rico's Land

As the global climate continues to change, Puerto Rico is affected uniquely due to its location and island topography. Puerto Rico is located among the tropical Caribbean islands and has varying elevations from sea levels to mountains (Mogil et al, 2020). This creates a particular set of risks relating to climate change's effects on the island. Compared to surrounding islands, Puerto Rico is seeing much larger increases in air temperature with a likely trend that San Juan will have an average temperature of 27°C by 2050 from 25.5°C in 1950, showing an increase of 0.022°C each year (Jacobs et al., n.d.).

Related to temperature rise, a driver of land change along the coast is sea level rise. Sea level rise will tax the coast of Puerto Rico with increased erosion and damage to coastal infrastructure. There will also be a loss of vegetation along the coast in marshes and dryland as they are submerged by water (United States Environmental Protection Agency, 2016). An increase in water levels would also strengthen the effects of flooding when it occurs because more water is surrounding the island. Figure 7 displays the increase in inches of sea level along the coasts of the United States and territory of Puerto Rico. With continued warming of the planet, the sea is likely to continue to rise around the globe. It is projected that the rise seen on the shore of Puerto Rico could reach a maximum of 0.914 m in the next century (United States Environmental Protection Agency, 2016).

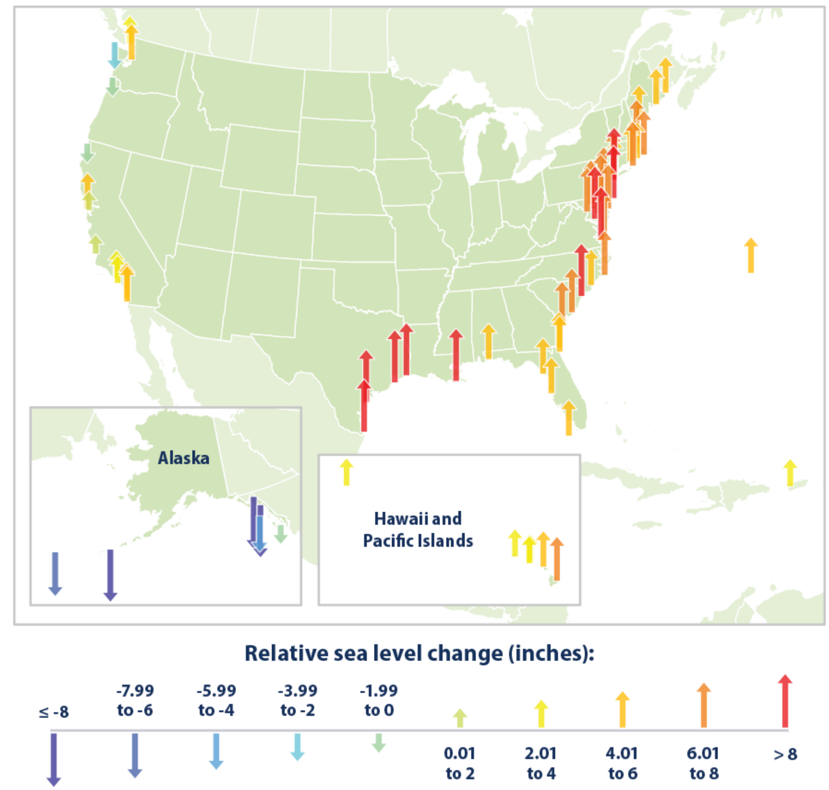


Figure 7. Relative Sea Level Change on US Coasts 1960-2015.
Each arrow in the figure represents the amount of sea level rise in an area. Puerto Rico has an arrow representative of 2.01-4 inches of sea level rise in the time frame 1960-2015 which follows similar trends to the rest of the eastern coast of the United States. (Adapted from the United States Environmental Protection Agency, 2021)

Climate change has caused a concerning change to weather patterns. Changes are seen as the increase in intensity of extreme weather events. Increases in atmospheric temperatures are contributing to increases in sea surface temperature in Puerto Rico which has warmed by 0.008°C per year (1900-2010) (Jacobs et al., n.d.). Hurricanes in Puerto Rico are becoming stronger as the water temperature of the ocean rises. This allows storms to pick up more energy from the ocean, putting more moisture in the air, leading to heavier rainfall (Jacobs et al., n.d.; Elsner et al, 2008). Figure 8 shows cyclone activity in the North Atlantic in respect to the power dissipation index (PDI). The PDI considers the frequency, strength, and duration of hurricanes and tropical storms. The increase in PDI represents more frequent and stronger storms alongside an increasing trend in sea surface temperature. Hurricanes that bring heavy rainfall and winds can cause flooding, erosion and landslides posing a threat to the island's infrastructure and watersheds (Jacobs et al., n.d.; The Economist., 2017; Van Beusekom et al., 2018).

Rising temperatures and changing weather patterns are increasing the extremes of weather globally and in Puerto Rico, by creating longer dry periods and more intense precipitation (IPCC, 2020). Puerto Rico's precipitation trends are variable. There has been an increase in dry days that lack rainfall. However, the island is also seeing a 37% increase in heavy downpours and more days with extreme temperatures (Jacobs et al., n.d.). The dry seasons affect Puerto Rico each year with some years including long periods of droughts. Long dry periods put the people and land at risk by decreasing water levels in reservoirs and riverways and drying up the soil. Figure 9 shows the maximum areas of drought as registered by the U.S. Drought Monitor between 2000 and 2016.

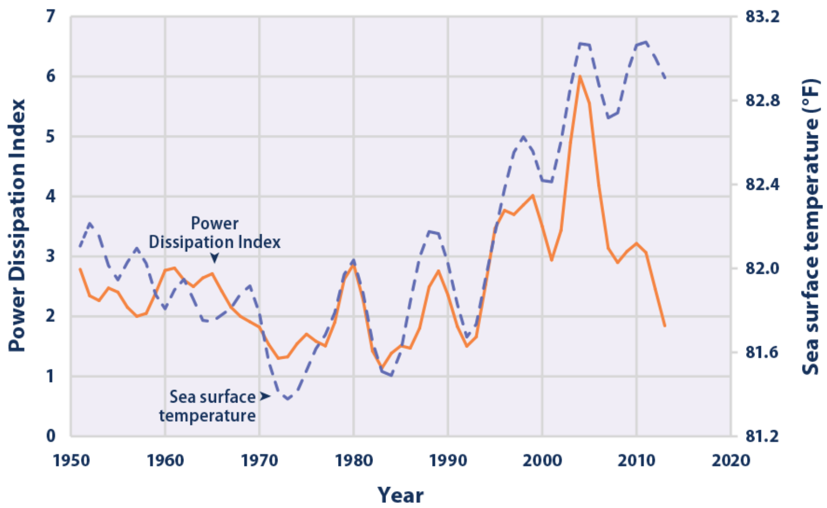


Figure 8. North Atlantic Cyclone Activity 1949-2015.
(Adapted from the United States Environmental Protection Agency, 2021)

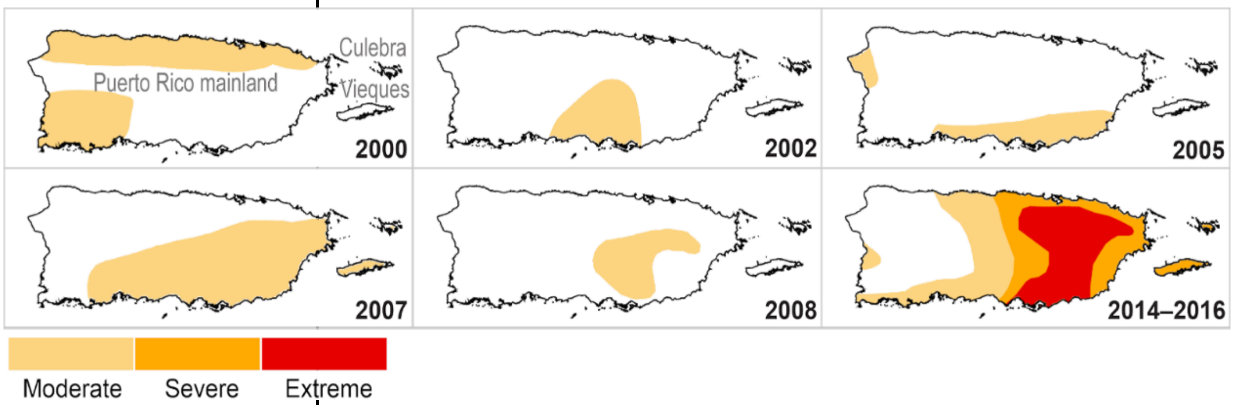


Figure 9: Registered droughts in Puerto Rico between 2000 and 2016. Between 2000 and 2016 there were six drought events registered. The most severe event was from 2014 to 2016. The most severe conditions in the drought were on the eastern side of the island, as seen in the figure. In comparison, the previous droughts, from 2000 to 2014, were documented as moderate and short lived. (Adapted from Álvarez-Berríos & Holupchinski, 2017)

Outside of climate change the driving forces of land change within Puerto Rico are related to a combination of urbanization of the island and natural factors. Urbanization leads to land change because ill-planned infrastructure can weaken the soil, leading to faster erosion. Urbanization can also push back natural vegetation out of an area and take away land that has the potential to be used for agriculture (Martinuzzi et al., 2007). Removing vegetation from the area can increase pollution in soil, water, and air due to less filtration through plants.

An additional driver of land change in Puerto Rico is earthquakes. They have less direct effects in a specific land area but the most recent earthquakes in January 2020 caused the island to shift 5.6 cm northwest (Damiani, 2020). River pathways or soil types were not directly affected but could be in the future. In soft soils earthquakes can cause liquefaction, when the soil loses all structure and behaves like water. This can lead to soils moving across great distances and changing the soil type in an area. Earthquakes can also cause landslides, moving rocks or softer soils to a new area (USGS, n.d.). These landslides have the potential to affect rivers if the waterway becomes blocked by soil, requiring the river to reroute around the land. It is evident that the consequences of climate change are growing each year in Puerto Rico, posing future concerns for the island and its people.

Impacts on La Plata Reservoir and River

The changes in weather and climate within Puerto Rico have had varying effects across the island. La Plata is most susceptible to droughts and extreme weather events, as both affect the watershed and reservoir.

Droughts in Puerto Rico are shown to be related to the North Atlantic Oscillations (NAO) of air pressure. Dry periods occur when NAO values are high, and inversely, wet periods occur when NAO values are low (Larsen, M. C., 2013). Contrary to droughts in large continents, droughts on small islands like Puerto Rico can vary in severity across distances of a few 10's of kilometers (Morris and Vázquez, 1990). The longest drought that Puerto Rico has experienced, since the start of 2000, lasted 80 weeks, from May 6, 2015 to November 8, 2016 (National Integrated Drought Information System, 2021). This drought caused the water levels in La Plata Reservoir to drop about 15 meters at the lowest point, reducing the water level by 30% (USGS, 2021). On the scale that measures how severe droughts are (C1-C4), droughts in Puerto Rico never reach the highest severity. When droughts occur in Puerto Rico they last for a long time at a lower severity (C1 or C2). These droughts still pose a threat to drinking water availability. Droughts can cause the level of the reservoir to drop dangerously low. When reservoir levels drop too low the citizens are required to ration their water, and in extreme cases can go days without access to tap water.

Flooding is also a serious threat in Puerto Rico when hurricanes occur. They bring heavy rainfall and strong winds. From Hurricane Maria in September of 2017, La Plata river rose 3.048 m (Viner, 2018). This caused severe flooding in the towns surrounding the river and destroyed many homes. Flooding is a problem for rivers because it can change the course of the river if sustained. As the river levels return to normal, erosion or obstructed pathways may change the river's original course, creating a more direct path for the river to take. Changing the course of the La Plata River and diverting it away from the reservoir could reduce the community's access to potable water. Landslides are another hazard created from heavy rainfall, such as that from a strong hurricane or tropical storm. Large landslides along the banks of a river could offset the river course or create blockages that form a lake (Othman, 2013).

Similar to landslides, erosion of riverbanks can redirect river flow. Land use that reduces the amount of vegetation in an area makes it susceptible to erosion (López et al., 1998). Heavy rainfall also can lead to faster erosion due to increased water levels. Drought is another proponent of erosion, as dryer soils lead to less stable vegetation along the riverbanks. Another big factor in erosion is slope of the riverbanks. Generally, the steeper and smoother the slope the faster it will erode (Huron River Watershed Council, n.d.). Erosion is a negative influence on riverways because it can increase the width of the river, change its course, or decrease flow as a result of sedimentation.

Sedimentation is the removal (scouring) or deposition of soil from one location to another (Li et al., 2020). It is a compounding result of drought, flooding, landslides, and erosion. Disasters, like hurricanes, increase the effects of sedimentation. Sedimentation can also be described as excess soil in water that settles to the bottom of the river or reservoir (Huron River Watershed Council, n.d.). For this reason, sedimentation becomes an issue in the reservoir system at La Plata. Sedimentation in the reservoir has increased in recent years, decreasing its capacity. Typically, sedimentation in a reservoir will decrease the longevity of a reservoir's dam. La Plata reservoir's originally predicted lifespan has been extended by the USGS through the year 2149 assuming the sedimentation rates of about 0.23 Mm^3/yr. as of 2016 remain consistent (Gómez-Fragoso, J., 2016). Lifespan decreases as sedimentation increases because it reduces carrying capacity of water volume as the reservoir fills with sediment (Sedimentation Surveys in Puerto Rico, n.d.).

Assessing Land Change

Researchers use several methods to assess land change. Most commonly, Geographic Information Systems (GIS) and satellite imagery are used to compare specific land features from one time period to another. Images from different time periods can be overlayed to show the visible changes. Common GIS applications include ArcGIS and ArcView which are used to clip specific images to overlay for comparisons or geoprocessing, by extracting geographical data into spatial analysis outputs, to assess the land in different periods to determine forestry cover or growth (Krajewski et al., 2006). ArcGIS can also be used to compare land classes and land uses over time as it relates to land changes (Smiraglia et al., 2015). ArcInfo can be used to view digital measurements of a geographical feature in an area, such as earthquake damage to the Puerto Rican coastline (Torres-Pulliza et al., 2002). The USGS National Aerial Photography Program (NAPP) and Landsat contain aerial images of land (Liu et al., 2015). These programs typically work with satellites and data from the United States Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), and the National Aeronautics and Space Administration (NASA) to create a database of satellite images of the earth throughout time. Furthermore, LIDAR, a system of laser scanning an area, and Digital Elevation Modeling, a 3D scan of an elevation, technology is a common practice to survey land characteristics (Krajewski et el., 2018; Torres-Pulliza et al., 2002). These techniques can aid in the assessment of an area's topography and geographical components. Surveying an area over time will allow for comparisons of land change to be assessed.

Researchers look for several indicators of land change, such as water level, vegetation type and density, flora, and fauna. A study conducted in 2018 analyzed the effects and characteristics of Hurricane Maria, noting that wind, rain, and landslides were considered indicators for assessment in comparison with previous years (Van Beusekom et al., 2018). By using broad-scale maps of vegetation index loss along with maps of wind, rain, and landslides, changes and effects were estimated through generalized linear models in the United States Caribbean (Van Beusekom et al., 2018). Wind speed, storm travel speed, and rainfall were ultimately concluded to be the main factors causing destruction to vegetation during storms. Researchers simulate remotely sensed spatial patterns of hurricane effects, recreating hurricane wind forces in the simulations. The enhanced vegetation index is used with MODIS satellite imagery to detect how much "greenness" is lost from the storm (Van Beusekom et al., 2018). Using remotely sensed data, reflected information about land through radiation emissions, combined with physics-based calculations and field data, landscape variations of specific vegetation that is susceptible to these hurricane effects were identified and categorized.

In one study of Hurricane Maria's effects, researchers sampled seven large reservoirs in Puerto Rico in 2018, comparing pre- and post-hurricane characteristics of water quality and fish communities (Neal, J. W. at al., 2020). Testing for the volumetric flow of rivers and water quality revealed that increasing amounts of sediments were found in the water, showing the clear change of water quality between the two periods. Solid particles from sediment were found to block water from flowing further downstream which can cause reservoir overflow.

A study in Singapore used a new form of MapSync and WebGIS under mixed methods research to create a dynamic understanding of the land with a combination of historical maps and google street view (Ick-Hoi Kim et al., 2018). Historical maps were layered on one another and adjusted for transparency to create a sense of palimpsest landscape analysis which traces alterations to previous documents (Ick-Hoi Kim et al., 2018). The study used WebGIS to compare historical maps at the same time with a drawing tool for a polygon approach (Ick-Hoi Kim et al., 2018). Figure 10 shows an image from this study, and the area researchers looked at. This tool focused on a selected area over different time periods for spatiotemporal analysis. The study integrated ArcGIS and Google maps/street view to provide more specific details of the land (Ick-Hoi Kim et al., 2018).

The Singapore study used much of the traditional concepts of ArcGIS and satellite imagery comparisons through the polygon approach that other studies completed in Poland and Atlanta, Georgia (Krajewski et al., 2018; Liu et al., 2015). However, the Singapore study found that ArcGIS is not the best tool when WebGIS systems and Google street view combinations provide for a much more integrated and publicly accessible tool for land change analysis. Unfortunately, the benefits of Google street view for our project are minimal since very few street level images have been taken for the areas around the La Plata River and Refuge.

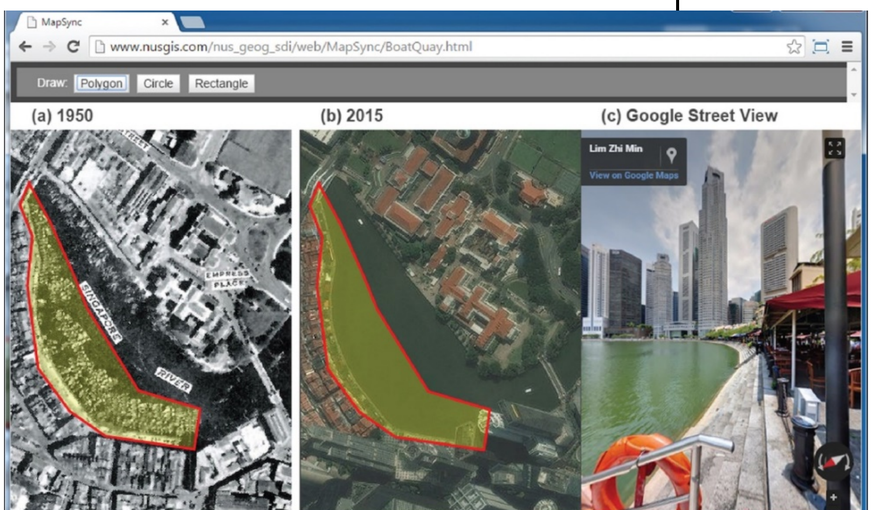


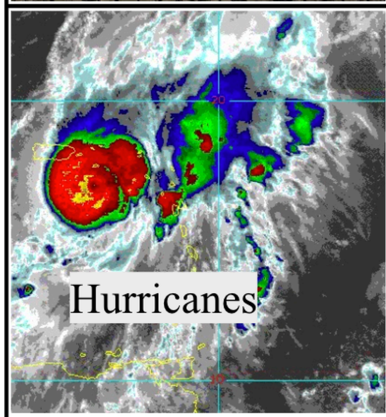
Figure 10. Polygon Approach.
This figure displays a section of Singapore's Boat Quay using the polygon approach combined with Google street view. The polygon approach highlights a certain area which is to be overlaid on each image in the time period, allowing for clarity in understanding the area being observed. (Adapted from Ick-Hoi Kim et al., 2018

In general, the DNER lacks documented satellite imagery for the region. Thus, we plan to obtain satellite images from past years to analyze the impacts climate change has had on La Plata Refuge and River. When assessing landscape change, the process is carried out in a three-pronged approach; system definition, system analysis, and system synthesis (Bürgi et al., 2005). System definition outlines the study area, the focus of the study, and the study period. For our purposes this would include the watershed area of La Plata as detailed in Figure 3 focusing on land change in water, vegetation, and development for the time period of 2003-2020. System analysis focuses on subsystems of change and persistence of physical landscape elements, actors, institutions, and driving forces. For La Plata we will look at natural disaster events and development and how they correlate with observed land change. Lastly, the system synthesis allows for the actors, institutions, and driving forces to be linked in causal relationships with their given impact on the elements of the landscape in which the study is conducted. This will be displayed in the relationship between the visual changes observed at La Plata and the known driving forces of natural disasters and human development.

Table 1 summarizes the severe weather events we have discussed above, the potential impacts they can have, and the technologies we can use to track those impacts in La Plata. In the following chapter, we elaborate on the procedures we will use to collect this information and form our understanding of land change on La Plata.

Table 1. Indicators, Impacts and Analysis.

This table displays the indicators considered for the La Plata region, and what affects these indicators have on the land. The tools or methods used to assess land change from these indicators, events, and effects are listed on the right most column of the table.

Event	Indicator	Impacts	Secondary impacts	Tools
 Droughts	High temperatures	Dying vegetation	Unstable soils	Interviews with water dept. employees
	Low rainfall	Dry soils	Increased erosion	NOAA events database
		Low water levels	Dead aquatic animals	US Drought Monitor
				Satellite Imagery
 Hurricanes	Heavy precipitation	Wind damage	Loss of vegetation	Interviews with climate change experts
	High winds	Flooding	Erosion	Interviews with water dept. employees
		Landslides	Sedimentation	NOAA events database
				Satellite Imagery
 Earthquakes	Movement in tectonic plates	Liquefaction of soil	Change in soil type	PR Seismic Network
	Ground shaking	Cracks in ground	Exposure of new soils to air	USGS data and maps

METHODOLOGY AND RESULTS

The goal of this project is to assess landscape changes of the La Plata Refuge and greater watershed area to provide data to inform future management plans for the DNER. To accomplish this goal, we completed a set of four objectives shown in Figure 11.

Objective 1: Interviews

To understand how natural disasters and climate change impact land change and resource management, we conducted six interviews with various experts. The interviews also supported additional background understanding of climate change, land change, and their impacts on Puerto Rico and La Plata. Each interview is described in the following sections. We held interviews over the phone or zoom. Before beginning the interview process we wrote a consent script and read it at the beginning of each interview. This ensured that requests for confidentiality and any requests for no recording device to be used were respected. The interview procedure, consent script, interview notes and interview transcripts can be found in Supplemental Materials, Section C (SM-C)[1].

Climate Change Experts

The team held two interviews with Patrick Gonzalez, a climate change expert from University of California (UC) Berkeley, and Jay Lund, a climate change expert from UC Davis who focused on watershed science. Interviewees were selected based upon their knowledge of the topic and availability. We discussed weather patterns, the climate and how they are changing, or have changed, to help us better understand how they affect Puerto Rico's land change. We learned about indicators of climate change and used them to inform land management strategies. These results are discussed in more detail below.

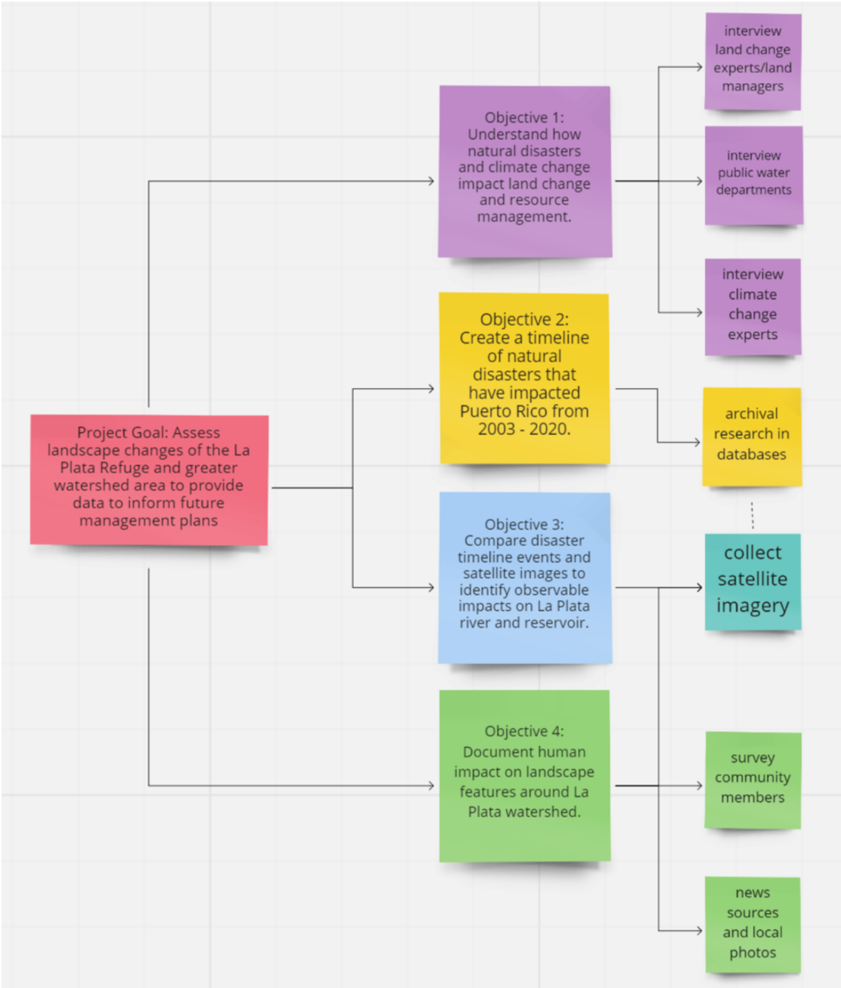


Figure 11. Objectives and Associated Methods.
The figure shows a flow chart from our goal to objectives and then the methods we used to complete them. The arrows show the workflow and connect methods that were used to complete multiple objectives.

[1] Supplemental Materials for this project may be found at https://digital.wpi.edu/ by using the browser to locate Puerto Rico projects and then searching with the project title.

The interview with Patrick Gonzalez helped to provide relevant information to support our background research. He directed us to the US National Climate Assessment which confirmed our background research as well as USGS National Land Cover Data which can be used in conjunction with ArcGIS in a future project (Chapter 4 Recommendations and Conclusion). Patrick Gonzalez provided key information to the impacts of climate change, mentioning that the most effective thing to do to combat climate change is to change our behaviors as a global society or behaviors on the island of Puerto Rico to reduce carbon emissions. Our interview with Jay Lund affirmed our understanding of indicators from Table 1. He also discussed analysis of climate change using predictive modeling from our current analysis of land change that is based on historical observations.

Interviewees mentioned similar indicators of temperature, precipitation, and extreme events that were important to display the effects of a changing climate. Interviewees also provided similar insight into climate change analysis by using historical records, including images and databases, for predictive modeling of future projections. This is important as our satellite images and timeline aim to provide the historical details needed for the creation of a predictive model. More details on predictive modeling can be seen in Chapter 4 Recommendations and Conclusion. Lastly, these interviewees considered it important to understand the relationship between the land and social factors of communities, governments, and economics. These social factors could be lacking in our research due to our physical distance to the study area.

Land Change Expert/Land Manager

The team held an interview with William Gould, an expert in the field of landscape ecology, who works for the United States Forest Service in Puerto Rico and other Caribbean territories. He gave our team information on indicators for land change within the island. By interviewing an expert who analyzes land similar to La Plata, we were able to better understand how the La Plata reservoir, river and watershed might be affected by land change and how we can analyze the changes. We also better understand how land management in Puerto Rico has been affected by natural disasters and how to adapt land use plans for a future that involves climate change. The information gained from these interviews also helped us in forming a recommendation to the DNER. Results are discussed below.

William Gould provided insight towards the organizational struggles within Puerto Rico that often make natural disasters occur without proper mitigation. Disconnection between groups such as municipalities, local governments, and farmers leads to a lower response and recovery rate due to an inefficient distribution of resources. In many situations, the resources and personnel are available to respond and recover from natural disasters, but the communication in Puerto Rico is not prevalent to make the process occur. Additionally, Mr. Gould highlighted that the main indicators for land change in Puerto Rico are changes in vegetation, land cover, and slope. These changes should be analyzed in comparison to specific events or disasters on both a macro and micro scale to view and understand what was there before and after the event. Remote sensing with GIS is a tool often used to analyze these indicators and effects. Although we did not use ArcGIS directly in our project, we observed these indicators when viewing satellite imagery through Google Earth.

Public Water Department Employees

The team held three interviews with employees at various public water departments throughout the US and Puerto Rico: Francisco Catalá Míguez, an environmental planner with the DNER; Gene Camargo from the Water Storage Distribution Department of the City of Rockport Public Works in Texas; and Wyatt Arnold from the California Department of Water Resources. Interviewees were selected based on them being employed at a public water department. They were also selected if they had experience with natural disaster management at a drinking water source, such as while there was a drought, or extensive flooding. From these interviews we learned more about how water resources are managed after a storm and what indicators departments look for in the weather before a storm. We used the indicators mentioned in these interviews to broaden the indicators displayed in Table 1. The information from these interviews also helped us to understand how La Plata Reservoir might be affected by natural disasters. It also helped us provide a better recommendation to the DNER about their management plans for future years. Results from these interviews are discussed below.

Our interview with Francisco Catalá Míguez gave us new insight into land change factors in Puerto Rico. Talking to him also helped us to understand how Hurricane Maria affected the whole island as well as some of the impacts on La Plata. He gave us sources from the National Oceanic and Atmospheric Administration (NOAA) on effects from Hurricane Maria and Land Cover Change in Puerto Rico. The interview with Gene Camargo, who works in Rockport, Texas, gave us insight into how important communication is within a department and with other water departments, especially when preparing for a severe storm. This information ties in with similar points from the Land Change Expert/Land Manager interview as previously discussed. We learned more about reaction to severe storms from him as well, such as creating a schedule for when water access for the public was turned on or off and having a space for employees of the department with food and water while they are managing storm damages. From Wyatt Arnold, an engineer for the California Department of Water Resources, we understood the importance of disaster management. He gave us an example of a time when a disaster was averted during intense rainfall. He also gave us information about the short- and long-term weather and water level indicators they watch for within the water department. These indicators help them to manage water letting from the dam to prevent flooding as well as shortage of water supply. Although the interviews each gave us different information to consider we were able to work all of it into our project in a new way.

See Table 2-4 for summary of key information discussed in all interviews.

Table 2. Summary of key points from Expert Interviews on Climate Change

Indicators of Climate Change	• Temperature increase • Change in precipitation • Frequency of extreme events
Methods to Analyze Climate Change Impact	• Historical records of land use/cover change • Future predictions from models
Additional Factors/Considerations	• Population density • Figure out people involved such as: ○ Organizations ○ State and local governments ○ Groups of people • Economic activity ○ Socioeconomics

Table 3. Summary of key points from Expert Interviews on Land Change/Land Management

Indicators of Land Change	• Change in vegetation and land cover: ○ Impervious surfaces ○ Man made cover ○ Forest cover • Landslides after hurricane: ○ Slope and rainfall ○ Affected sediment load
Land Change Impact Analysis	• Disconnection between groups/organizations ○ Slow response and recovery • Management actions should account for long term
Additional Factors/Considerations	• USGS remote sensing data used for different cover and categorization • Warming and drying trends affect human/vegetation cover for various species ○ Changes environmental conditions

Table 4. Summary of key points from Expert Interviews on Water Departments.

Weather/Water Indicators	• **Short term:** ○ Air temperature ○ Water salinity ○ Water flow in channels between reservoirs • **Long term:** ○ Model forecasts of precipitation ○ Temperature of snow
Severe Weather Impact	• Rivers change course from heavy rainfall • Sediment collects in water after flooding • Damage can be incurred to water and power lines
Additional Factors/Considerations	• Communication is important to keep severe weather from becoming a disaster and have surrounding towns and counties on the same age

Objective 2: Timeline of Disaster Events Impacting Puerto Rico

We created a timeline of natural disasters that impacted Puerto Rico from 2003-2020. The timeline contains information about hurricanes, earthquakes and droughts that occurred in Puerto Rico during this time. The timeline allowed us to look for connections between severe weather events and indicators detailed in Table 1.

To create the timeline we gathered data from the United States Geological Survey (USGS), NOAA, National Aeronautics and Space Administration (NASA), United States (US) Drought Monitor and the Puerto Rico Seismic Network[2]. The main use of the USGS and Seismic Network was to find information about earthquakes, such as where and when they occurred. We also looked at the magnitude as well as any other impacts of shaking or damage in the USGS database. We used the NOAA events database to find information about droughts, flooding, and tropical storms. The US Drought Monitor website helped us cross reference data about the severity and length of droughts with the NOAA events data, noting which droughts were the most significant. We also used NOAA and NASA reports on hurricanes/tropical storms to better understand their location and impacts relative to Puerto Rico.

Early in the data collection process we made a spreadsheet detailing, when a disaster occurred, what type it was, the intensity rating, how long it lasted and secondary impacts. Secondary impacts include but are not limited to flooding and landslides caused by a hurricane, or restrictions on water usage from a drought. After initial collection, we created a horizontal timeline marking significant disaster events and land changes incurred from them. Hurricanes and tropical storms that impacted Puerto Rico were added to the timeline. However, only magnitude 3.5 or larger earthquakes, severe, extreme, or moderate droughts, and significant flooding were added to the timeline. This helped to minimize overcrowding the timeline with events.

Timeline Results

The first data collected for the timeline was information on all events that had occurred in Puerto Rico. Once the data was in the spreadsheet, we narrowed down the options to events that had significant impacts on Puerto Rico, especially those that affected La Plata. The significant events were then compiled into an excel spreadsheet to create a visual timeline, as seen in Figure 12. The vertical height of the event, on either side of the midline, along the timeline indicates the severity, with taller events being more severe and shorter ones less. Event duration was also accounted for in this timeline, shown as the blue bar extending right from the event.

[2] A detailed list of citations can be found on slides with each corresponding event in the timeline https://prezi.com/view/XnSSHt90PQRDbxTIM1Bz/

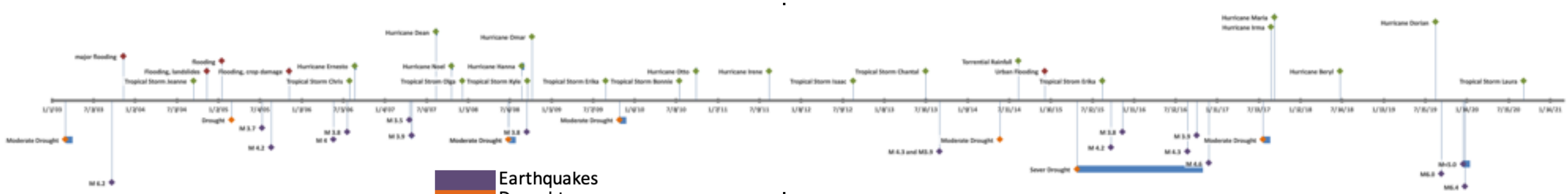


Figure 12. Timeline of Disasters in Puerto Rico, 2003-2020.

Once the timeline was compiled in one place it was easy to see patterns in the events. The most frequent events on the timeline were flooding and earthquakes. Flooding resulted from either heavy rainfall from smaller weather fronts moving by the island, or as an impact from hurricanes. From our analysis of the impacts, flooding from hurricanes was more widespread across the island than flooding from weather fronts. Multiple hurricanes occurred from July 2007 to July 2008, some of the first to occur on the timeline.

Droughts were the least frequent events with only six moderate to severe/extreme droughts recorded. As mentioned in the Chapter 2 Background, drought conditions are more variable in island climates. This made droughts in Puerto Rico more difficult to track throughout the timeline. Another limitation was that we did not have a source showing where the drought was occurring, just how much of the island was in drought. We decided to focus on moderate to severe/extreme droughts because they were the most likely to have a broader impact. From the timeline we saw that droughts lasted for about a month, with one exception: the drought in 2015 and 2016 that lasted 80 weeks.

The last events we added to the timeline were earthquakes. We narrowed the search to magnitude 3.5 earthquakes and above to limit the number of events, as there are a lot in Puerto Rico due to the island's location on multiple fault lines. We also noted the epicenter of earthquakes and observed "did you feel it" maps from USGS (when available) to determine the potential impacts at La Plata Reservoir and River. The "did you feel it" maps are created from community input that USGS requests on its website. The maps are then color coded to show the range of shaking felt across the island (Figure 13).

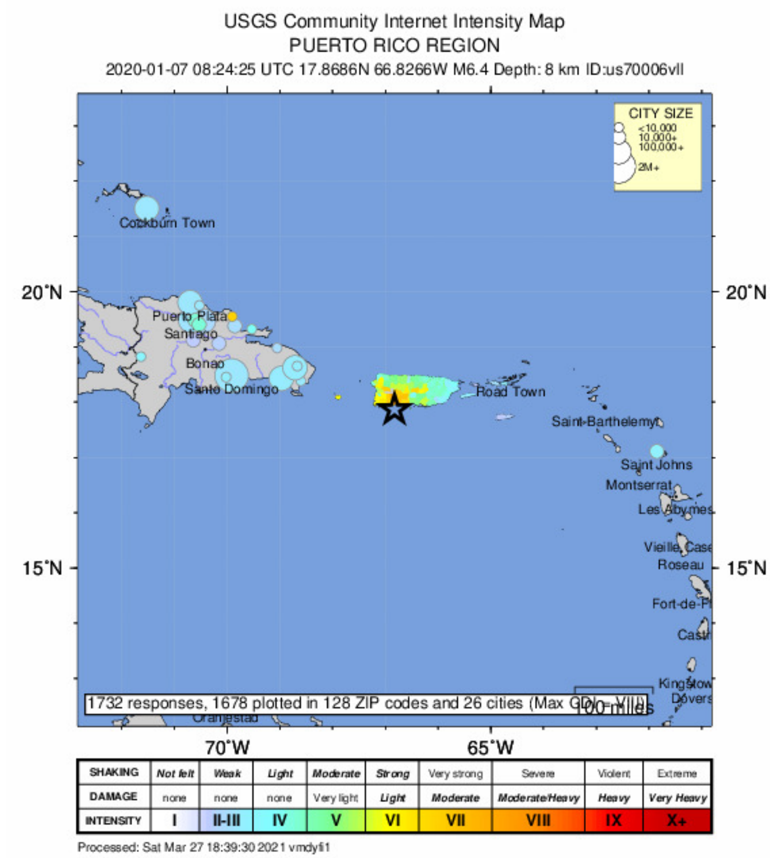


Figure 13. USGS Earthquake Did You Feel It Map.
(Adapted from M 6.4 - 13km S of Indios, Puerto Rico, 2020)

As the timeline progressed, we decided to make it an interactive timeline that could display detailed information based on the user's selection of events. We shifted the timeline from the excel format (Figure 12) to a Prezi[3] (SM-I). This allowed us to combine information about event impacts, date of the event and duration in one place. Figure 14 has examples from the comprehensive timeline of events in categories of hurricanes, droughts, and earthquakes. We put in these events to show how storms have changed from 2003 to 2020. The events listed, except Hurricane Jeanne, were also the most important to the managers of La Plata Refuge and Reservoir.

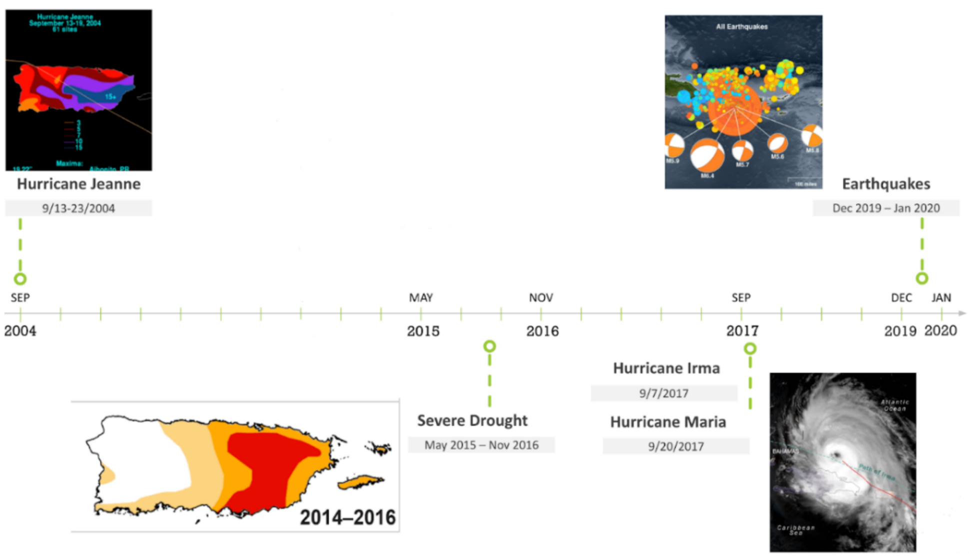


Figure 14. Timeline of Significant Weather Events.
Example timeline of events created from our research in events databases. (From 2004 to 2020 images are adapted from *Effects of Hurricane Jeanne in Puerto Rico*, 2021; Álvarez-Berríos & Holupchinski, 2017; Karklis et al., 2017; PacificTWC, 2020)

Hurricane Jeanne 2004

From the article *Tropical Storm Jeanne* (2004), we learned that Hurricane Jeanne made landfall in Puerto Rico in September 2004 as a tropical storm on the verge of becoming a hurricane. The storm tracked diagonally across the island from the southeast corner to the northwest. The most extensive damage was caused by severe flooding across the island. Rainfall from the storm corresponded with more than a 100-year return period. Classifying the storm as having the highest recorded rainfall in the last 100 years. Puerto Rico received 28-35 cm of rain over the 3 days of the storm. The nearby island of Vieques received about 38 cm of rain in a 24-hour period. This led to landslides and damages to the power grid, water supply and damage to the island's infrastructure. In flood zones, over 3,000 people were forced out of their homes. Wind speeds were recorded with gusts of 114km/h and sustained wind speeds of 79km/h, in official reports from Carolina, PR. Unofficial reports recorded sustained winds speeds of 101km/h with gusts of 114km/h, in Salinas, PR.

Droughts 2015-16

From May of 2015 to November 2016, Puerto Rico experienced severe drought conditions across the island. The most severe conditions were on the eastern side of the island, as seen in Figure 14(Álvarez-Berríos & Holupchinski, 2017). In June, the eastern side of the island had record low stream flows. Groundwater and reservoir water levels were dropping, leading to rationing of water in San Juan (State of the Climate: Drought for Annual 2015, 2016). From an article by Almodóvar (2015) in July 2015 the eastern municipalities of the island were declared natural disaster zones. These municipalities were in extreme drought, with the rest of the eastern side being in severe drought. The western side of the island was in moderate drought to abnormally dry conditions. The only area with no drought conditions was the central-western mountain range. As a result, there were impacts on agriculture from drying. Drying vegetation also made cattle

[3] https://prezi.com/view/XnSSHt90PQRDbxTIM1Bz/

grazing difficult. The frequency of drought events is likely to increase with climate change, so it is important for farmers to be prepared for this.

Hurricanes Irma and Maria 2017

From the NOAA and National Weather Service report (Cangialosi et al., 2018) the eye of Hurricane Irma passed 92 km northwest of San Juan, Puerto Rico on September 7th, 2017 as a category 5 hurricane. Although direct landfall was not made in Puerto Rico, many of the impacts were still experienced. A storm surge of 3-6 m along the coast of the island, and rainfall of 25-38 cm at higher elevations in the central part of the island were some of the impacts from the storm. The heavy rain and strong winds brought power and water outages across the island for several days. The storm caused damage to homes and businesses, trees were uprooted, and weak structures collapsed.

The NOAA events Database (Hurricane Maria, 2017) recorded that on September 20th, 2017 Hurricane Maria made landfall on the southern shore of Puerto Rico in the municipality of Yabucoa. After landfall, the category 4 hurricane travelled northwest across the island. The hurricane had sustained winds of 250km/h as it travelled. Locals reported feeling the ground and their houses shaking throughout the storm. Trees were defoliated, lost medium to large branches or were snapped in half from the force of the wind. The infrastructure in Puerto Rico could not withstand the wind either. Although most structures are built from concrete, many sustained significant damage. Roofs made with materials other than concrete were completely ripped off or severely damaged. A category 4 or higher hurricane has not made landfall in Puerto Rico since Hurricane San Felipe II, a category 5 hurricane, in 1928. Storm surge and coastal erosion from Hurricane Maria was similar to that from San Felipe II (Catalá, F. (2021, March 31). Personal communication [Zoom video]).

Earthquakes 2019-20

An article by Cartier (2021) from the news source EOS outlined the timeline of the earthquakes. Starting in December 2019, more than 500 earthquakes larger than magnitude 2 occurred in Puerto Rico. The earthquakes continued building in size throughout the month and into January 2020. On January 7th, the largest earthquake shook Puerto Rico, with a magnitude of 6.4. The epicenter of the quake was off the southern shore of the island, closest to Ponce, PR. The magnitude of this earthquake caused damage across the island. Homes, schools, municipal buildings, roads, and bridges were all damaged in the southern part of the island. This led to widespread power outages and almost 300,000 homes without water. In the USGS earthquakes report (Magnitude 6.4 Earthquake in Puerto Rico, 2020) impacts from the event were described. First, due to damage from the earthquake, 7,500 people left their homes to seek different shelter, some even going to their cars or tents. Aftershocks of magnitude 3 from the event continued for 6 months. The strength and number of aftershocks will decline but they are predicted to continue each week from 1.5 years to a decade. An earthquake of this magnitude has not been felt since 1918, so it took many people by surprise.

Objective 3: Observable Land Change in La Plata River and Reservoir

To identify observable impacts on La Plata river and reservoir, we used satellite images on Google Earth Pro. Using the history tool, we looked at images between the years of 2003 and 2020, with a focus on images taken before and after significant events on our timeline for the La Plata river and reservoir. Images were pulled from areas A2 and B2 as detailed in Figure 15.

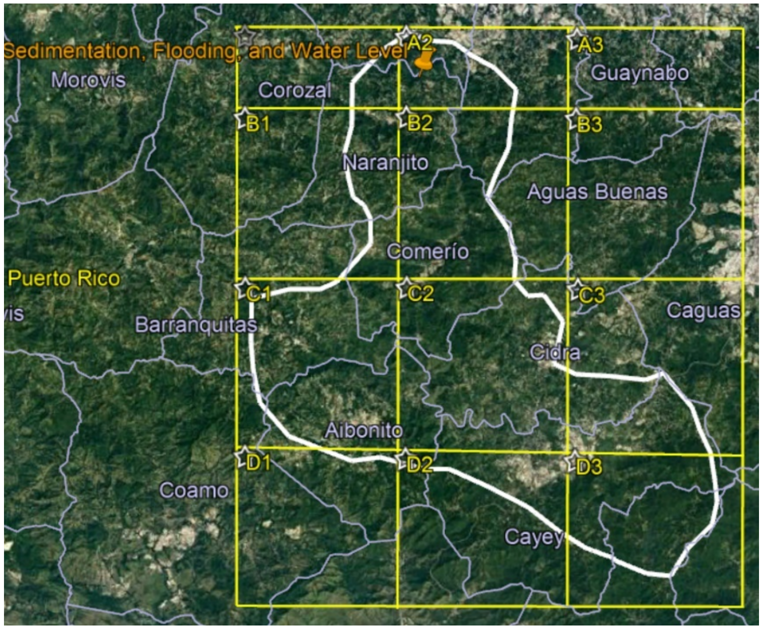


Figure 15. La Plata Watershed with Timeline Focus. This image details a grid system for the La Plata watershed. Sections A2 and B2 contain the La Plata river and reservoir, the focus of our satellite imagery in relation to timeline events.

We used assessment techniques adapted from Liu et al., 2015 to identify changes through a comparison of satellite images surrounding severe weather events (Figure 16). Next, we created map layers, overlaying paths, and polygons, to outline the riverbanks, and pins, to mark an exact location, onto corresponding satellite imagery to observe changes between time periods. An example of our process is shown in Figure 16.

We gathered and time stamped images showing observable land changes and integrated them with the interactive natural disaster timeline. In the timeline users can click on a year and see events, their impacts and satellite imagery comparisons. This process gave a visual of the landscape at La Plata years ago versus what it looks like now in relation to our timeline. Visual connections between satellite imagery and the timeline helped to determine how strong the influence of disasters and their secondary effects were on land change in Puerto Rico, with a focus on La Plata Reservoir and River. The connections between images and the timeline also helped to inform our understanding of long-term impacts, such as sedimentation in the reservoir during a hurricane or low water levels in a drought. Comparison of the disaster timeline with significant landscape change data from the satellite imagery deepened our understanding of how these disasters have affected Puerto Rico and its' waterways. Below we note the biggest changes we were able to observe via this imagery.

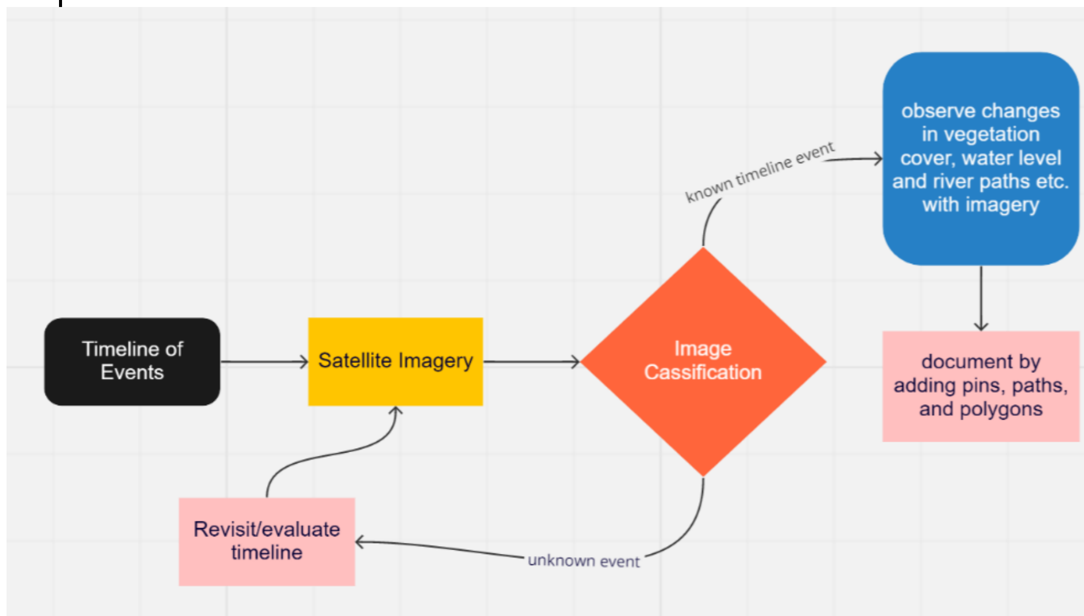


Figure 16. Timeline and Satellite Imagery Process.

Changes to River and Reservoir: Results

In this section we focus on some of the impacts that were most noticeable in satellite images. A link to additional satellite imagery observations from the Google Earth Pro File can be found in the SM-I for this report. A combination of the timeline events and satellite images from those events are in a Prezi presentation linked in SM-I. A User Guide for Google Earth Pro can be found in SM-I in the forms of a video and slide presentation.

Sedimentation and Flooding

We observed flooding and sedimentation caused by hurricanes Irma and Maria. Figure 17(A-D) details the observable change we saw in satellite imagery from before Hurricane Irma to two months after Hurricane Maria. The location we observed in Figure 17(A-C) is pinned as Sedimentation, Flooding and Water Level in Figure 15 above. Figure 17A is an image from before the hurricanes occurred, taken in April 2017. The water in this image is blue/green, indicating the water is clear. Image B (Figure 17) was taken just after Hurricane Irma occurred, on September 7, 2017. The water in this image is brown which we interpreted as soil and sediment in the water. This is caused by the flooding and erosion occurring upstream that is putting soil from the banks into the water. Another image, Figure 17C, was taken on September 23, 2017 just after Hurricane Maria. The water again in this image is brown, showing there is still sediment in the water after Hurricane Maria. The most significant observation we had from these images was in Figure 17D that was taken in November of 2017. This image is a zoomed-out view of the Reservoir which includes the island observed in the other images(outlined in red). The image is important because it shows that sediment was still in the water based on the brown river upstream of the reservoir. This observation is significant because it means that there was more soil build up from these storms, this build up can cause more damage to the reservoir and lower the water capacity of the river and reservoir.

Similar sedimentation and flooding can be seen in the satellite imagery surrounding other hurricane events. In Figure 17(A-C) the water line has been traced by varying colors to show the change between dates. Viewing sedimentation only by color changes in these satellite images is limited in that we do not know exactly how much erosion has occurred and how this sediment affects water depth in the reservoir. This information is important to find out for future predictions on longevity of the reservoir.

Water Levels

We observed lower water levels during droughts. Satellite images detail these changes before, during, and after the 2015 drought as seen in Figure 18(A-C). Figure 18A shows the area before drought occurred in January of 2015. The dark blue lines in the image outline the riverbanks when the water is at a normal level. Figure 18B, taken in July 2015 shows the area during extreme drought. The light brown soil exposed in the satellite images indicates the water level drop because vegetation is not growing there. In January 2016, water levels had returned to normal as seen in Image C (Figure 18). Looking at the image, the light purple line shows where the banks were in drought so a comparison can be drawn between the water levels during drought and in normal conditions.

Our research in images lacks information on numerical values for water level changes. It is valuable to note that the percentage of Puerto Rico still in drought (from our timeline information) drops significantly from that in 2015 which helps to explain why images from La Plata appear to have returned to normal by January 2016 despite the drought in Puerto Rico continuing until November 2016.

Figure 17(A-D). Sedimentation Before and After Hurricanes Irma and Maria.

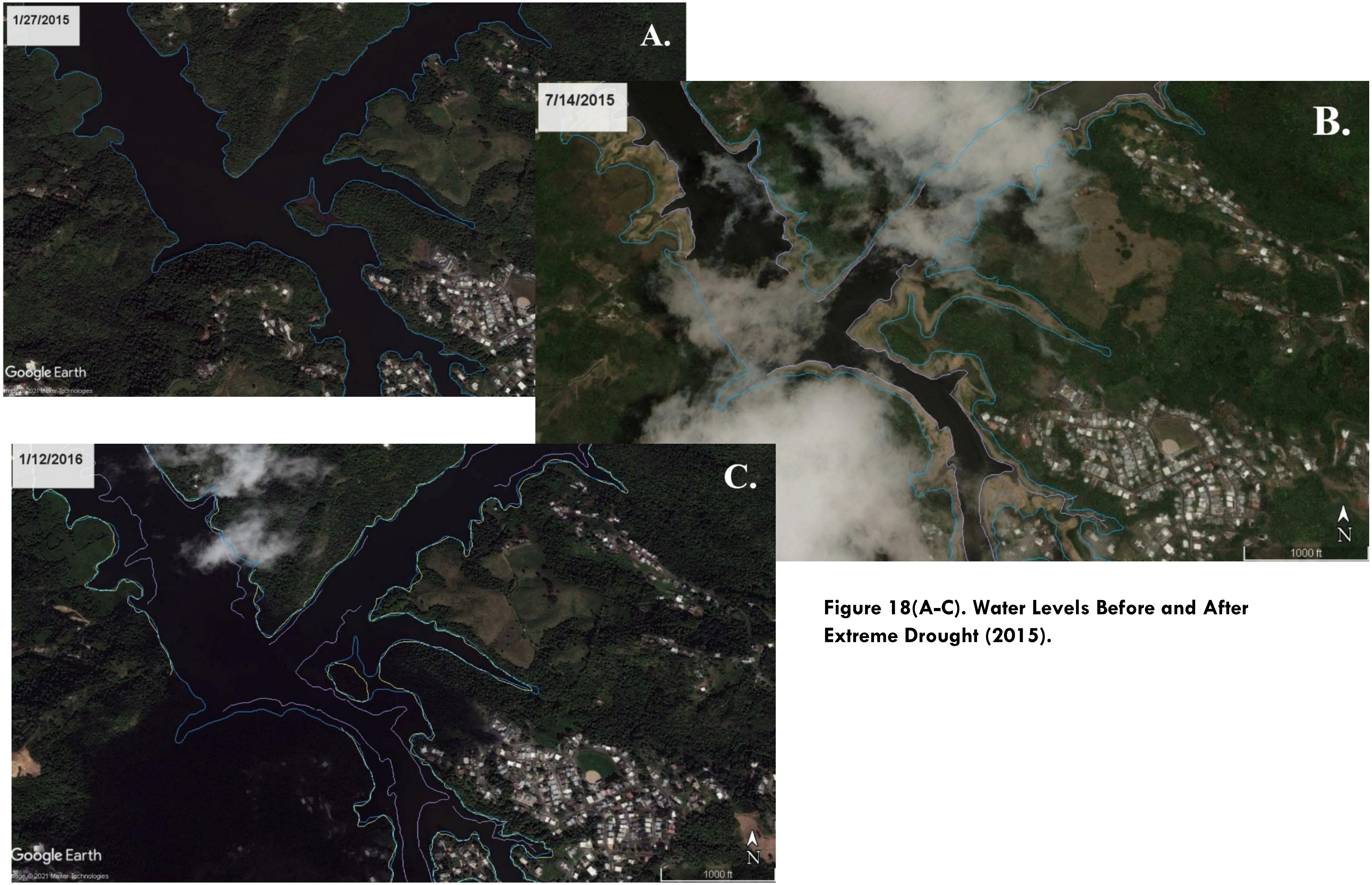


Figure 18(A-C). Water Levels Before and After Extreme Drought (2015).

Objective 4: Observable Changes of Vegetation and Development in the La Plata Watershed

We continued using Google Earth Pro to observe changes in the whole watershed region driven by human factors other than climate change between 2003 and 2020. We broke up the area into a grid as shown in Figure 19.

Figure 19. La Plata Watershed with Development Focus.

Within each grid we observed changes by taking an image of one grid section from 2003 and looking at it side by side with the same grid section from 2020. An example of this comparison is shown in Figure 20.

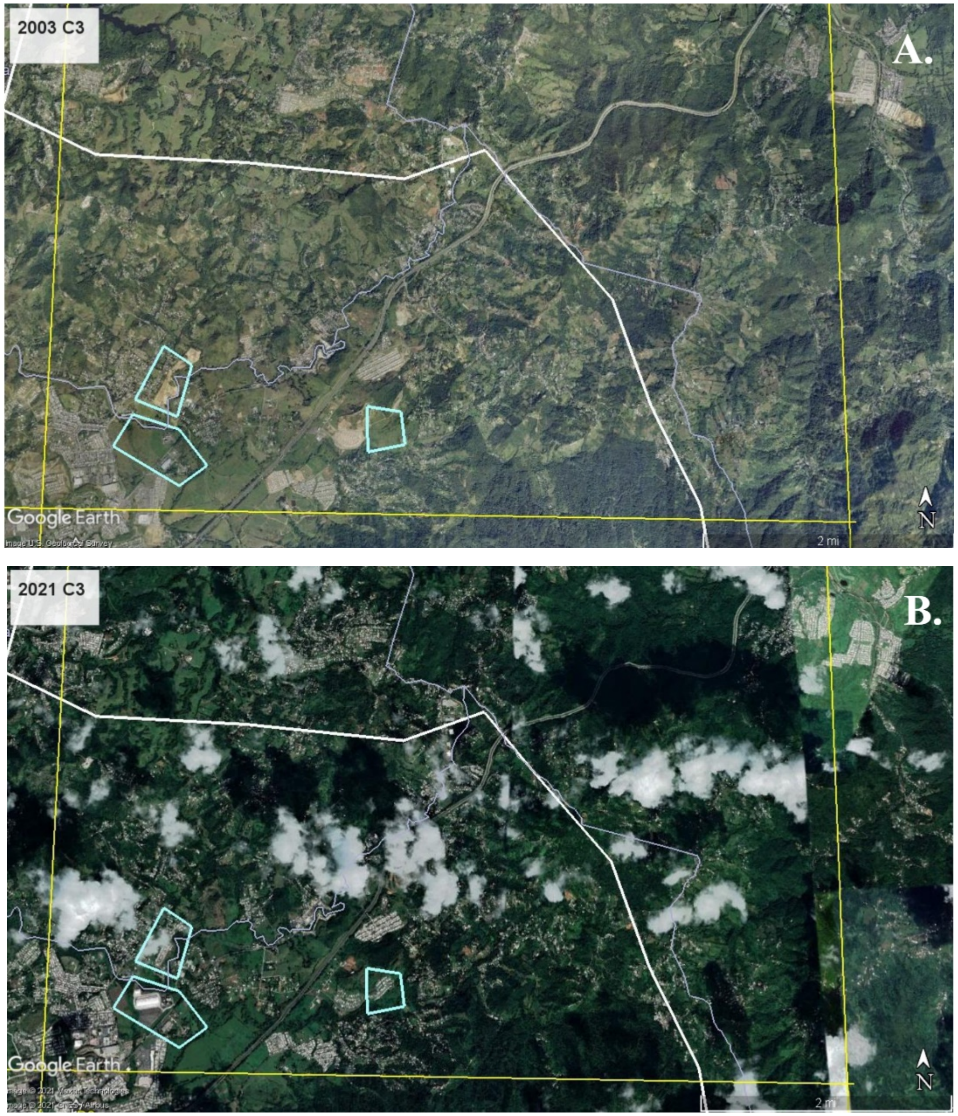


Figure 20(A-B). Section C3 2003 and 2021 side by side.

We compared vegetation density, apparent from visual coloration, and any notable construction in the area. We marked with colored polygons (the bottom left of the image) areas where we observed changes in the grid square.

Changes in Vegetation and Development: Results

The most noticeable impacts on vegetation and infrastructure to the La Plata watershed are described in detail here, using select images to show changes. Additional satellite imagery can be found in the Google Earth Pro File in the SM-I for this report. A combination of the timeline events and satellite images from those events are in a Prezi presentation as linked in SM-I. A User Guide for Google Earth Pro can be found in SM-I as a video and slide presentation.

Looking between 2003 and 2020 we saw expanded development and vegetation loss in closeup satellite imagery of the watershed. The images displayed in Figures 21(A-D) and 22(A-C) show two examples of these areas, the exact location of the images are marked in Figure 19 with blue and green pins. The image in Figure 21A was taken in December of 2010 and until then there was no development in the area. Figure 21B, taken in March 2013, shows vegetation loss in preparation for development. In January of 2017(Figure 21C) construction was started on a structure. Completion of the structure was in June 2019(Figure 21D). We can determine this because the structure now has a solid roof on the top and a parking lot was added next to it. We also know because looking into more recent imagery, there was no change to the area after that point. Figure 22(A-C) shows an example of vegetation loss along the banks of the reservoir. In Figure 22A, taken in December 2003, there was not yet vegetation loss but the areas where loss later occurred are outlined in pink. The first sign of vegetation loss occurred in September 2012, as outlined in blue in Figure 22B. The next area of vegetation loss occurred in May of 2020 as shown in Figure 22C and outlined in orange. Although no construction was done this area was of interest to the land managers of La Plata Nature Refuge, so we examined it on Google Earth Pro.

Implications from the development and vegetation loss include increased pollution in La Plata river as it flows to the reservoir. The development and vegetation loss both are along the river's edge, as shown with the thin white line in the images. Limitations to analyzing the development and vegetation loss in Google Earth is that we cannot compare the amount of pollution entering the river before and after the destruction occurred. We also cannot compare the rate of erosion before and after these changes happened. These measurements are important to understand how development impacts land change in the area. In future management of the area, water testing could be done to determine pollution impacts on the area near construction. Surveying could be done periodically to measure where the riverbanks are and if they have moved from erosion. To limit the likelihood of erosion, control measures could also be used in areas of construction. A larger collection of development and vegetation loss can be seen in the Prezi bubble detailed Development in Watershed (SM-I).

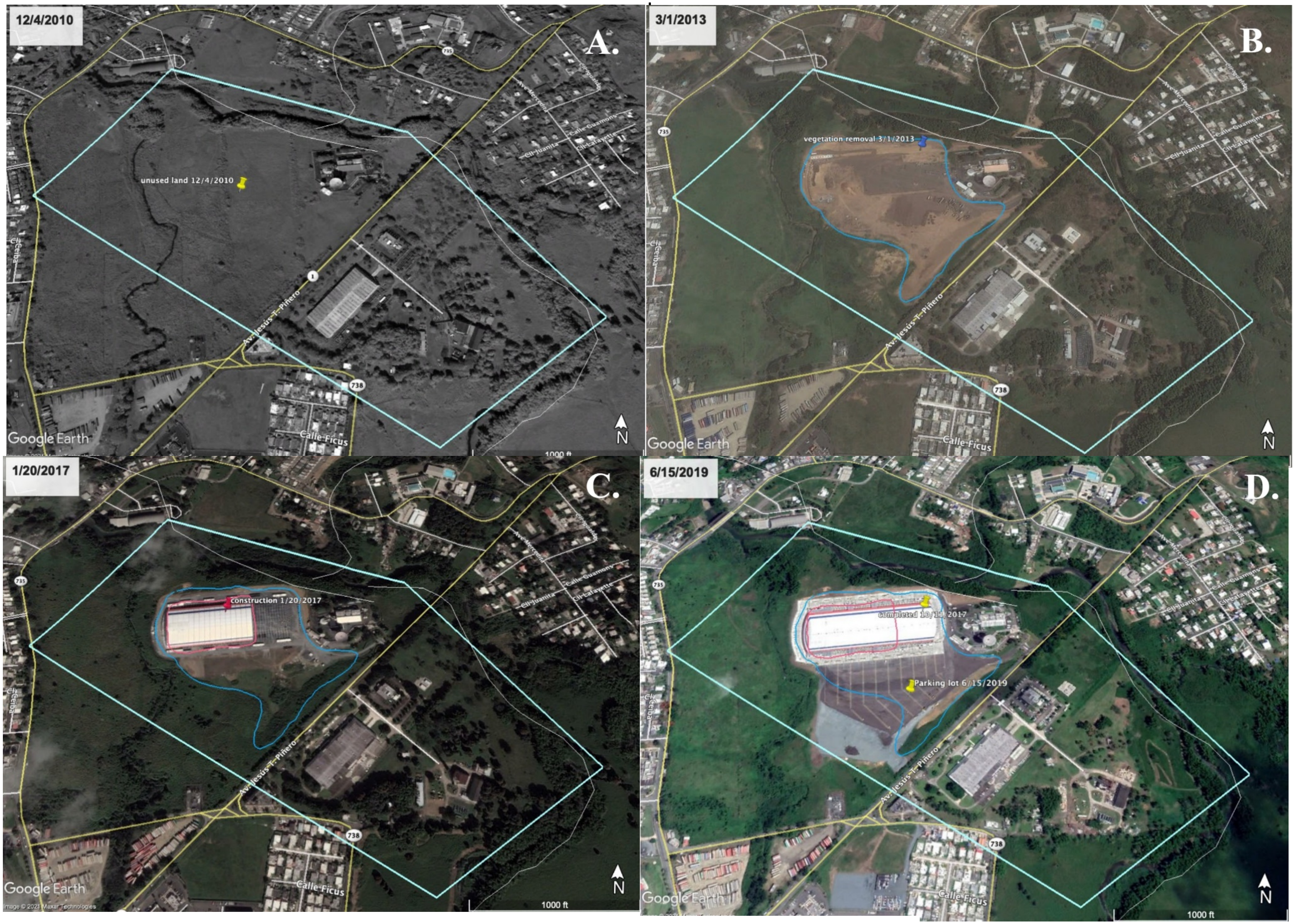


Figure 21(A-D). Development in section C3.
Loss of vegetation and new development as observed by our team when examining satellite imagery of the watershed.

Figure 22(A-C). Vegetation in section A2. This coordinate was a point of interest given by the managers of La Plata where they have observed deforestation along the reservoir.

Although the satellite imagery was helpful in showing large changes in an area, there still are limitations. Using satellite imagery we could not see smaller impacts from storms and droughts, such as landslides or other environmental impacts. To gain more insight into the smaller impacts we turned to local community members and news sources.

Surveys with La Plata Community Members

The DNER distributed one survey to three community members that are connected to the La Plata region. The community members selected consisted of people whose lives are somewhat influenced by the La Plata refuge and reservoir, either for recreational use or those who benefit and are affected by the water source of the reservoir. These included people that live in the watershed boundaries that filter into the La Plata River. The surveys asked community members to express their concerns relating to change in the Reservoir area and share photos they might have of damage from storms. This gave us a personal insight into how the community views the region and how damages to the area impact them. The survey form can be found in SM-D. Results from the surveys are discussed below.

The DNER was able to distribute the survey to community members in La Plata to give our team a complete understanding of the social aspect of our project and how weather events, disasters, and land change affect residents of the area. The survey responses can be found in SM-D. From these surveys, we learned that the greatest impacts during severe weather events were a loss of electricity and water. It is noted that the reservoir levels from their perspective are continuing to drop at an alarming rate during drought, which aligns with our team's observations of the area. They are also concerned that the recreation area is closed frequently due to these natural disasters and the slow response rate for cleaning debris, restoring water and power, and rebuilding infrastructure. Slower responses to recovery often lead to long periods of closure for the recreational area of the refuge.

Table 5. Community Views on Changes at La Plata.

Effects experienced from Hurricane Maria	• Loss of electricity ○ Started using power plants [generators] • Loss of running/drinking water

Uses for La Plata Refuge	• Recreational activities
	  ○ Fishing
	  ○ Exercising
	  ○ Hiking
	  ○ Kayaking
	• Community space
	• Potable drinking water

Greatest concerns and hazards for La Plata Refuge	• Annual drop in reservoir level • Water restrictions • The recreational area closing • Earthquakes and aftershocks destroying dam • High drought rate ○ Loss of water source • Trash in the reservoir and river
Greatest change observed to La Plata Refuge	• The La Plata reservoir used to be a river and then was turned into a dam ○ Changed landscape

News and Local Photos

No photos were obtained from community interviews, so we searched in news sources and asked the La Plata land managers for any they had. The news sources we searched in were: El Nuevo Día, The San Juan Daily Star and WAPA.tv. The goal was to see if we could obtain ground level images along the La Plata Reservoir or River. We searched by typing in keywords such as “drought” or “hurricane” to find any relevant images and then opened each of the resulting articles. We briefly read the articles relating to disaster aftermath and looked for images of La Plata or images with clear storm damage during that time. We put these images into one news source document. In addition to images from news sources we were given images of La Plata Reservoir from the land managers we worked with. These images supplemented our understanding of the impacts from severe weather in the context of our project.

News and Local Photos: Results

First, some of the photos confirmed what we were seeing in satellite imagery, such as water level drops during drought. The images also helped us see impacts that were not visible in satellite imagery, like how severe flooding was and damage from earthquakes. The images specific to La Plata helped to confirm the change we were seeing in satellite images even more specifically.

Hurricanes

Images from a gallery of photos taken after Hurricane Maria were posted by WAPA.tv but were sourced from several different places. Figures 23-25 show the three different impacts on land from the storm: vegetation loss, sedimentation, and landslides. The images demonstrate one of the limitations of using satellite imagery, which is we can only zoom in so far and in doing so, the image becomes blurry. Figure 26 is an image from the land managers of La Plata Refuge showing what flooding looked like around the reservoir after a hurricane. The exact time of this image is not known; however, we were told flooding generally looks the same each time. This image also is a helpful supplement to satellite imagery because it gives a much more focused view of the reservoir during a flood.

Figure 23. Vegetation loss from Hurricane Maria. Aerial photo of the damage from Maria. (Adapted from Tama, 2020)

Figure 24. Sedimentation from Hurricane Maria. La Plata dam on September 25, 2017, 3 days after Hurricane Maria. (Adapted from Raedle,) 2020

Figure 25. Landslide from Hurricane Maria. (Adapted from Chavez, 2020)

Figure 26. Flooding at La Plata. (Sr. Rafael A. Rodriguez Santiago)

Droughts

The images displaying drought in Puerto Rico came from the news source El Nuevo Día. The images were all from the 2015-16 drought in Puerto Rico, which is the most severe in the 21st century. In the images we saw the severe water level drop as a result of this event. The news source had images of La Plata during the drought as well, shown in Figures 27and 28. Figure 29 is an image of a dam in Puerto Rico, however not the La Plata dam. We also received images from the land managers at La Plata of the reservoir during a previous drought. These photos were taken from a plane by the National Guard on August 25, 2014. The images work with the satellite imagery to show the water level drop around this time. The pavilions seen in Figure 30A are usually close to the water, and in the back the dock is visible. In normal conditions this dock is floating in the water and serves as a fishing platform. Figure 30B shows a more distant photo of this same area. Figure 31 shows a river connected to the reservoir where a drop can be seen in the water level. The wide river is now a narrow stream. Figure 32(A-B) shows an impact of drought we could not see with satellite imagery. Due to the drop in water level hundreds of fish died and floated to the surface of the water, increasing impacts of drought because water would be less viable to drink.

Figure 27. La Plata Reservoir in Drought. (Adapted from Rosario, 2015)

Figure 28. La Plata River from Drought. (Adapted from El Nuevo Día, 2014)

Figure 29. Guajataca Reservoir in Drought. (Adapted from Guzmán, 2019)

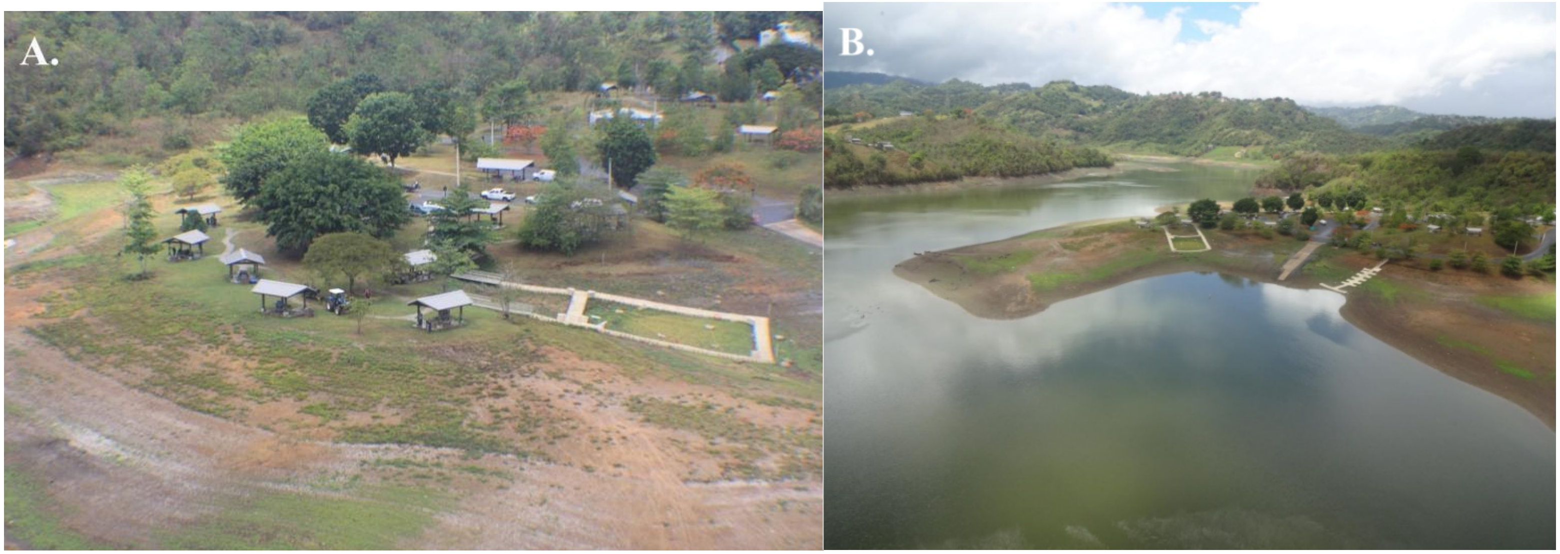


Figure 30(A-B). Pavilions During Drought at La Plata Reservoir.
(National Guard)

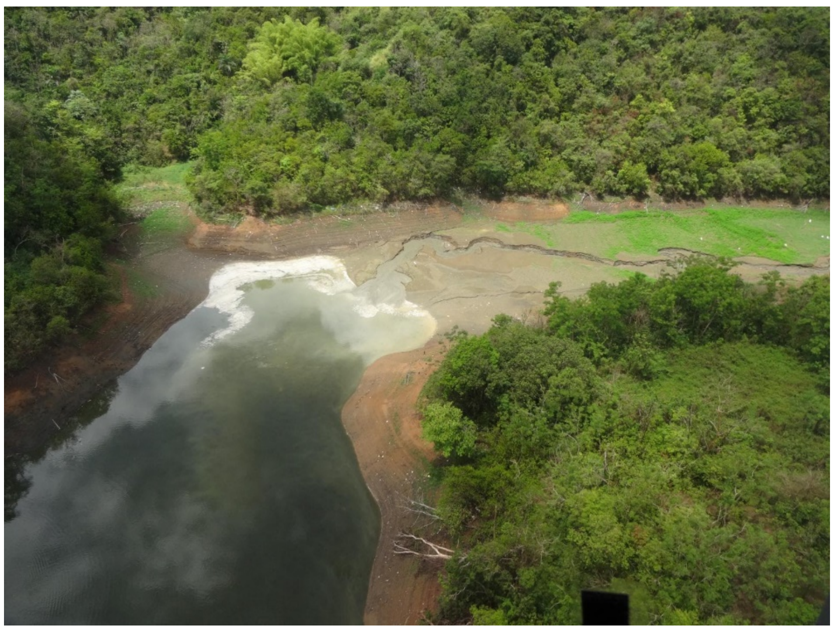


Figure 31. River in La Plata Reservoir During Drought.
(National Guard)

Figure 32(A-B). Dead Fish in La Plata During Drought.
(Sr. Rafael A. Rodriguez Santiago)

Earthquakes

The images we chose from the news sources came from a gallery of photos taken after earthquakes in Puerto Rico. The photo in Figure 33 is from the San Juan Daily Star, and Figure 34 was posted by WAPA.tv. Figures 33 and 34 show the different impacts on infrastructure and landslides, from earthquakes. These were changes we were not able to see from satellite imagery, which is a limitation of that method. However, these images supplement the imagery to show that there are impacts from earthquakes and they can be in the form of land change. We have no images of La Plata after the earthquakes because there was no documented and severe damage there. However, during the earthquakes in 2019 and 2020 shaking was felt within the Nature Refuge. This suggests that over time there could be a compounding effect from many small events, leading to change.

Figure 33. Building Collapsed After Earthquake.
(Adapted from McPhaul, 2021)

Figure 34. Landslide after Earthquake.
(Adapted from *The first images of the 6.4 earthquake in Puerto Rico*. n.d.)

Summary of Results

Through our interviews with experts in the fields of climate change, land change/land management, and public water departments, we were able to better support our methodology and better understand the effects of climate change on land. These interviews helped us to develop key indicators to climate change or disaster events as well as gather advice on the importance of communication in preparing for such events. Our timeline explains weather effects of events such as hurricanes, droughts, and earthquakes. The trends of rainfall or water level are similar along the timeline. However, by connecting our satellite imagery with our timeline of disaster events it was clear that events seem to be getting more severe in each category and land change impacts over time. Sedimentation and flooding were most noticeable in the imagery after large hurricanes passed over or passed very close to the island. Browning of the water can be seen all along the main river which could significantly impact the carrying capacity and longevity of the reservoir. Effects of droughts were seen with water level drops corresponding to the severity of the drought. Water level loss was more obvious around islands or peninsulas in the river and reservoir area. This influences the peninsula the refuge is located on as the water depth is already much shallower to begin with. Loss of vegetation can be attributed to the effects of drought, infrastructure development, and deforestation. This could cause issues as less vegetation leads to weaker soil structure and more erosion along the riverbank. Additionally, development along the river and watershed can cause issues in water pollution and erosion. The closer the development is to the river the more impact it will have on the reservoir. The development as observed seems to have expanded over time and could cause issues if gone unregulated. Based on surveys with community members all these effects from climate change and human development are concerning as they impact the community's ability to use La Plata Refuge and Reservoir as sources of recreation and potable water.

Recommendations and Conclusion

As with all research projects there were strengths and limitations to the methods we decided to use. All of our land change assessment was completed using satellite imagery on Google Earth Pro. We chose this platform because it is easily accessible as a free internet download. Some of the other platforms we considered, like ArcGIS, required a paying account. A full analysis of satellite imagery platforms is in SM-G. Google Earth Pro is also very user friendly with easy-to-follow tutorials. We created a simple tutorial video for the land managers of La Plata Nature Refuge so that they will easily be able to understand and use the platform as well. An additional positive is that the Google Earth Pro file can easily be added to and viewed to see the work we have done. The process to save a file of the work we have done and share it with others is easy to carry out. Google Earth Pro provides an archive of images that can be analyzed as sedimentation resulting in brown water, or water level changes based on the current event.

A limitation to using Google Earth Pro is that the closer the requested view is, the fewer images there are. This is true especially in the early years between 2003 and 2010. Having fewer images limits the impacts we can see from the events on our timeline. Also with Google Earth we were not able to collect much quantitative data. This limited the predictions we could make about future changes in the area.

A second limitation to our project was due to the COVID-19 pandemic, which restricted us from traveling to Puerto Rico. Without being able to travel there we were limited in our interactions with local communities. This impacted our project because we wanted to personally survey community members about their observations living nearby and using La Plata Reservoir. To substitute, we shared survey questions with the land managers and had them talk to a few people. However, we did not receive as much information as we wanted and were not able to clarify points or follow up with the people surveyed due to lack of access and language barriers. Also because we were not able to be there in person, we could not survey the current landscape ourselves. Thus most of our conclusions about land change were based on general observations from images that were available on Google Earth Pro, and at the time of the project there were no images after July 2020.

Management Recommendations

Based on our observations we have recommendations for managers of La Plata. Currently all the notations we made in Google Earth are compiled into one file. These observations can be updated by reopening the file in Google Earth and comparing more recent photos to our observations. We recommend that the file be looked at and updated every 3-6 months depending on the availability of images. The file can also be used to mark new areas of development observed by the managers of La Plata Nature Refuge. These new pins could be added to the observation list moving forward. We have also left pins on the Google Earth file where development occurred in the past, which should be looked at periodically to see if development has continued or is complete.

The timeline of events created in Prezi, can also be updated. This would be more effective to do at the end of a year to note all the events and impacts from them that have occurred. This would allow long term impacts to be taken into account as well as short term impacts. Finally, we recommend that another student team or other group continue this project and transfer data to ArcGIS to create predictive models for future climate change and weather events.

Steps for a Future Project

Due to time and location constraints we recommend this project be continuously added to and further developed in a second stage. The second stage of this project includes predictive modeling based on quantitative measurements of our observed changes. To complete Stage 2, data must be collected by measuring differences in water level outlines in our Google Earth file (Chaaban et al., 2012). This will aid in measuring detailed patterns of change that have occurred and been recognized in our project as presented throughout this report(Stage 1) (Boulila et al., 2011). An organized chart of Stage 1 and 2 is shown in Figure 35.

Predictive modeling can be completed with GIS Matrix Modeling (GMM) (Jiménez-Perálvarez et al., 2008), a process that involves: taking inventory of land and development changes observed in satellite imagery over time. Our inventory was completed in Google Earth Pro. Additional satellite imagery could be included based on sources noted in SM-G; these images would fill in gaps and add detail. Additional inventory can be taken in the form of field surveying of the La Plata Refuge and Reservoir land (Jiménez-Perálvarez et al., 2008). A land survey was not completed due to travel restrictions at the time of project completion. We would recommend looking into land surveys for specific areas of change that we have observed.

To formulate a predictive model, necessary features could include but are not limited to waterways and land use. Waterways can include rivers, reservoirs and streams that are located in the La Plata Watershed. Land use can include vegetation change or cover and development of roads and urbanization. Remote sensing could be used to measure vegetation cover, although such technology

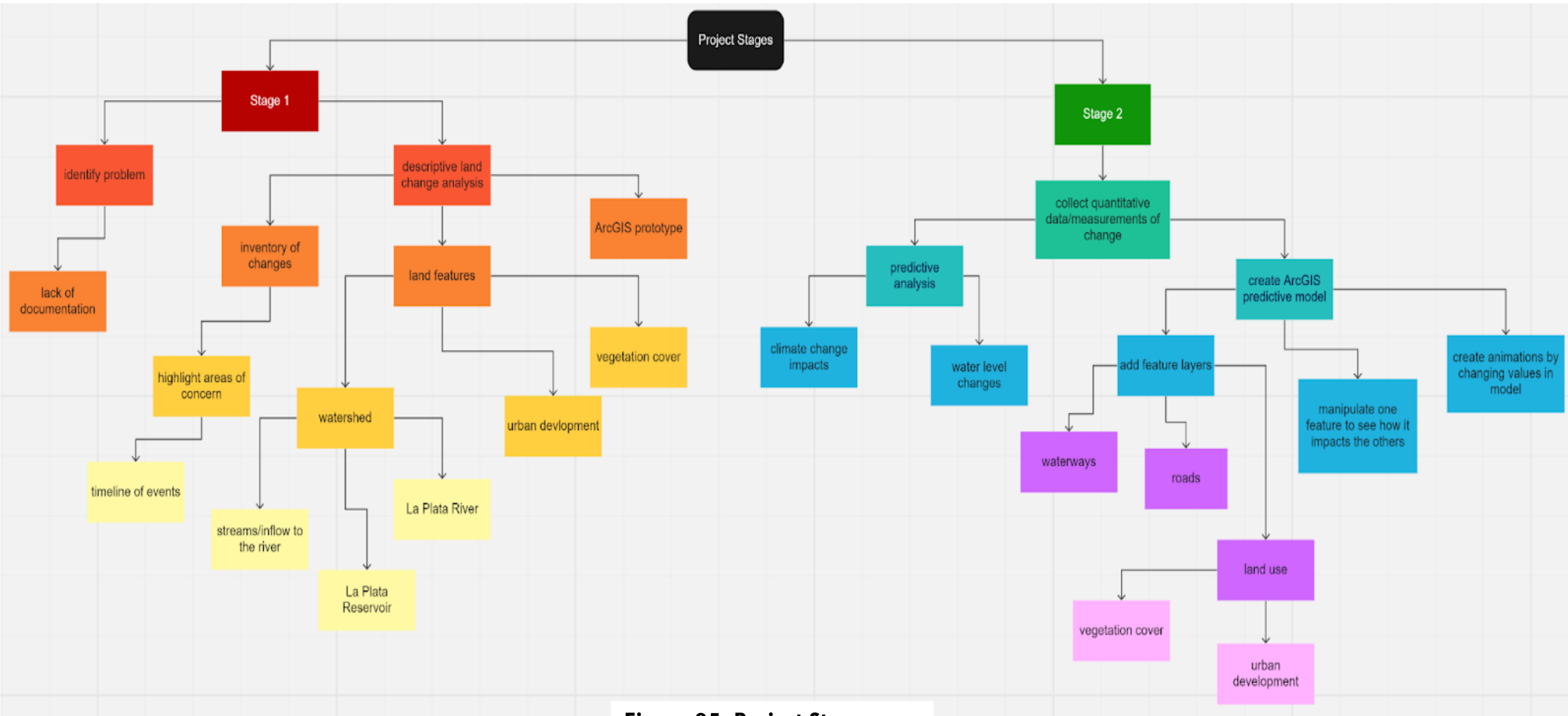


Figure 35. Project Stages.

may not be available as it is quite expensive. Features in waterways and land use are valuable to understand the changes occurring in the region. Additional features in the form of quantitative data, geographic coordinates or other measurements could be included in the model as layers of population density, soil type, and ecosystem changes to further predict future change in the area. In order to continue the GMM process, significant factors to land change as identified in Stage 1 (Table 1) must be assigned values and developed into a matrix in relation to the features listed above (Jiménez-Perálvarez et al., 2008). A basic set of features have been added to a prototype ArcGIS[4] file also linked in SM-I.

During Stage 1 there was a limited amount of time to produce a valuable and quality product in ArcGIS. We recommend starting with our prototype and adding additional feature layers as described above. Next, measurements can be digitized based on Stage 1 observations of waterline paths or manually taken in Google Earth Pro using the measurement tool (Chaaban et al., 2012). Additionally, due to time constraints we were unable to fully develop ArcGIS skills and recommend that predictive modeling be done with the ArcGIS Pro Model Builder tool (Jiménez-Perálvarez et al., 2008). Understanding ArcGIS can be complex and time consuming, but we recommend exploring it as an option to track changes and predict future changes. Data tables can be used in ArcGIS with measurements of changes over time in relation to features and climate change observations. To predict future changes to the landscape run a descriptive model in ArcGIS over and over with different values in varying sets of feature layers. We recommend turning off certain feature layers at a time to run animations and observe changes to that specific feature layer in the future. Changes in one feature layer could also impact features in other periods of time. Additional details are provided in SM-I.

Recommendations made here are meant to further develop this project to aid DNER in their mission of conservation and protection of land.

Conclusion

The goal for this project was to assess overall landscape change at the La Plata Nature Refuge and the greater watershed area to inform future management plans of the area. By focusing on specific severe weather and disaster events from 2003-2020 and by comparing satellite imagery, we were able to pinpoint patterns of land change. This process allowed our team to provide the DNER with documentation of several short- and long-term changes that have occurred over the La Plata region. We also provided an accessible method for continuation of documentation for future changes that will occur in the area. Due to a limited time frame our team was given for this project, we were unable to create a predictive ArcGIS model. To continue this project, we suggest a future team use the data collection methods we have provided with the basis of our prototype ArcGIS file to create a fully predictive model. This model would include specific measurements of land change and outline possible future change of the La Plata Refuge and Watershed.

[4] https://arcg.is/CK4P00

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PHOTO CREDITS

Sr. Rafael A. Rodriguez Santiago, Assistant Biologist for Department of Natural and Environmental Resources (DNER) at La Plata Reservoir Refuge (pg. 28 and 30)

National Guard, aerial photos (pg. 30)