Assessing the Lifespans of Reservoirs in Region 2 of Puerto Rico

May 5, 2011

Report Submitted to

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Abstract

This project, sponsored by the Conservation Trust of Puerto Rico, provides a set of recommendations for reducing the frequency of dredging of reservoirs in Puerto Rico. It combines data from sedimentation surveys, water-use data reports, census reports and interviews to form a more complete understanding of the lifespans of freshwater reservoirs. Using ArcGIS and Microsoft Excel software, maps and graphs were created to visually represent the data for the four major reservoirs included in our study. Based on past studies and statistical data, recommendations were made to control upland erosion in the feeding streams of reservoirs.

Acknowledgements

We would like to thank our sponsor, Sr. Juan Rodríguez Hernández for allowing us the great opportunity to work with the Conservation Trust of Puerto Rico. We would also like to thank other employees of the Conservation Trust of Puerto Rico who helped us in our project. These employees are: Glorimar Toledo, Omar Monzón, Frank Cosme, Nancy Beck, Miriam O'Neill, Ray Ramírez and Elizabeth Padilla.

We would like to thank numerous workers for their time and assistance in our project. They assisted us by allowing us to interview them or providing us with data that we used in the report. These people that helped us are Laura Medrano, Pedro Diaz, Wanda Molina, Francisco Maldonado, Joel Mercado, Luis R. Soler-López, Matthew C. Larsen, Gregory L. Morris, Ariel E. Lugo, and Gisel Reyes.

For their guidance on our project we would like to thank our advisors and professors that assisted with our project experience. Thank you to Professors Svetlana Nikitina, Reinhold Ludwig, Creighton Peet and Susan Vernon-Gerstenfeld.

For their additional help and assistance in our experience in Puerto Rico we would like to thank Beatriz Arsuaga and all of the IGSD staff at WPI.

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Executive Summary

The Conservation Trust of Puerto Rico sponsored our project to assess the lifespans of the reservoirs in Puerto Rico and to provide recommendations to reduce sedimentation in those reservoirs. In Puerto Rico, sedimentation and population growth reduce the availability of freshwater from reservoirs. Companies such as the Puerto Rico Aqueduct and Sewer Authority (PRASA) intervene to increase storage capacity with dredging, but alternative, sustainable solutions need to be implemented. To find a viable solution, our group analyzed population data, freshwater withdrawal rates, sedimentation surveys and land use in watersheds.

We collected population data and freshwater withdrawal rates for Puerto Rico. By determining the relevance of population to withdrawal rates, we were able to better understand what the withdrawal rates of freshwater will be in the future. Using graphs and tables, we found correlations between the datasets from 1985-2005. The withdrawal rates of freshwater from reservoirs increased over this twenty year period as the population increased. The dependence of the island on surface water increased as well, while ground water use decreased. These findings showed that the reliance on freshwater reservoirs on the island will increase. In order to understand the lifespans of the reservoirs in context with these data, we looked into sedimentation rates in the reservoirs.

Sedimentation is a growing problem in the reservoirs of Puerto Rico because it reduces storage capacities. This reduction of storage capacities decreases the availability of freshwater. Experts in the Conservation Trust of Puerto Rico and the United States Geological Survey (USGS) recommended reservoirs in Puerto Rico for us to investigate, so we found sedimentation surveys done by the USGS on these reservoirs. By assessing the sedimentation surveys in each reservoir, we were able to determine their lifespans. Our results showed that Lago Loíza and Lago La Plata have short lifespans, while Lago de

Cidra and Lago Carite will not fill with sediment for a long time. To determine why the sedimentation rates of the reservoirs are what they are, we analyzed the land use in the watersheds of the reservoirs.

Land use is the way in which the land of an area is used, e.g. pasture, forest or developed land. Different land uses yield different amounts of sediment into a stream or reservoir, so by knowing the land use in the watershed of a feeding stream to a reservoir we can provide better, more specific recommendations. Using aerial photography provided to us by the International Institute of Tropical Forestry (IITF) and ArcGIS software we determined land use of Río Grande de Loíza. Based on these data, we found the most problematic regions along the river. Using these problem areas, we were able to determine a solution based on the land use of the area.

In order to find the most appropriate solution to sedimentation in Puerto Rico, we looked at many possible solutions. After analysis, we decided that reforestation in the riparian zone, the area immediately next to a stream, was the best method to use. The Conservation Trust has a reforestation program, so, in conjunction with this program, sedimentation can be reduced in the reservoirs of Puerto Rico.

Our recommendations included three different solutions based on the land use and sedimentation rates of an area. If the land use is a pasture with low sedimentation rates, our recommendation is to put up a fence 150 ft. from the stream and allow the forest to naturally reestablish itself. If the land use is a pasture or developed area with a moderate sedimentation rate, our recommendation is to put up a fence 150 ft. from the stream and plant grass in the area between the stream and the fence. If the land use is a developed area such as a construction site where the sedimentation rate is severe, we recommend putting a fence 150 ft. from the stream, planting grass and planting exotic trees. In the future our report can be used as a reference for people who wish to expand this research to all of Puerto Rico or other parts of the world.

Chapter 1: Introduction

Clean water is critical for both sustainable living and development. The availability of it is becoming an increasing problem worldwide. In the 20^{th} century the population of the world tripled and the demand for water resources jumped six-fold (World Water Council, 2010). Metropolitan areas are most significantly affected by the limited availability of water resources due to their dense population and thriving industries. As population and industry continue to grow, the amount of freshwater required to sustain these areas increases. Sedimentation also greatly contributes to the limiting availability of freshwater. Approximately 25% of the total global sediment, which is supposed to empty into the ocean, actually ends up settling and blocking 45,000 large dams constructed around the world (Takeuchi, 2004). Sedimentation significantly reduces storage capacities of water sources and, combined with urbanization and industrialization, drastically limits the lifespans of the reservoirs. With only about 1% of the Earth's water being fresh surface water (Daniels & Daniels, 2003, p. 69), it is important to protect all natural freshwater sources. This is especially true on islands where freshwater resources are limited.

In Puerto Rico, the large population and the industrial-based economy depend heavily on the availability of freshwater; thus, any disturbances in the water supply system can negatively impact the island. Industrialization began in the 1940s, causing an urbanization movement in which rural areas were abandoned and the cities expanded. As a result of this rapid expansion, the water distribution infrastructure became insufficient for future supply. The industrialization also brought about poor wastewater disposal practices, resulting in the pollution of the water supply. The consequence of this was the closing of a number of wells, which subsequently increased the island's reliance upon surface freshwater reservoirs. Furthermore, hurricanes and deforestation have decreased the storage capacity of water reservoirs by increasing the rate of sedimentation.

The Puerto Rico Aqueduct and Sewer Authority (PRASA), the main supplier of potable water in Puerto Rico, has addressed some of the problems associated with the freshwater resources on the island. In an attempt to increase the storage capacity of San Juan's primary water resource, Lago Loíza was dredged by PRASA in 1997-1998 (Soler-López & Gómez-Gómez, 2005). Also, as a result of being cited by the U.S. Environmental Protection Agency, PRASA has begun a $195 million project to renovate piping and treatment systems in Puerto Rico (Emerson, 2011, para. 4). Despite these attempts at finding a solution to the freshwater problems facing Puerto Rico, the lifespans of the water resources will be limited until a more permanent solution is found. Although studies have been done on the sedimentation rates in Puerto Rico, there has yet to be research combining freshwater withdrawal rates, population trends and sedimentation data to accurately assess the current and future health of reservoirs.

The goal of our project was to assess the lifespans of reservoirs in Puerto Rico and to provide recommendations on how to reduce sedimentation in those reservoirs. Our team researched the four major suppliers of potable water in Region 2: Lago Loíza, Lago La Plata, Lago de Cidra and Lago Carite. These reservoirs were chosen by the Conservation Trust of Puerto Rico due to the lack of prior knowledge of freshwater resources in the area. In order to achieve this goal, we completed four main objectives. The first objective was to collect population data and freshwater withdrawal rates for Puerto Rico to establish a correlation between the two. The next objective was to analyze sedimentation surveys to determine the lifespans of major reservoirs. The third objective was to evaluate the land use in riparian zones of relevant watersheds by identifying the land development of the areas. The final objective was to determine the methods used to reduce sedimentation in reservoirs in an effort to lessen the frequency of dredging. Upon the completion of the four objectives, informed solutions were proposed for the watersheds under study. If our solutions are implemented, sedimentation should be reduced in the reservoirs of Puerto Rico, therefore increasing the availability of freshwater for the Puerto Rican people.

Chapter 2: Background

The following chapter contains background information, gathered from various sources, that directly relates to the current project. It presents explanations regarding the geography of Puerto Rico and Region 2, the hydrological cycle and the function of watersheds. It talks about the main supplier of freshwater to the island and the collection of water-use data to stress the necessity of this project. It also provides a recent history of the economy in Puerto Rico and how it has affected the population distribution, along with land use. Additionally, this section introduces the current problems with watershed management in Puerto Rico and the four reservoirs under study.

2.1 Geography of Puerto Rico

The Caribbean island of Puerto Rico is located east of the Dominican Republic and west of the U.S. and U.K. Virgin Islands. The geographic coordinates of Puerto Rico are 18° 15’ N latitude and 66° 30’ W longitude (Rivera, 2011a, para. 3). On the north side of the island is the North Atlantic Ocean, while the Caribbean Sea is on the south side. The total area of the island is 9,104 square kilometers.

The island has a mild tropical marine climate (Rivera, 2011b, para. 24). With an average temperature of 82 °F, there is little seasonal temperature variation (Figueroa, 2011a, para. 1). The dry season is from November to May, and the rainy season is from June to November.

Puerto Rico has three main physiographic areas: the central interior mountain ranges, the northern karst area and the coastal plains (Figueroa, 2011b, para. 4). The hydrology of the island consists of ground water and surface water resources that are supplied by heavy rainfall over the mountainous interior of the island and receptive, sedimentary rocks around the island's periphery (Zack & Larsen, 1994). The porous rocks on the periphery of the island form a large aquifer system. The island does not have any naturally large lakes, but does have man-made reservoirs. These reservoirs are located on principal water courses to collect runoff and are used for water supply, flood control, and limited hydroelectric power generation (Zack & Larsen, 1994).

The availability of freshwater resources is a problem on islands due to their unique geography, population growth and urban development. Puerto Rico is not an exception to this problem. Although rainfall supplies an abundance of freshwater to the island, the reservoirs and water distribution systems lack adequacy. These reservoirs are increasingly filling with sediment. The heavy rainfall directly affects the rate of sedimentation in the reservoirs by triggering landslides and causing erosion. These rainfall-triggered landslides are the most common type in the central interior mountain ranges of Puerto Rico.

The location and geography of the island of Puerto Rico affect the hydrology and the freshwater resources available to the inhabitants. It is important to understand the overall geography of the island to further identify the causes of the problems in the freshwater supply.

2.1.1 Defining Region 2 in Puerto Rico

The United States Geological Survey (USGS) has divided the island of Puerto Rico into five main watershed regions (U.S. Geological Survey, 2011a). Using the USGS region borders as a reference, the Conservation Trust of Puerto Rico has created their own five regions of the island. Although the regions

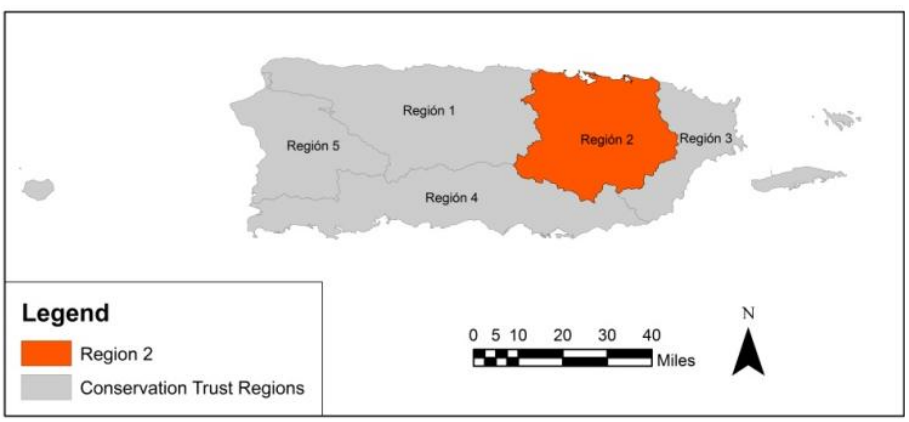


Figure 1: The Conservation Trust of Puerto Rico Regions

(Adapted from the Conservation Trust of Puerto Rico Database, 2011) share some borders, they are not identical. The new boundaries were created due to logistical reasons of operating sites that are owned by the Trust in different parts of Puerto Rico.

This report will concentrate on Region 2, as defined by the Conservation Trust of Puerto Rico, highlighted in Figure 1. This region contains five major water reservoirs and 23 municipalities. The complete list of the municipalities can be found in Table 1. This region was chosen for us by the Conservation Trust of Puerto Rico due to the lack of prior research on the reservoirs in this area. Four of the five major reservoirs in Region 2 are analyzed in this report. The four reservoirs under study are: Lago Loíza, Lago La Plata, Lago de Cidra and Lago Carite. The lifespans of these reservoirs were assessed in order to provide recommendations to reduce sedimentation, which is the main problem that freshwater resources are facing in Puerto Rico.

Table 1: Region 2 Municipalities (Adapted from the Conservation Trust of Puerto Rico Database, 2011)

Aguas Buenas	Carolina	Guayama	San Juan
Aibonito	Cataño	Guaynabo	San Lorenzo
Barranquitas	Cayey	Gurabo	Toa Alta
Bayamón	Cidra	Juncos	Toa Baja
Caguas	Comerío	Loíza	Trujillo Alto
Canóvanas	Dorado	Naranjito	

Region 2 borders were selected according to major watersheds and not by municipal borders. This resulted in a number of municipalities falling under more than one region, as seen in Figure 2.

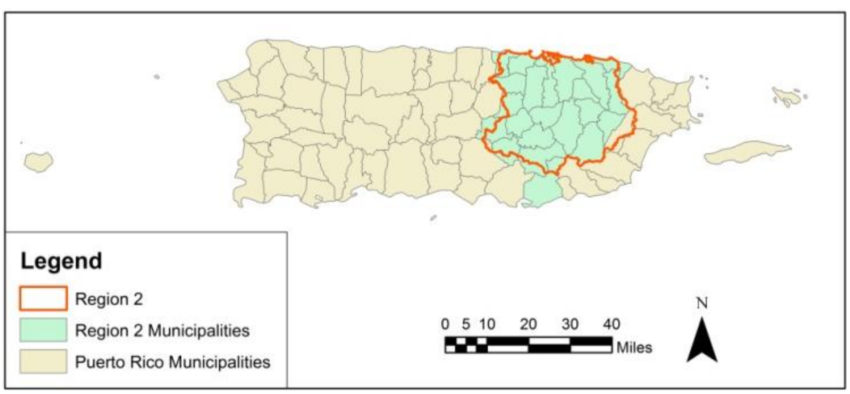


Figure 2: Comparison of Region 2 and Region 2 Municipality Borders

(Adapted from the Conservation Trust of Puerto Rico Database, 2011)

Therefore, when the municipalities of Region 2 are referred to in this report, they are the municipalities highlighted in blue in Figure 2. Any data analyzed from Region 2 municipalities include data from the entirety of each of the municipalities.

2.2 Hydrological Cycle

In order to make constructive recommendations to reduce sedimentation in reservoirs in Region 2 and assess their life expectancy, it is necessary to have a fundamental grasp of the hydrological cycle and the function of watersheds. Thoroughly understanding the hydrological cycle, the process of how reservoirs are formed, will aid in pinpointing the causes of sedimentation and the manner in which it is transported.

2.2.1 Watersheds and the Formation of Reservoirs

Much of what is considered hydrology revolves around the interactions of a watershed, typically defined as “the land area that drains into a particular river system, including its tributaries” (Daniels & Daniels, 2003, p. 69). The location and size of any given watershed is an important factor in an assessment of the quantity of water available to a region.

In watersheds, a portion of the water that comes from the rainfall enters streams and rivers as runoff; the remaining water from precipitation is either absorbed by plants or seeps through the ground and becomes ground water. The rivers that absorb the runoff usually flow into a larger body of water, in the United States it is typically an ocean, creating large basin sites (Daniels & Daniels, 2003, p. 69).

Hills and mountain ridges define the boundaries of a watershed, while the soil composition and slope affect how much water seeps into the ground and the speed of the runoff. Soils with higher clay content or steeper slopes have faster runoff and increase the potential for erosion and flooding. Another factor is the amount of land covered by vegetation. Shrubs and grasses tend to hold soil in place and absorb small quantities of water, while larger trees with expansive root systems absorb large quantities of both rainwater and runoff (Daniels & Daniels, 2003, p. 70).

The amount of surface water available to a region could be significantly higher than the surface runoff within the local watershed. Local ground water sources can actually add to and increase surface water, providing a buffer during dry periods or even droughts. Local bodies of water act as reservoirs and can replenish ground water aquifers (Daniels & Daniels, 2003, p. 71). Areas considered wetlands- swamps, marshes and bogs- are particularly efficient at replenishing ground water. These areas can also collect a certain amount of runoff water during relatively dry seasons.

Puerto Rico withdraws most of its water from surface water sources, which supply its potable drinking water, irrigation systems, and industrial uses. The formation of surface water sources and the transport of sediment can both be explained by the hydrological cycle. Understanding this will help us distinguish the major causes of sedimentation and the manner in which it is transported.

2.2.2 Lifespan of Reservoirs

Surface water sources in Puerto Rico, specifically reservoirs, develop from major feeding water streams. The sources collect water runoff from the precipitation, occurring off of the watersheds. Dams regulate and control the flow of water, forming reservoirs (Morris & Fan, 1998, p. 3.5). Reservoirs are designed to operate for a finite amount of time but often their lifespans are reduced by sedimentation (p. 2.13). Design life is "the planning period used for designing the reservoir project" (p. 2.13). The design life of these projects is usually based on 50 years or 100 years. Despite the design life, reservoirs realistically have a project life defined as the "period during which the reservoir can reliably serve the purposes it was originally constructed" (p. 2.13). The reaching of project life, the failure to meet design needs, occurs typically before half of the storage volume of the reservoir is reduced from sedimentation (p. 2.13). The storage capacity, or reservoir yield, is expressed "as a function of available storage volume in the conservation pool" (p. 3.19). The capacity in-flow ratio is "the ratio of total reservoir volume to mean annual inflow" (p. 3.6). The capacity in-flow ratio is a better indicator of the actual volume of water in regards to managing sedimentation deposits in a reservoir.

The trapping efficiency and sediment yield are useful indicators to determine the lifespan of a reservoir. These two descriptors provide vital information to the potential amount of sedimentation that could accumulate. Sediment yield is the "amount of eroded sediment discharged by a stream at any given point" (Morris & Fan, 1998, p. 6.2). Trapping efficiency is expressed as a ratio that describes the mean annual sediment yield that is deposited or trapped in a reservoir (Soler-López & Gómez-Gómez, 2005, p. 22).

2.2.3 Summary

With only about 1% of water on Earth being fresh surface water (Daniels & Daniels, 2003, p. 69), it is important in any water assessment efforts to determine the quantity of water available to a community or region. In Puerto Rico approximately 70% of the water used is from surface water systems (Zack & Larsen, 1994). The municipalities of Region 2 depend heavily on reservoirs for their public and industrial demands. The investigation of the many steps in the hydrological cycle will guide us to solutions to reducing high sedimentation rates.

2.3 Water Infrastructure Issues and Freshwater Management in Puerto Rico

Puerto Rico's water distribution system is considered among the most complex in the world. In order to have a better grasp of water management on the island, it is important to have knowledge regarding the conditions of potable water infrastructure. The following sections provide information about the Puerto Rico Aqueduct and Sewer Authority, the main provider of potable water in Puerto Rico, and the problems that have plagued the water infrastructure system for years. They also touch upon the methods which are used to monitor and calculate water-use on the island. Studying the health of the freshwater infrastructure and analyzing water-use data is necessary in order to assess and solve the problems of the freshwater supply.

2.3.1 Puerto Rico Aqueduct and Sewer Authority

The Puerto Rico Aqueduct and Sewer Authority (PRASA), which is also known as Autoridad de Acueductos y Alcantarillados (AAA), is the primary supplier and distributor of potable water in Puerto Rico (Autoridad de Acueductos y Alcantarillados, 2011). It provides potable water to approximately 98% of residents of Puerto Rico, which includes residents of the islands of Vieques and Culebra. It operates a network of 130 filtration plants, 328 wells, over 7700 miles of pipes, 1679 water storage tanks, as well as thousands of pump stations throughout its water distribution system. PRASA also operates 60 wastewater treatment plants which serve 55% of the total population. These plants process an average of 308 million gallons of wastewater on a daily basis.

The mission of the Puerto Rico Aqueduct and Sewer Authority is to “ensure that Puerto Rico has a system of water supply and sewage to promote a healthy quality of life and a strong economy for present and future generations” (Autoridad de Acueductos y Alcantarillados, 2011). In order to achieve its goal, PRASA implements methods of preventive maintenance, modernization of technologies, and replacement of leaky pipes along with watershed protection of management of aquifers.

The Puerto Rico Aqueduct and Sewer Authority is the main user of surface freshwater resources on the island and thus has a great affect on water reservoirs. The health of water reservoirs can be jeopardized due to PRASA’s poor water infrastructure system.

2.3.2 Water Infrastructure and its Effects on Freshwater Resources

Due to rapid expansion in urban areas, newly placed pipes throughout Puerto Rico were quickly rendered obsolete due to their small diameters. The Condado beach sewers in San Juan metropolitan area were built in 1995, prior to the construction of hotels and resorts along the beach (Hunter &

Arbona, 1995). This resulted in an overload of the sewage system and by 1995 the recreational use of the beach was bacteriologically hazardous. The article “Paradise Lost: An Introduction to the Geography of Water Pollution in Puerto Rico” (Hunter & Arbona, 1995) points out that rapid urbanization, along with industrialization, in the 1980s were responsible for the lag of Puerto Rico’s water and sewage infrastructures.

There are also a number of issues with the freshwater distribution system on the island. In 1987, 391 million gallons of freshwater were withdrawn from public-supply sources, yet only 221 million gallons were delivered to consumers. This shows that there was a 43% loss of water in the distribution system. According to the U.S. Geological Survey, loss of water in the distribution system is considered to be unaccounted use and includes losses due to “system distribution leaks, illegal connections, and accounting errors” (Molina-Rivera, 1998, p. 7). Throughout the years, water loss in the distribution system remained fairly constant at 41% in 1960, 43% in 1987, and 42% in 1995 (Hunter & Arbona, 1995; Molina-Rivera, 1998).

Due to outdated potable water infrastructure in Puerto Rico, the Puerto Rico Aqueduct and Sewer Authority has been cited for numerous violations. PRASA had to pay large settlement sums, make costly upgrades to its facilities, and perform remedial work on a number of lakes throughout recent decades (Hunter & Arbona, 1995; U.S. Department of Justice, 2010).

In February 2002, U.S. Justice Department charged the Puerto Rico Aqueduct and Sewer Authority for discharging raw sewage into waters from 471 pumps throughout Puerto Rico (Environmental Protection Agency, 2011). These discharges were found to pose threats to human health and Puerto Rico’s environment. As a result, On March 19th, 2003, the U.S. Justice Department and the Environmental Protection Agency announced a settlement in which PRASA had to take remedial action in order to eliminate noncompliance at 185 sewage pump stations.

In a press release on June 6th, 2006, the Environmental Protection Agency (2006) announced that the Puerto Rico Aqueduct and Sewer Authority pled guilty to an indictment charging 15 felony counts of violating the federal Water Act. The charges were brought up due to illegal discharge of pollutants from five drinking water treatment plants along with nine sanitary wastewater treatment plants. Under the plea agreement, PRASA was forced to pay a criminal fine of $9 million. Also, as part of the civil settlement, PRASA promised to implement a number of capital improvements over a 15-year period. These improvement projects were estimated at $1.7 billion and included remedial work at 61 wastewater treatment plants.

On May 4th, 2010, Office of Public Affairs of the Department of Justice released an article stating that PRASA had been alleged in a number of violations of not only the Clean Water Act (CWA), but also the Safe Drinking Water Act and three others (U.S. Department of Justice, 2010). In particular, PRASA was charged for discharge of harmful pollutants from 126 drinking water treatment plants into lakes, rivers, and streams that are used as sources for potable water. As a result of these charges, PRASA had to pay a $1.02 million civil penalty along with $2.5 million to improve water quality in lakes Toa Vaca or Lake Cidra by addressing the growing amount of nutrients in those lakes. In order to bring its drinking water treatment plants to compliance with the EPA's standards, PRASA is estimated to pay upwards of $195 million for the remedial work in the next 15 years.

Unaccounted loss in the water distribution system can put great stress on freshwater resources. Freshwater delivery system leaks result in great amounts of water being wasted. During recent decades, poor condition of the freshwater infrastructure system in Puerto Rico has resulted in a number of discharges of pollutants into rivers and reservoirs, which caused harm to the environment along with the water supply. Understanding current issues with the water infrastructure system can help us better assess the lifespans of freshwater reservoirs. This can be done by identifying the freshwater withdrawal rates from a number of reservoirs and by analyzing these data to determine withdrawal rate trends over time.

2.3.3 The Importance of Water-Use Data Collection

The analysis of water-use data for Puerto Rico is necessary to assess the freshwater problems the island encounters. “One of the major challenges that water managers confront is the need to provide sufficient freshwater availability” especially in the densely populated areas (Molina-Rivera, 2008, p. 1). The National Water-Use Information Program of the United States Geological Survey (USGS) “is a Federal-State Cooperative Program designed to compile, store and disseminate water-use information locally and nationwide” (Molina-Rivera, 1998, p. 1). The USGS has compiled data in the United States at 5-year intervals since 1950 on the amount of water used by homes, businesses and farms. They have also described how that use changed with time. The program began operation in Puerto Rico in 1980. Creating a database of this information is important for assessing many of the critical water problems facing Puerto Rico. To create this database, the USGS collects water-use data from the Puerto Rico Aqueduct and Sewer Authority (PRASA), the Puerto Rico Department of Natural and Environmental Resources (PRDNER), the Puerto Rico Department of Health (PRDOH), the Puerto Rico Electric and Power Authority (PREPA) and the Puerto Rico Environmental Quality Board (PREQB). The USGS also obtains data from the U.S. Census Bureau and the U.S. Mine Safety and Health Administration (MSHA). Water-use data are provided for the 78 municipalities of Puerto Rico.

The USGS also provides the total population served of each municipality and the total population served by the public-supply water systems. The population served by the public-supply systems is also broken down by the population served by the public-supply ground water and public-supply surface water. The USGS collects the population data from the U.S. Census Bureau.

The water-use data are subdivided into offstream and instream uses (Torres-Sierra & Avilés, 1986, p. 4). “Offstream use is the freshwater diverted or withdrawn from a surface-water or groundwater source and conveyed to the place of use" (Molina-Rivera, 2008, p. 1). This is opposed to instream use which is defined as "water that is used, but not withdrawn, from ground or surface- water sources for such purposes as thermoelectric-saline withdrawal and hydroelectric power" (Molina-Rivera, 2008, p. 1).

Three factors are considered when determining the amount of water used: withdrawals, deliver/release, and return flow (Torres-Sierra & Avilés, 1986, p. 4). Withdrawals are the amount of water that is withdrawn or diverted from a ground or surface water source. Deliver/release is the amount of water that is delivered at the point of use and the amount that is released after use. The difference between these amounts will sometimes be considered the consumptive use, which is no longer available for subsequent use. Return flow is the amount of water that reaches the ground or surface water source after it is released from the point of use. The return flow then becomes available for further use.

The offstream water-use data are subdivided into five categories: public-supply water withdrawals, domestic self-supplied water-use, industrial self-supplied withdrawals, agricultural water-use, and thermoelectric power freshwater use. Two additional categories are analyzed: power generation instream use and public wastewater treatment return flows. The data include fresh and saline water as well as ground and surface water.

This report will focus on the offstream water-use data; specifically, freshwater withdrawal rates from the public-supply and self-supply uses will be analyzed. The data will be analyzed for the whole island and also for the 23 municipalities in Region 2.

The public-supply water withdrawal use is defined by the USGS as "water withdrawn by public and private suppliers that furnish water for at least 25 people, or have a minimum of 15 service connections" (Molina-Rivera, 2005, p. 1). Although PRASA is the main public supplier of water, there are other public-supply systems as well. The USGS labels these as Non-PRASA public suppliers. Non-PRASA systems refer to community-operated water systems, those which serve a rural or suburban housing area (Molina-Rivera, 2008, p. 1). The USGS receives the water-use data of other public suppliers through the Puerto Rico Department of Health. Some of the water-use data files show the public-supply separated by PRASA and Non-PRASA public-supply, but this report will combine the two and will furthermore refer to it as public-supply water.

Self-supply water is defined as “water withdrawn from a surface- or ground water source by a user rather than being obtained from a public supply” (Molina-Rivera, 1998, p. 14). The self-supplied water-use includes the domestic, industrial, agricultural, and thermoelectric power use on the island. The unaccounted water-use is also included in some of the USGS data. Thermoelectric power use is not considered because the saline-water withdrawal is considered an instream use (Molina-Rivera, 2008, p. 1). Definitions of these terms can be found in the Glossary in Appendix B.

2.3.4 Summary

The Puerto Rico Aqueduct and Sewer Authority operates a complex network of treatment plants and water distribution systems. It currently provides potable water to 98% of Puerto Rico’s population. Due to rapid industrialization and urbanization in the recent decades, maintenance and upgrades to water and sewage infrastructures have lagged behind. This resulted in pollutant discharges into lakes and streams which negatively impact surrounding ecosystems and cause harm to human health. PRASA has been cited for numerous violations of the Clean Water Act and, as a result, has made costly upgrades to its facilities and performed remedial work on a number of lakes.

Water-use data in Puerto Rico are monitored by The National Water-Use Information Program of the U.S. Geological Survey. It began its operation in Puerto Rico in 1980 and has since compiled water-use data at 5-year intervals. Water-use data are collected from a number of agencies, such as Puerto Rico Aqueduct and Sewer Authority, the Puerto Rico Department of Natural and Environmental Resources, the Puerto Rico Environmental Quality Board, and others. Analyzing the water-use data for

Puerto Rico is necessary to assess and recommend solutions to the freshwater problems the island encounters.

2.4 The Economic Shift in Puerto Rico and its Influence on the Watersheds

Puerto Rico had a mainly agricultural-based economy until the 1940s. In the 1940s, the government decided to transform the reputation of the island from underdeveloped to developed. This transformation decreased the amount of agriculture on the island and increased the industry with manufacturing and tourism. Due to this economic change from 1940 to 2010, there has been a tremendous change in the residential and working population distribution.

The changes in the residential and working population distribution changed the land use near the watersheds. Land use affects the sedimentation in reservoirs, and therefore plays an important role on the health of watersheds. The history of the economic development of the island helps us to identify the changes in land use. This information will aid us in understanding the impact the land use has had on the health of the watersheds over the years.

2.4.1 Economic Shift Causes Industrial Growth in Puerto Rico, Straining Water Resources

Although the United States gained control of Puerto Rico in 1898, socioeconomic conditions remained unchanged until 1940 (Grau, Aide, Zimmerman, Thomlinson, Helmer, & Zou, 2003). Beginning around 1940, when Puerto Rico was a mainly agricultural island, the Puerto Rican government decided that an increase in industrialization was necessary for the island to be considered a more developed region (Rivera, 2010). The government first encouraged the lower classes of agricultural workers to migrate from the island to the mainland in the United States. Although these agricultural workers would have to pick up their lives and start a new life in the United States, the idea that they would be making more money and living a more successful life was incentive enough.

The Puerto Rican government also motivated potential industrial investors from the United States to bring their companies to the island. Their main incentives were tax exemptions and differential rental rates for industrial buildings (Rivera, 2010). These incentives to bring industry to Puerto Rico actually began in 1948 when Puerto Rico passed the Industrial Incentives Act of 1948, also known as Operation Bootstrap (Stathis, 1993). Under this act most of the United States' subsidiaries in Puerto Rico were either entirely or partially exempt from Puerto Rican taxes. In 1976, the U.S. Congress passed the Internal Revenue Code section 936. Section 936 exempted the United States' subsidiaries from U.S. income tax. The newly developed tax policies were quite beneficial to U.S. subsidiaries that located themselves in Puerto Rico because there were no minimum wage laws. Due to the lack of minimum wage requirements, the average tax benefits of some companies far exceeded the total wages paid to their employees. The low wages were certainly not beneficial to the Puerto Rican employees, however.

The fact was brought to the U.S. Congress' attention that United States companies were taking advantage of these tax exemptions. So Congress adjusted the section 936 provisions in the 1982 Tax Equity and Fiscal Responsibility Act and the 1986 Tax Reform Act (Stathis, 1993). These adjustments were made to reduce the amount of federal revenue loss. The main adjustment was the "tax treatment of income derived from intangible assets (such as patents, trademarks, and trade names) and passive investments" (Stathis, 1993, p. 3). The 1982 Act required that companies allocate some of their income earned in Puerto Rico from intangible assets to their U.S. parents. The 1986 Act required an even greater portion of their income be allocated to the parent company. These tax policies "have attracted considerable manufacturing industry to the island" (p. 3). So even after the acts from 1982 and 1986, the industry continued its growth on Puerto Rico.

As a result of this rapid industrial expansion, the water distribution infrastructure became insufficient for future supply. The use of freshwater quickly changed from agricultural purposes to industrial, which required a larger amount of freshwater. The industrialization also brought about poor wastewater disposal practices, resulting in the pollution of the water supply. The consequence of this was the closing of a number of wells, which subsequently increased the island's reliance upon surface freshwater reservoirs.

2.4.2 Economic Shift Changes Population Distribution in Puerto Rico, Straining Water Supply

The population in Puerto Rico has varied greatly over the past century due to economic development. Two factors that affect this variation are job opportunities and health conditions. "The shift toward an industrial and service-dominated economy in Puerto Rico has recently led to rapid urban expansion" (Helmer, 2004, p. 30).

Since the United States took over Puerto Rico in 1898, health conditions on the island began to improve, leading to a huge increase in population (Mathews, Wagenheim, & Wagenheim, 2011, para. 10). The improvement in health conditions created a decrease in the death rates, while the birth rates remained steady. Puerto Rican residents saw a "clear and present sense of development and progress" (Rodríguez, 1989, p. 3). Then, between the years of 1930 and 1950 there was heavy migration on the island from rural mountain regions to the urban areas. This was first influenced by the introduction of automobiles and the construction of highways and roads. These made the mode of transportation to and from the city much easier. The migration to the city led to the need for more housing and public services such as education, grocery stores, clothing stores, sewage systems and hospitals.

Between 1946 and 1964 there was a migration from Puerto Rico to the U.S. mainland called "The Great Migration" (Rodríguez, 1989, p. 3). This migration consisted of the lower class agricultural workers. In the 1950s there was an average of 45,000 Puerto Ricans who migrated to the U.S. annually (p. 6). All research has shown that the migrations from Puerto Rico to the United States were mostly influenced by job opportunities. Researchers have found that when national income increased and unemployment decreased in the United States, there was a larger migration of Puerto Ricans to the U.S. The average number of Puerto Ricans who migrated to the U.S. annually decreased from 45,000 in the

1950s to 20,000 in the 1960s (p. 6). Researchers say this is due to the increase in factory jobs on the island that Operation Bootstrap provided. Figure 3 illustrates the increasing population on the island of Puerto Rico between 1940 and 2010. The gradual increase in population from 1950 to 1960 was due to the decrease in migration to the U.S. because of the increase of factory jobs.

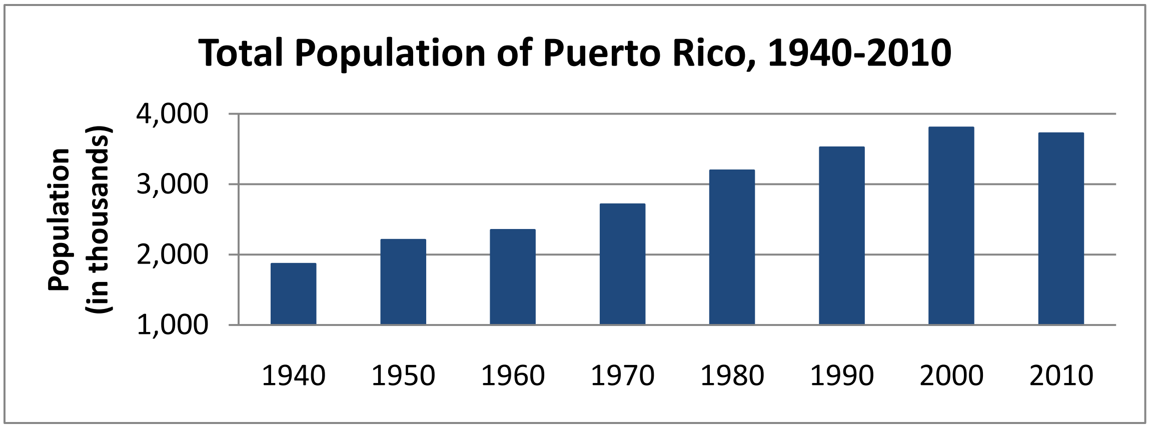


Figure 3: Total Population of Puerto Rico, 1940-2010

(Adapted from U.S. Census Bureau, 1940-2010)

As shown in Figure 3, there was a large population jump between the years of 1970 and 1980. The population jump in the 1970s was due to a recession in the United States, resulting in a migration of

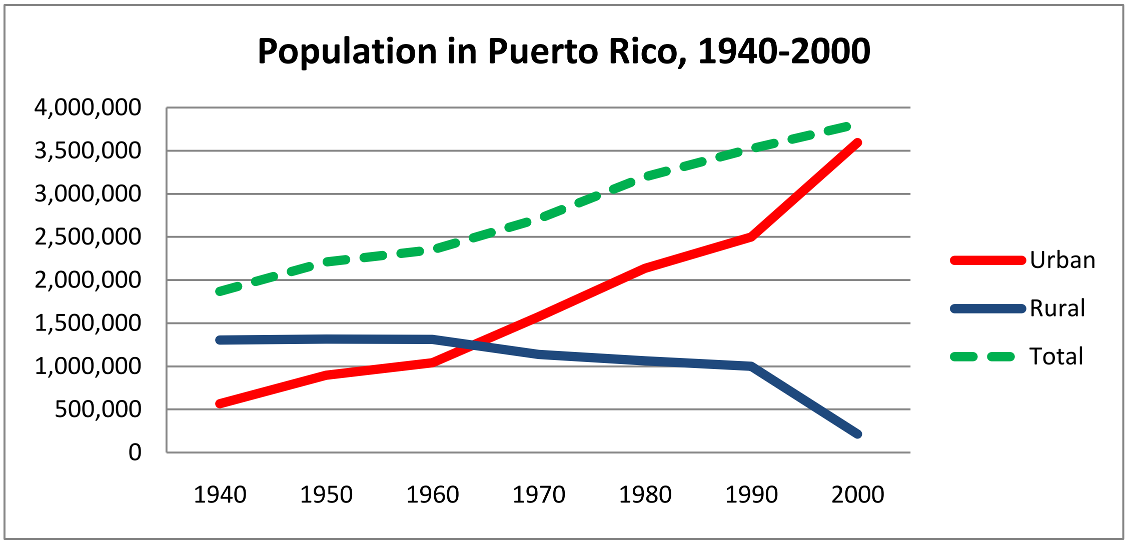


Figure 4: Population in Puerto Rico, 1940-2000

(Adapted from U.S. Census Bureau, 1940-2000)

Puerto Ricans back to the island (Rodríguez, 1989, p. 6). In 1980, 66.8% of Puerto Rico's population lived in urban areas (Lehman College, 2011). This is a huge increase from the 27.7% in 1930.

The graph in Figure 4 shows the total population of Puerto Rico and the comparison of the urban and rural population distribution from 1940 to 2000. The graph shows a large decrease in the rural population, and a large increase in the urban population over the 60 years. The increase in new job opportunities given by Operation Bootstrap not only caused a decrease in migration to the U.S., but caused an increase in migration from rural to urban areas on the island.

This shift in population distribution created a strain in the freshwater supply in the urban areas due to the density of the population.

2.4.3 The Economic Shift and its Effect on the Land Use and Health of the Watersheds

Land use change is intense in tropical developing areas characterized by economies based on agriculture and rapidly increasing human populations (Grau, Aide, Zimmerman, Thomlinson, Helmer, & Zou, 2003). This is particularly true on the island of Puerto Rico where migration from rural areas to urban areas and to continental urban areas in the United States has been encouraged by the economic shift from agricultural to industrial. Not only has the spatial distribution of the population changed, but the human population of the entire island has changed as well. These changes have affected the land use around the watersheds. The land use near watersheds directly affects the amount of sedimentation in a reservoir. Understanding these changes in land use is necessary for the sustainable management of affected reservoirs.

The changes in land use on the island, caused by the industrial and urban expansion, bring about many concerns. The main concern is over the loss of agricultural or forest lands and how the land use change impacts the environment. Our project deals specifically with how land use affects the water resources.

Due to emigration from rural to urban areas, and immigration to the United States mainland, widespread forest recovery has increased (Helmer, 2004). Emigration and immigration were not the only factors in the decrease of agricultural activities; the working population in the rural areas also decreased due to an increase in non-farm labor because of Operation Bootstrap (Grau, Aide, Zimmerman, Thomlinson, Helmer, & Zou, 2003). Most of the non-farm jobs were located in urban or suburban areas and the development of roads and transportation made it easier to work in those areas.

The agricultural lands have been abandoned due to the increase in non-farm jobs. Therefore, the land use changed from agriculture to grasslands and shrubbery over the past 50 years. In the late 1930s, about 90% of land on the island was some form of agriculture. In 2000, agriculture covered 3.1% of the land. Forest cover increased from about 6% in the late 1940s to about 40% in 2000. Forested areas on the island are increasing due the natural reestablishment of secondary forest in those shrub lands and grasslands (Parés-Ramos, Gould, & Aide, 2008). It appears that, while before 1940 there was a negative relationship between human population and forest cover, after 1940 the relationship became positive with economic and urban growth being accompanied by forest expansion (Grau, Aide, Zimmerman, Thomlinson, Helmer, & Zou, 2003).

Different types of land use around watersheds affects the sedimentation rates in the reservoirs. This is because land use determines the stability of the soil near the watersheds. If the soil is unstable there is more of a risk of sedimentation occurring in the watershed than if the soil were stable. It is important to understand these effects in order to provide recommendations regarding reducing sedimentation in the reservoirs.

2.5 Watershed Management

There are many factors that influence the sustainability of freshwater resources in Puerto Rico. The following section discusses these factors and possible solutions to the problems the reservoirs are currently facing.

2.5.1 Land Use and its Effect on Sedimentation in a Watershed

Land use plays a crucial role in the sedimentation rates of freshwater resources, both in and outside of the watershed (Gingold, 2007, p. 7). It can be broken down into different uses, specifically forest, pasture and urban/developed areas. The way the land is used affects sedimentation in two ways, the stability of the soil and the velocity of a stream carrying sediment.

The stability of the soil can affect sedimentation when there is precipitation, with the different land uses contributing different amounts of sediment. Forests provide the most soil stability because the roots of the vegetation in the watershed hold the soil together and prevent it from eroding (Aide, Lopez, & Scatena, 1998, p. 299). The vegetation also can stop sediment that is already being carried into the water by providing a barrier (Hall, Scatena, & Wu, 2007, p. 2955). However, pastures do not have the complex root system that forests have and can be affected by extreme precipitation, such as a hurricane. Urban areas are the least effective soil stability providers, and actually make the soil less stable during construction (Aide, Lopez, & Scatena, 1998, p. 304). Besides the soil that is directly underneath a structure, any soil in an urban area can be easily washed away by precipitation and end up in a water stream or reservoir.

The velocity of a stream can greatly affect the amount of sediment carried by the stream. Land use directly affects the velocity of a stream. If the area in a watershed has been converted for urban use, it can increase the stream velocity during precipitation because of increased runoff (Hall, Scatena, & Wu, 2007, p. 2955). The increased velocity also increases the amount of sediment that, instead of being deposited on the bottom of the stream, remains in the water. This sediment will eventually end up in a reservoir, or in the ocean, where it will most likely need to be removed in the future. The effects from forest and pasture areas on stream velocity are similar. Both keep the stream at its natural velocity by not significantly affecting runoff (Hall, Scatena, & Wu, 2007, p. 2955).

Economic value also plays a crucial role in determining land use, especially when viewed by the government or a business. Each type of land use has different economic uses, giving credibility to each one. Forests provide income from tourism and in the past encouraged people to conserve land with incentives. Pastures can provide income through crops and livestock, but give no incentives. Urban areas can be used for a plethora of income-providing services, including but not limited to offices, restaurants, roads, factories and warehouses (Gingold, 2007, p. 60).

Land use is a controversial topic between conservationists and capitalists who both have very different views of the world. In Puerto Rico, organizations such as the Conservation Trust of Puerto Rico and the International Institute of Tropical Forestry push for land conservation while the government continues to approve more land for building hotels and office buildings. These differences can make it difficult to determine land uses which have a direct effect on sedimentation rates into reservoirs (Gingold, 2007, p. 3). This project will evaluate the land use in relevant watersheds to identify the land development of the areas. By doing this, we will be able to provide recommendations to reduce sedimentation in those watersheds.

2.5.2 Sedimentation and its Effect on Reservoirs

Sediment deposits have been reducing the storage capacity of reservoirs in Puerto Rico for many years. The reservoirs are constantly being filled by sand and other sediment. Controlling sedimentation is a problem due partially to the climate and terrain of Puerto Rico. Hundreds of tons of suspended sediment are transported into reservoirs due to the intensity and frequency of rainfall on the island (Zack & Larsen, 1994). The heavy rainfall triggers landslides which, in the past, have sent an average of 300 metric tons/km^2/year of sediment into streams. The sediment is then transported downstream to the reservoirs (Zack & Larsen, 1994). A great portion of this sediment is derived from poorly controlled agricultural practices and urban development within the watersheds. Sr. Soler-López (2001) studied 14 principal reservoirs in Puerto Rico and sedimentation was responsible for an average storage capacity reduction of 35% in those reservoirs with individual losses ranging from 12%-81% (para. 1).

In order to assess the lifespans of the reservoirs in Puerto Rico, we needed to have an understanding of how the sedimentation affects the storage capacity. With an understanding of this, we were able to continue our research to find methods of reducing sedimentation.

2.5.3 Dredging as a Solution to Sedimentation

The technique of dredging is used to impede the decrease in storage capacity in reservoirs due to sediment deposit. Dredging is “the relocation of underwater sediments and soils for the construction and maintenance of waterways, dikes, and transportation infrastructures and for reclamation and soil improvements” (International Association of Dredging Companies, 2011, para. 1).

Although dredging removes sediment, there are two negative factors incorporated with the use of it. The first is the negative impact on the marine environment and water quality; the second is the cost.

Due to the movement and loss of sediment from the dredging process, the marine environment and quality of water are negatively impacted. The release of the soil in the water causes an increase in turbidity. Turbidity is “murkiness or cloudiness of water caused by particles” (Mapa de Vida Protocol). Turbidity shields the light entering the water and therefore reduces the amount of light received by the flora and fauna. The reduction of received light on the flora and fauna inhibits their growth. The disturbed soil can also cover and kill the flora and fauna. Lastly, turbidity can introduce contaminates, impacting the quality of water.

Another problem with dredging is cost. The Puerto Rico Aqueduct and Sewer Authority invested $60 million on dredging in the Carraízo reservoir from 1997-1999. Approximately 5.8 million cubic meters of sediment were removed. Unfortunately, after investing money and time into the project, the life expectancy of the reservoir was only extended by 18 years (Soler-López & Gómez-Gómez, 2005). In

2008, the average cost per cubic meter for maintenance and for new dredging were respectively, $5.50 and $13.16 (U.S. Army Corps of Engineers, 2009, p. 3). The small extension of life expectancy is not worth the high cost of dredging projects.

Dredging is a costly procedure and can have significant negative effects on the environment. To effectively increase the lifespans of reservoirs while minimizing these consequences, preventative measures, such as reforestation, must be implemented to reduce sedimentation in reservoirs and thus reduce the frequency of dredging.

2.5.4 Reforestation in a Watershed as a Solution to Reduce Sedimentation

Reforestation, or the concept of an emerging forest, is when a forest is grown in an area where one is not located presently (Helmer & Lugo, 2003, p. 146). The term secondary forest is used to describe an emerging forest where deforestation had previously occurred. Reforestation is most commonly used to describe the process of humans growing a secondary forest. As mentioned in a previous section, forest cover is more helpful in decreasing sedimentation and runoff in a watershed than an urban area. Puerto Rico is an island primarily covered by secondary forests, as shown in Figure 5. Due to this fact, Puerto Rico has actually been the focus of many studies on secondary forests. There is considerable debate on whether reforestation is best done naturally or with human intervention, and also whether to use endemic or exotic species of trees. Endemic species are those found only in that area, while exotic species are those not native to an area but which are now living there.

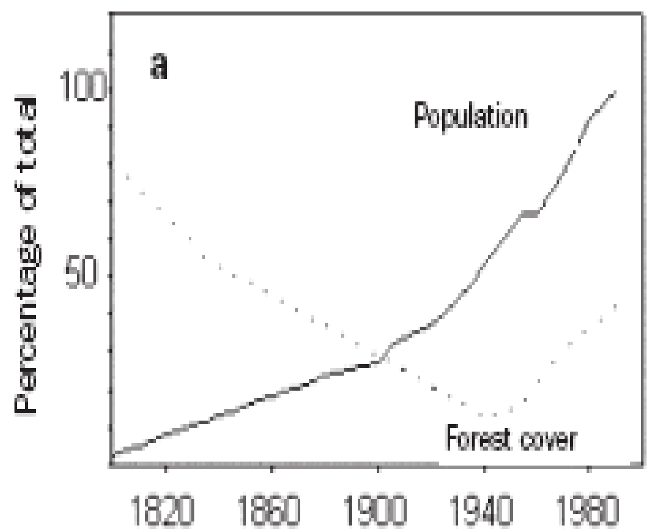


Figure 5: Puerto Rico Forest Cover and Population (Aide, Zimmerman, Pascarella, Rivera, & Marcano-Vega, 2000)

Secondary forests that are the result of natural regeneration without intervention have shown to increase forest cover density quickly in the first twenty-five years (Aide, Marcano-Vega, Pascarella, Rivera, & Zimmerman, 2000, p. 330). After just forty years of growth, the forests had the same characteristics as a primary forest growing naturally. The no-cost benefit of natural forest regeneration is the most appealing factor to those investing in reforestation. Natural regrowth can only happen in areas with low soil degradation, however. This renders it useful in a limited number of areas that have been abandoned. Also, the overall biodiversity takes many more years than the trees to recover fully. The time for the biodiversity to recover is estimated to be hundreds of years (Aide et al., 2000, p. 33).

In areas with high soil degradation or an area where an increased recovery rate is desired, human intervention can be of help to reforestation. For human intervention to be helpful, knowledge of which trees and shrubs to plant is essential to the recovery of the forest (Aide et al., 2000, p. 332). The flow chart in Figure 6 illustrates the process of creating a secondary forest. The high cost and required maintenance of a reforested area are significantly more than that in having the forest grow back naturally. High or low intervention can be used and each requires different amounts of money. The level of degradation and the desired rate of recovery determine the method used. For example, if a site is being reforested to decrease erosion, intervention would be recommended depending on the desired speed of recovery (Aide et al., 2000, p. 336).

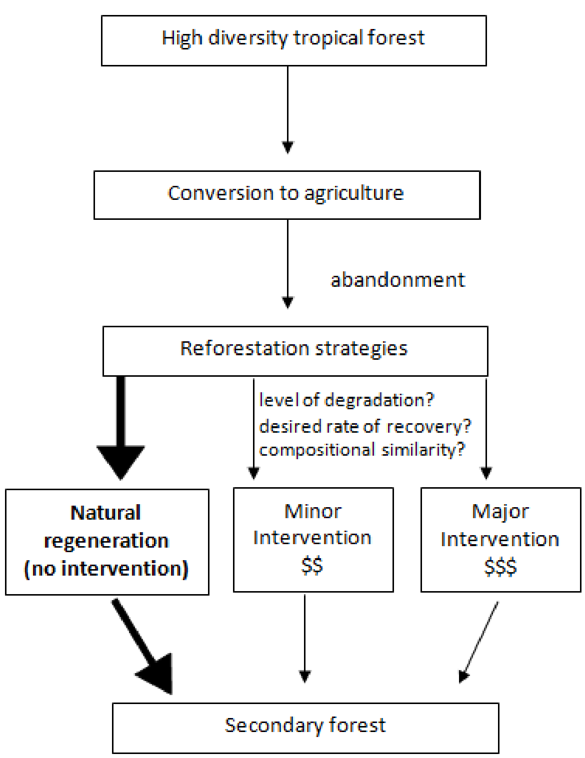


Figure 6: Reforestation Flowchart

(Adapted from Grau, Aide, Zimmerman, Thomlinson, Helmer, & Zou, 2003)

Exotic species have been present in Puerto Rico for many years, and are prevalent throughout the island. Programs, such as the Conservation Trust of Puerto Rico's Árboles… Más Árboles program, try to maintain the endemic species of the island and use only endemic trees in their reforestation program (Fideicomiso, 2007, Reforestation). Trees that are not endemic to the island are sometimes detrimental to the natural health of an ecosystem, as they could become invasive. Other times they can be effective in beginning a secondary forest before giving way to naturally grown endemic species (Aide et al., 2000, p. 335).

The species of trees that are planted, whether endemic or exotic, depend on the site of growth and the desired recovery time. Understanding reforestation techniques can help in reducing sedimentation in a watershed.

2.5.5 Summary

In order to fully understand the problems of the reservoirs of Puerto Rico, the watershed management must be accounted for. The current methods of watershed management have issues, but there are solutions to be found. Reforestation, for example, can be used to reduce sedimentation rates in the feeding streams of the reservoirs. Dredging is a costly and environmentally disruptive process, but is necessary in order to continue the use of reservoirs for freshwater. By reducing sedimentation and reducing the frequency of dredging the watersheds and reservoirs will be in better shape than they are in today.

2.6 The Major Reservoirs in Region 2

In Region 2, as defined by the Conservation Trust, there are five major reservoirs, four of which are still used for the potable water supply to the surrounding municipalities. A map of Region 2 with the five major reservoirs labeled is shown in Figure 7. The four reservoirs that supply potable water are Lago

Loíza, Lago La Plata, Lago de Cidra and Lago Carite. Lago Las Curias is also located in Region 2 but was shut down due to sedimentation. It is currently only used for recreational purposes.

The Conservation Trust requested we study the four reservoirs that supply potable water to the island: Lago Loíza, Lago La Plata, Lago de Cidra, and Lago Carite, because they are the major freshwater suppliers in Region 2.

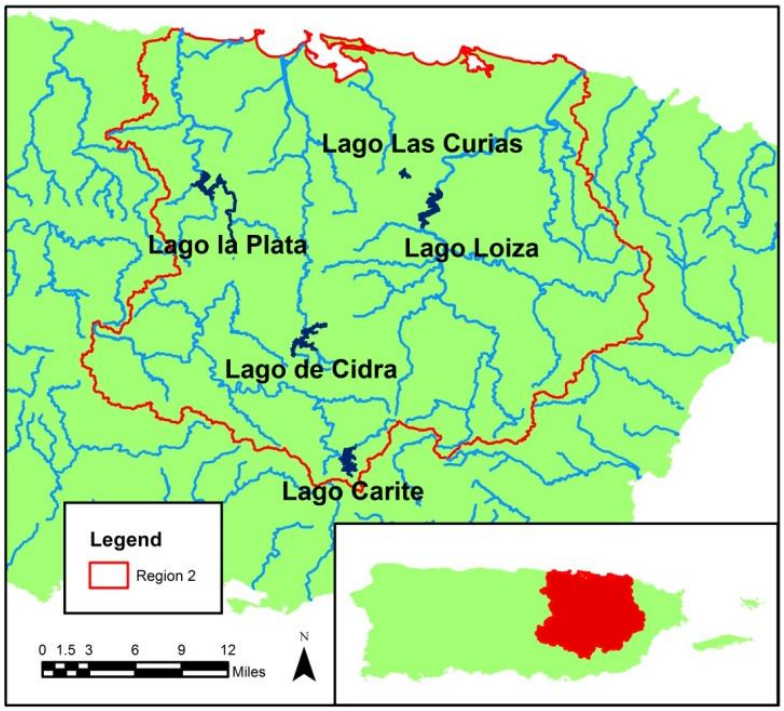


Figure 7: Region 2 Reservoirs

(Adapted from the Conservation Trust of Puerto Rico Database, 2011)

2.6.1 Lago Loíza

In 1953 the Río Grande de Loíza was impounded with the Carraízo Dam and Lago Loíza, also known as Lago Carraízo, was formed. The reservoir is located in the municipalities of Caguas, Gurabo and Trujillo Alto in northeastern Puerto Rico. There is a 538 square kilometer drainage area, making it the largest drainage basin of a reservoir in Puerto Rico. The Río Grande de Loíza, Río Gurabo and Río Canas all drain into Lago Loíza. Lago Loíza had an original storage capacity of 26.80 million cubic meters in 1953. The Sergio Cuevas Filtration Plant takes water from Lago Loíza and distributes it to the San Juan metropolitan area at a rate of about 394,000 cubic meters per day. Lago Loíza has had dredging done in 1997-1999 that increased storage capacity of the reservoir by about 5.8 million cubic meters after two hurricanes had drastically reduced the storage capacity with drastic amounts of sediment.

2.6.2 Lago La Plata

The Lago La Plata reservoir is located in the Naranjito and Toa Alta municipalities and impounds the waters from Río de La Plata, Río Guadiana and Río Canas. The Lago La Plata dam was built in 1974 and the reservoir has always been used for potable water for the San Juan metropolitan area. About thirty-five percent of the San Juan metropolitan area's potable water comes from this reservoir.

2.6.3 Lago de Cidra

At the confluence of Río de Bayamon, Río Sabana and Quebrada Pietra the Lago de Cidra reservoir is located. It is in the Cidra municipality and the dam that created the reservoir was created in 1946. Originally the reservoir was a 6.54 million cubic meter water supply for the San Juan metropolitan area but has since then lost storage capacity. The drainage area of the reservoir is 21.4 square kilometers about 3 kilometers northeast of the town of Cidra (Soler-López, 2010, Introduction).

2.6.4 Lago Carite

Lago Carite is located in the Río de La Plata watershed in southeastern Puerto Rico. It was constructed in 1913 by the Puerto Rico Electric Power Authority (PREPA) to create hydroelectric power. Due to priorities in the area, the power plants were eventually shut down and the reservoir was converted to be used for domestic and agricultural water purposes (Carrasquillo-Nieves, Soler-López, 1999, p. 1). The drainage area of Lago Carite has a high annual average rainfall, which contributes to a sedimentation problem the reservoir now faces. Despite the efforts of the government to protect the drainage basin by declaring it a forest reserve in 1935, agricultural practices continue in the area. The

Puerto Rico Department of Natural Resources designated an area in the basin to produce timber, continually cutting down and growing trees. The lack of protection for the soil because of the process also serves as a detriment to the area by increasing the sedimentation.

Chapter 3: Methodology

The goal of this project is to assess the lifespans of the reservoirs in Puerto Rico and to provide recommendations to reduce sedimentation in these reservoirs. Our team focused on four main objectives in order to reach this goal: 1.) to collect population data and freshwater withdrawal rates for Puerto Rico to establish a correlation between the two, 2.) to analyze sedimentation surveys to determine the lifespans of major reservoirs, 3.) to evaluate the land use in riparian zones of relevant watersheds by identifying the land development of the areas, and 4.) to determine the methods used to reduce sedimentation in reservoirs in an effort to lessen the frequency of dredging.

3.1 Population and Water-Use Data Collection

In order to collect population data and freshwater withdrawal rates for Puerto Rico, we obtained data from the U.S. Census Bureau and the U.S. Geological Survey.

3.1.1 United States Census Bureau

Laura Medrano is part of the Partnership and Data Services for the Boston Region of the U.S. Census Bureau. The Boston Region includes Maine, New Hampshire, Massachusetts, Vermont, 53 counties in upstate New York, Rhode Island, Connecticut and Puerto Rico. We met with Laura at La Concha Hotel in San Juan on Tuesday, March 29, 2011. Laura taught us how to use the U.S. Census Bureau's online FactFinder websites. The websites can be overwhelming and difficult to maneuver through, but Laura cleared these confusions. She also helped us obtain the Census population data and estimates from 1940 to 2010 for the municipalities in Puerto Rico.

3.1.2 United States Geological Survey

We were able to find water-use data for Puerto Rico from 1985 to 2005 on the United States Geological Survey's (USGS) official website. We contacted Pedro Diaz and Wanda Molina from the USGS for further information regarding water-use data. Pedro Diaz is the director of the USGS Caribbean Water Science Center. Wanda Molina is a part of the Puerto Rico Water-Use Information Program.

As explained in the Background chapter, the USGS has collected water-use data in the United States since 1950. Puerto Rico was implemented in this data collection starting in 1980. The USGS publishes reports of the estimated use of water in the United States for every five years that the data are collected. Some of the publications were available on the USGS's website, others were not available online. Pedro Diaz and Wanda Molina sent us the reports of the estimated use of water in the United States from 1960 to 2005. The reports explain the purpose of the National Water-Use Information Program and the importance of collecting and analyzing the water-use data. The reports also give the water-use data, which includes freshwater withdrawal rates. Our team used these freshwater withdrawal rates, along with the withdrawal rates found on the USGS's official website, to analyze the freshwater needs of the island.

3.2 Sedimentation Data Collection

In order to determine the lifespans of major reservoirs, we analyzed sedimentation surveys from the U.S. Geological Survey.

3.2.1 United States Geological Survey

The United States Geological Survey provided a great deal of information regarding the sedimentation of reservoirs in Puerto Rico. We found a list of publications of sedimentation surveys for Lagos Loíza, La Plata, de Cidra and Carite on the website for the USGS Caribbean District and the Luquillo WEBB program. Access was not available for reports published before the year 2000.

We contacted Luis R. Soler-López, Matthew C. Larsen, and Pedro Diaz from the USGS for information regarding the sedimentation of reservoirs in Puerto Rico. Señor Soler-López, the author of many sedimentation surveys conducted in Puerto Rico, participated in a phone interview with us. He provided us access to the sedimentation surveys that were unavailable online and to additional digital maps of the four reservoirs under study in Region 2. Señor Soler-López provided insight on the poor erosion control practices in Puerto Rico and discussed possible recommendation in decreasing sedimentation rates. Dr. Larsen was the Caribbean District Chief from 2000-2003 and the Luquillo WEBB project chief from 1991-2000. Although he was unavailable for an interview, he provided us with access to his reports on the Caribbean District's publications. He also recommended we contact the current District Chief, Pedro Diaz, for additional support or questions. Pedro Diaz provided our team with additional reports on sedimentation.

3.3 Land Use Analysis

By analyzing aerial photography from the years 2004 to 2010, we evaluated land development of the riparian zone of Río Grande de Loíza over a period of time.

3.3.1 Aerial Photography Interpretation

The land use analysis was performed with the help of ArcGIS software. Aerial photographs, which were available for analysis, were from years 2004 and 2010. Pixel sizes of the aerial photographs for each year were different, 3.3 ft by 3.3 ft in 2004 and 1ft by 1 ft in 2010. This means that 2010 photographs were much clearer and on numerous cases were used as a reference during classification of 2004 photographs.

At first, our group was hoping to identify major rivers of each reservoir and to analyze land use along those rivers but this proved to be impossible due to time constraints. The decision was made to perform the analysis for only one river that feeds into Lago Loíza. Río Grande de Loíza was chosen for the analysis as it is one of the two rivers that, when combined, constitute about 84% of the total annual inflow to Lago Loíza reservoir (Soler-López & Gómez-Gómez, 2005). Classifying land according to forest, grassland, and developed areas also proved to be time consuming and thus the final analysis only identifies developed areas which include buildings, bridges, and paved surfaces.

The step-by-step guide of how the analysis was performed can be found in Appendix C.

3.4 Evaluation of Solutions

To determine methods used to reduce sedimentation in reservoirs we interviewed experts on upland erosion control in Puerto Rico.

3.4.1 International Institute of Tropical Forestry

Dr. Ariel E. Lugo is an expert in the forests of Puerto Rico and is involved in the International Institute of Tropical Forestry, a department of the U.S. Department of Forestry, and in San Juan Urban Center Long-Term Research Area (San Juan ULTRA). There are many reports Dr. Lugo has published that discuss the feasibility of reforestation in Puerto Rico, the properties of various trees and the acceptance of exotic species on the island. A set of questions was prepared for him, and the interview was conducted on Wednesday, March 30, 2011 at the botanical garden in Río Piedras municipality. While at the botanical garden, both a librarian and former Conservation Trust employee agreed to help with the project by providing us with helpful, relevant publications and aerial photography, respectively.

3.4.2 Gregory L. Morris Engineering, P.S.C.

Dr. Gregory L. Morris is an expert on sedimentation and preventative measures who has an office located in San Juan, Puerto Rico. He has done many studies in and out of Puerto Rico, and is considered to be a top mind in the sedimentation field. A set of questions was prepared for him and the interview was conducted on Tuesday, April 12, 2011 at Dr. Morris's office in San Juan. Dr. Morris provided us with information about alternative solutions to reforestation and the drawbacks of using land use in a sedimentation analysis.

Chapter 4: Results and Analysis

This section details the results found from interviews, studies and interpretation of data that were found. Using these results we were able to create conclusions and recommendations to reduce sedimentation and assess the lifespans of reservoirs under study.

4.1 Population and Freshwater Withdrawal Rates

The total freshwater withdrawal rates from surface water sources were analyzed for the entire island and for the 23 municipalities in Region 2 between 1985 and 2005. Although ground water contributes to the freshwater supply, surface water is the larger supplier of the two sources.

Figure 8 displays the total freshwater withdrawals in Puerto Rico from 1985 to 2005 in millions of gallons per day. The total freshwater withdrawal rate is the sum of the public-supply and the self-supply withdrawals. This graph describes two things: 1.) a comparison between the freshwater withdrawal rates of the ground water, surface water and the sum of both ground and surface water, 2.) the trend of the amount of freshwater withdrawn throughout the 20 years. As seen in Figure 8, the withdrawal rates for surface water are much higher than those for ground water. The trend in the graph shows that the ground water withdrawal rates, and therefore the total freshwater withdrawals, vary over the 20 years. The trend for the surface water withdrawals shows that the rates were nearly constant for the first ten years (from 1985 to 1995), and then began to increase in the second ten years (from 1995 to 2005). Although the amount of total freshwater withdrawn varies every five years, there is an overall increase in the amount withdrawn from 1985 to 2005.

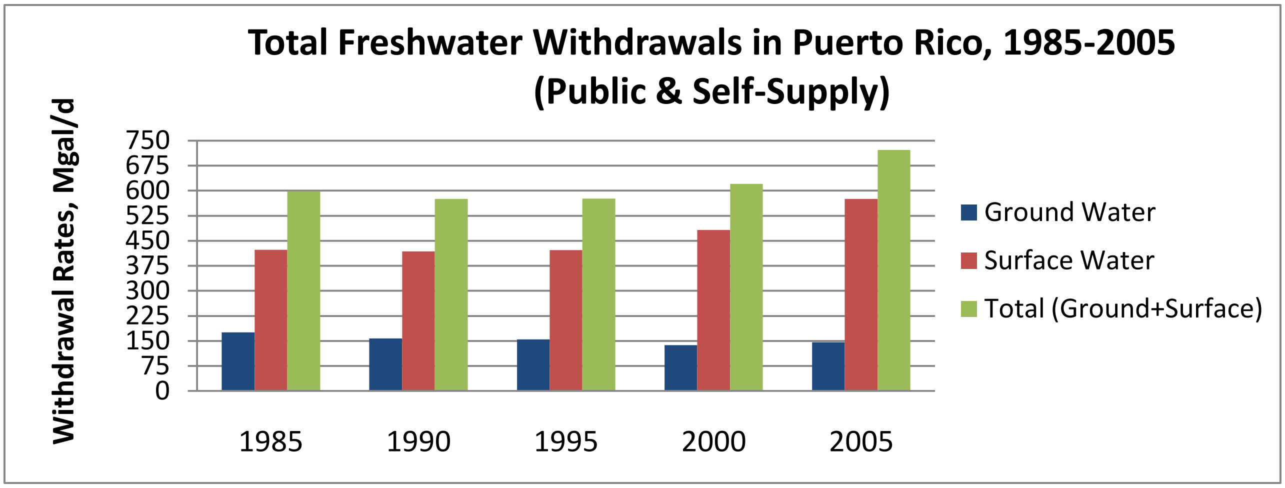


Figure 8: Total Freshwater Withdrawals in Puerto Rico, 1985-2005 (Public & Self-Supply)

(Adapted from USGS, 1990, 1995, 2010b, & 2010c)

These data brought us to forecast that, if the freshwater withdrawals from surface water sources are greater than the withdrawals from ground water sources for the entire island, then that may also be true for the 23 municipalities in Region 2. Figure 9 displays the total freshwater withdrawals in the 23 municipalities of Region 2 from 1985 to 2005 in millions of gallons per day. Our prediction was correct; the amount of freshwater withdrawals from surface water is much higher than the amount withdrawn from ground water. Additionally, the trend in the graph shows that the ground water withdrawal rates varied over the 20 years. However, the trend for the surface water withdrawals in the

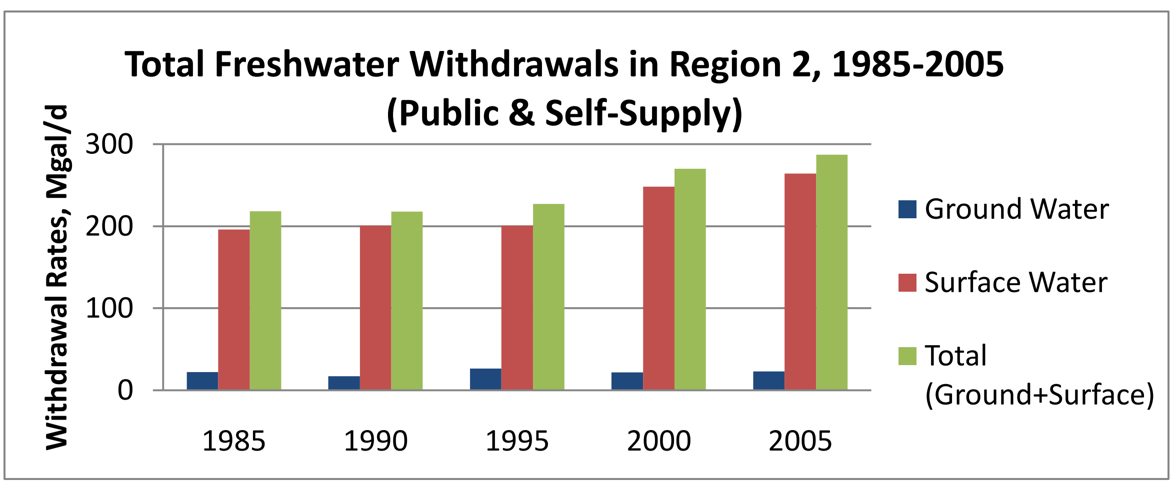


Figure 9: Total Freshwater Withdrawals in Region 2, 1985-2005 (Public & Self-Supply)

(Adapted from USGS, 1990, 1995, 2010b, & 2010c)

23 municipalities differs from the trend for the whole island. In the 23 municipalities, the withdrawal rates have increased from 1985 to 2005.

Both of these graphs prove that the amount of freshwater needed to support the island is increasing. They also prove that surface water is a greater supplier than ground water.

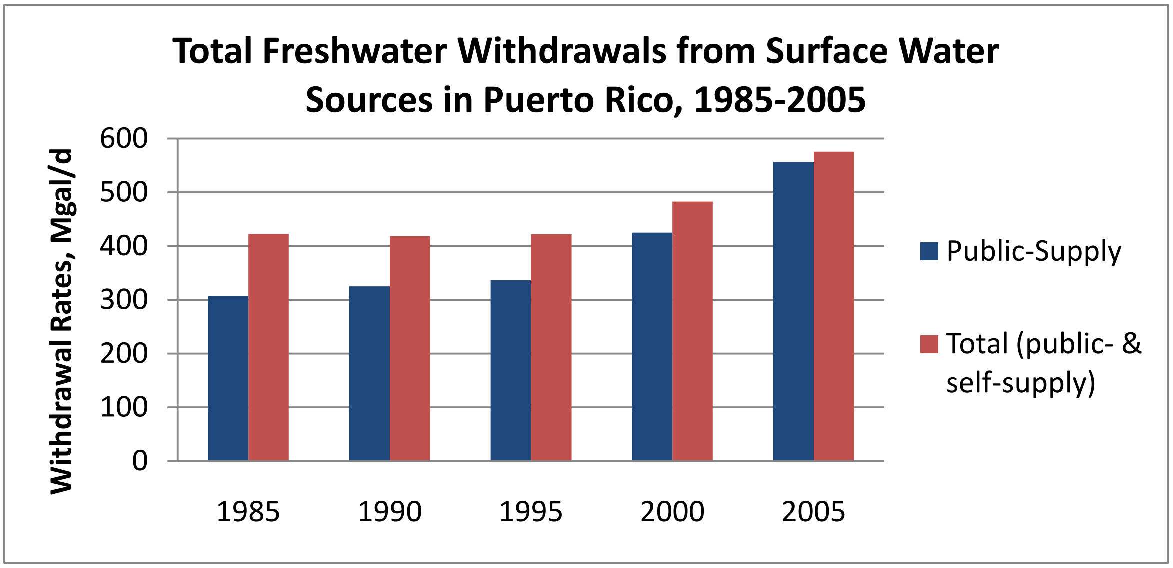


Figure 10: Total Freshwater Withdrawals from Surface Water Sources in Puerto Rico, 1985-2005 (Adapted from USGS, 1990, 1995, 2010b, & 2010c)

Figure 10 is a graph that compares the total public-supply withdrawal rates with the total freshwater withdrawal rates, which is a sum of public- and self-supply, on the island. All of the withdrawals in this graph come from surface water sources. This graph shows that the amount of freshwater withdrawn increased from 1985 to 2005. Additionally, the graph shows that the public-supply system withdraws most of the freshwater that is provided to the island. The graph also shows that, from 1985 to 2005, the amount of self-supplied withdrawals compared to the amount of public-supplied withdrawals decreased. We think the reason for this is the increasing pollution and contamination of underground aquifers and surface water bodies. The public-supply systems are required to clean freshwater by the means of industrial processes in compliance with EPA's Clean Water Act and other standards for quality of potable water set by a number of government agencies.

Therefore, freshwater users are relying more on public-supply as a source of their potable water, than on the means of self-supply.

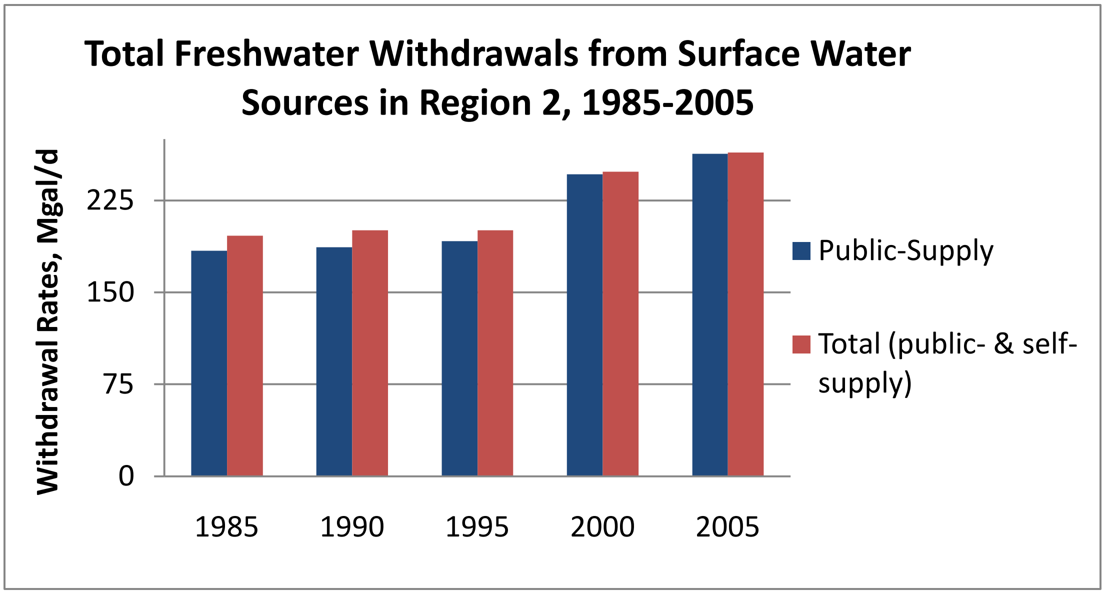


Figure 11: Total Freshwater Withdrawals from Surface Water Sources in Region 2, 1985-2005

(Adapted from USGS, 1990, 1995, 2010b, & 2010c)

Figure 11 is a graph that compares the total public-supply withdrawal rates with the total freshwater withdrawal rates, all supplied from surface water, for the 23 municipalities of Region 2. This graph shows the same trends as the graph in Figure 10. The public-supply system withdraws most of the freshwater that is provided to the island. The amount of self-supplied withdrawals compared to the amount of public-supplied withdrawals decreased from 1985 to 2005. The 2005 columns show that the public-supplied is almost equal to the total public- and self-supplied withdrawals.

Figure 12 shows the population of Region 2 municipalities and Puerto Rico from 1940 to 2010. The graph shows a general increase in the population of the island and of Region 2 municipalities from 1940 to 2010. Figure 13 is a graph showing the total freshwater withdrawals from surface water sources from Region 2 municipalities and also from Puerto Rico from 1985 to 2005. Both of the lines on the graph show an increase in the amount of freshwater withdrawn from surface water sources. Comparing the population trends in Figure 12 with the freshwater withdrawal rates in Figure 13, one could observe that a larger population requires a larger amount of freshwater. One can also observe that the majority of the freshwater withdrawn is from surface water sources.

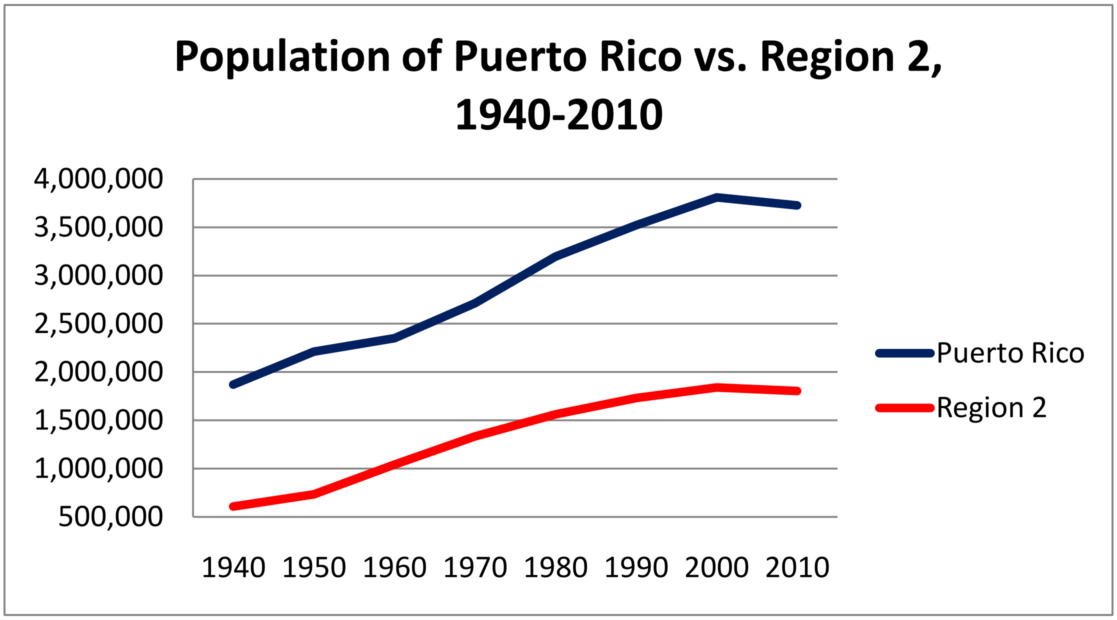


Figure 12: Population of Puerto Rico vs. Region 2, 1940-2010

(Adapted from U.S. Census Bureau, 2011)

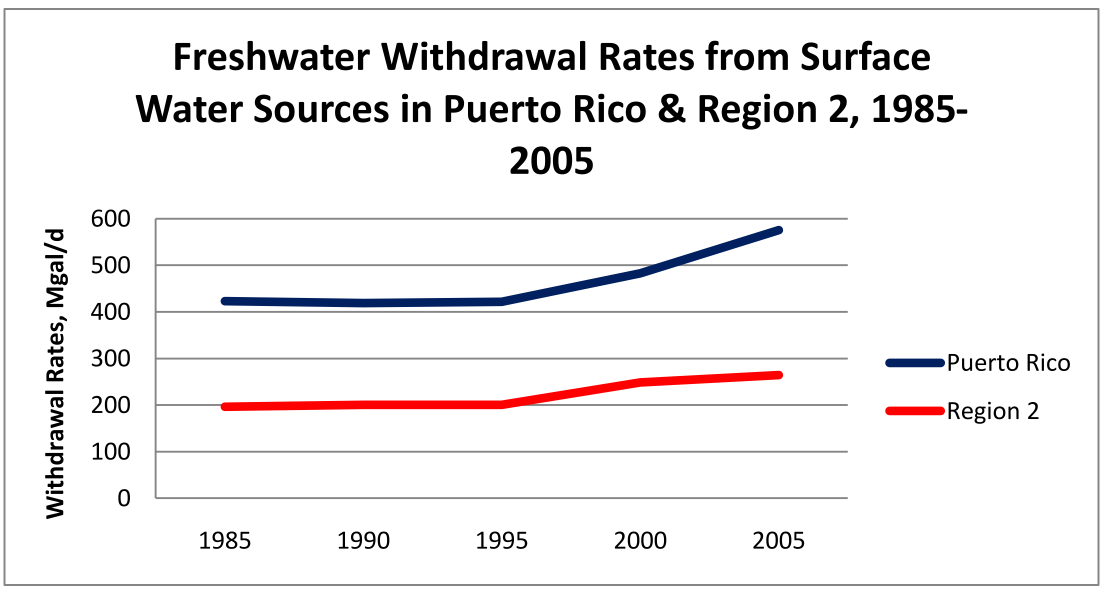


Figure 13: Total Freshwater Withdrawal Rates from Surface Water Sources in Puerto Rico & Region 2, 1985-2005

(Adapted from USGS, 1990, 1995, 2010b, & 2010c)

Detailed maps of freshwater withdrawal rates, along with population changes, can be found in Appendices D and E. The maps of the freshwater withdrawal rates show a side-by-side comparison of the surface water and ground water withdrawal rates of Region 2 municipalities for 1985, 1990, 1995, 2000, and 2005. Appendix E contains maps of the population change rates in Region 2 for 1950-1960, 1960-1970, 1970-1980, 1980-1990, 1990-2000, and 2000-2010.

4.2 Sedimentation Surveys

The main purpose of sedimentation surveys in reservoirs is to “determine the volume and weight of sediment accumulated between surveys, or during the recorded period of storage” (Hall, 2010, p. 1). The information provided by a survey of this type can be used to approximate sediment yields, assess sediment damages, and predict reservoir storage life expectancies (p. 1). These data are vital in creating and analyzing protective sedimentation measures in watersheds. The data provided in this section, for the following four reservoirs: Lagos Loíza, de Cidra, La Plata, and Carite, have been selected and summarized from USGS sedimentation survey reports from the USGS Caribbean District’s database.

4.2.1 Storage Capacities Decrease

The figures included in this section provide the storage capacity of reservoirs based on ranges of pool elevation. The years presented and displayed on the graphs correspond to data from bathymetric surveys that were conducted on each reservoir. The spillway dashed line in Figure 14 and Figure 15 represent the limit of the pool elevation in the reservoir. A spillway is a channel or passage that will direct overflowing water in a dam (Encyclopedia Britannica, 2011). The curves provide a comparison of volumes of the reservoirs for the years bathymetric surveys were conducted and illustrate the capacity loss they have faced from the years they were studied.

In Lago Loíza, Figure 14, the 1994 curve illustrates the volume of the reservoir before it was dredged and the 1999 curve shows the regained volume after the operation. The 2004 curve on this graph illustrates a decrease in capacity resuming.

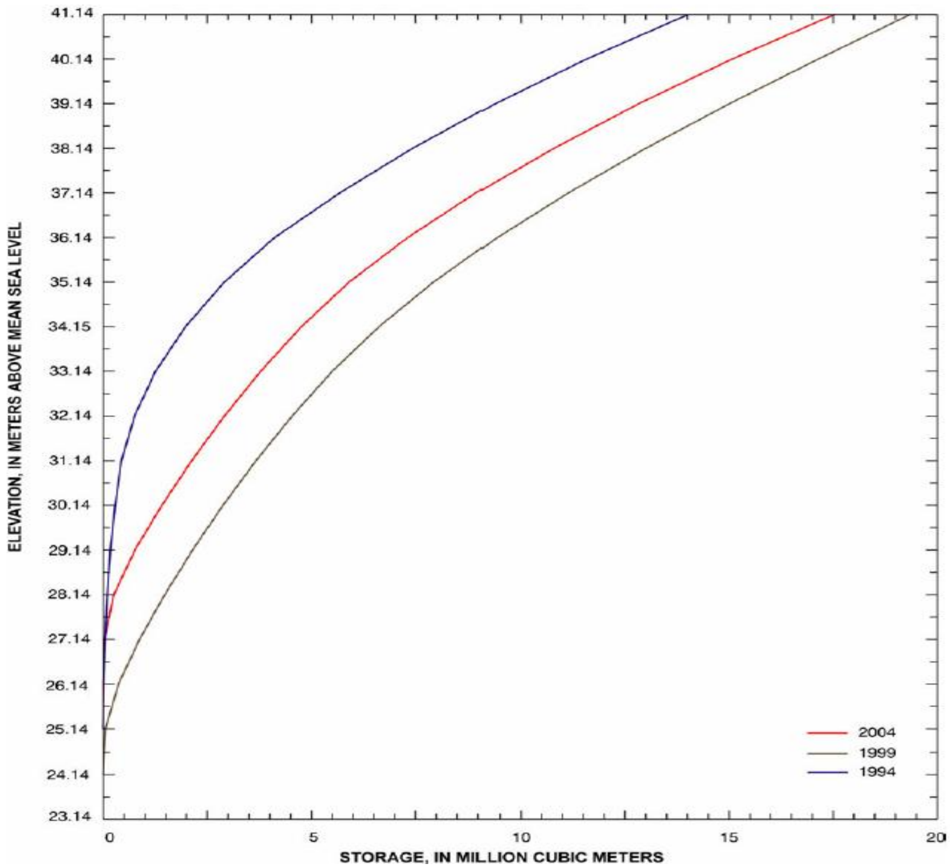


Figure 14: Water-storage Capacity and Pool Elevation of Lago Loíza, Puerto Rico, for 1994, 1999 and 2004

(Soler-López & Gómez-Gómez, 2005)

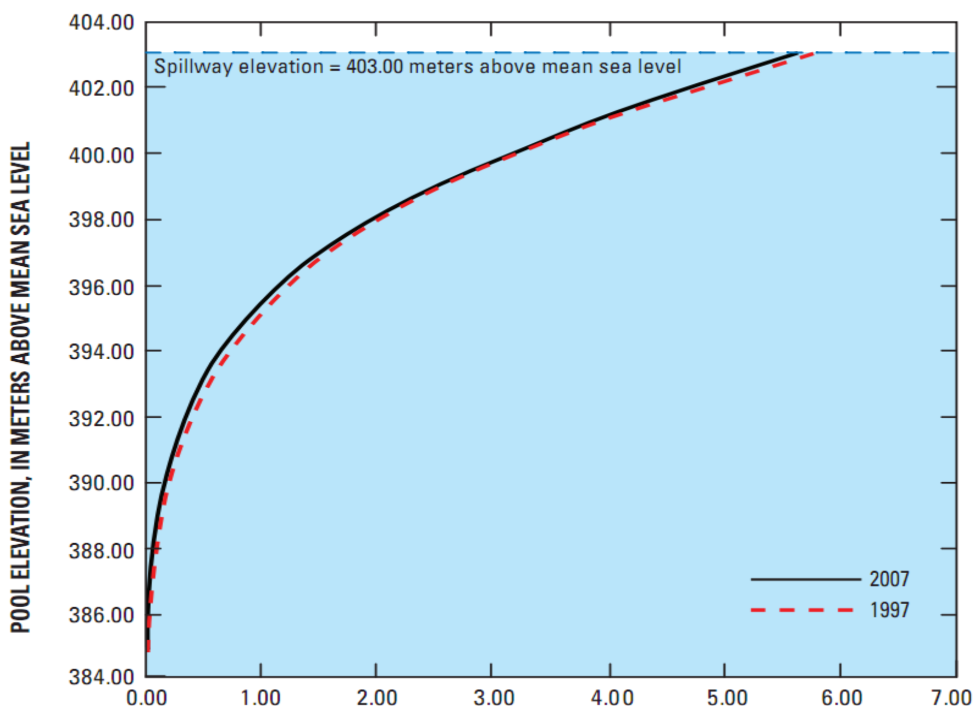


Figure 15: Water-storage Capacity and Pool Elevation of Lago de Cidra, Puerto Rico, for 1997 and 2007

(Soler-López, 2010)

Figure 15 shows the water-storage capacity and pool elevation of Lago de Cidra. As seen, the curves almost overlap each other. This shows how insignificant the storage capacity loss has been from 1997 to 2007. Additionally, the maximum volume that can be stored is showed with the spillway elevation dashed line which is 403 meters above mean sea level.

Figure 16 displays Lago La Plata with a more substantial loss from the evident space between the 1998 and 2006 capacity curve. This graph also provides its normal pool elevation which is 52 meters above mean sea level. In Figure 17, the Lago Carite graph shows the available storage it had for the year 1999 and its maximum pool elevation from the spillway elevation which is 543.64 meters above mean sea level.

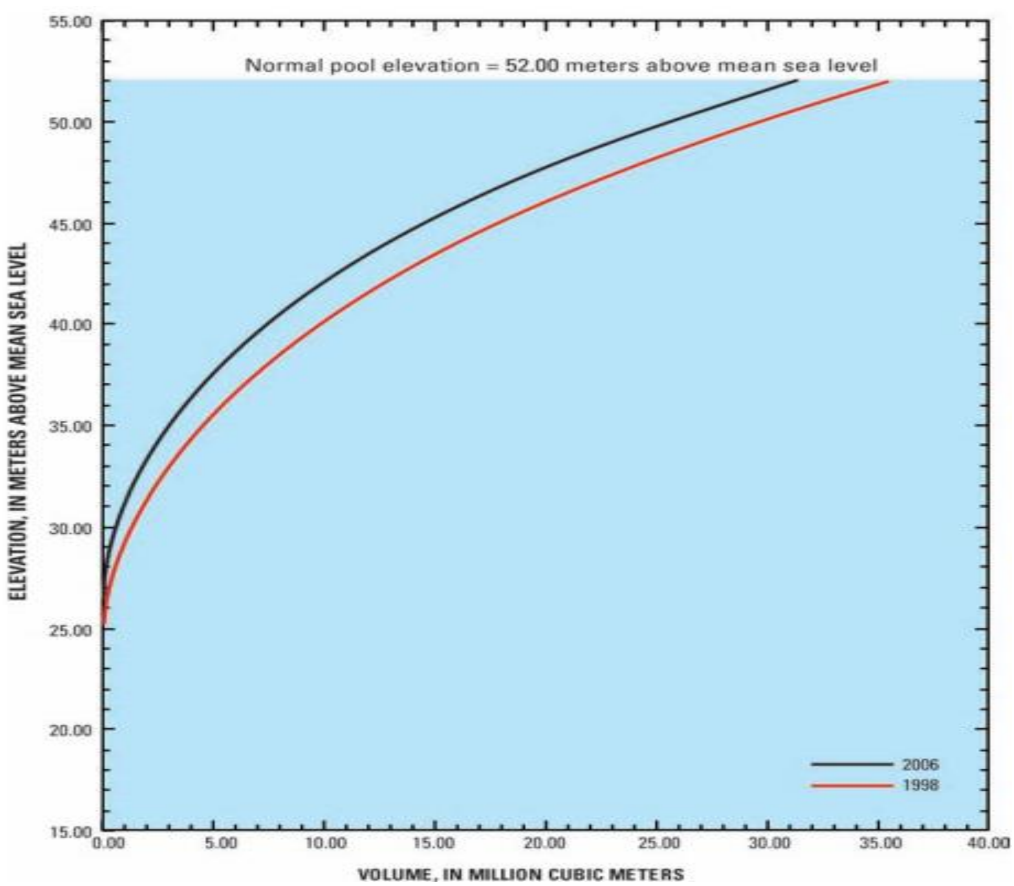


Figure 16: Water-storage Capacity and Pool Elevation of Lago La Plata, Puerto Rico, for 1998 and 2006 (Soler-López, 2008)

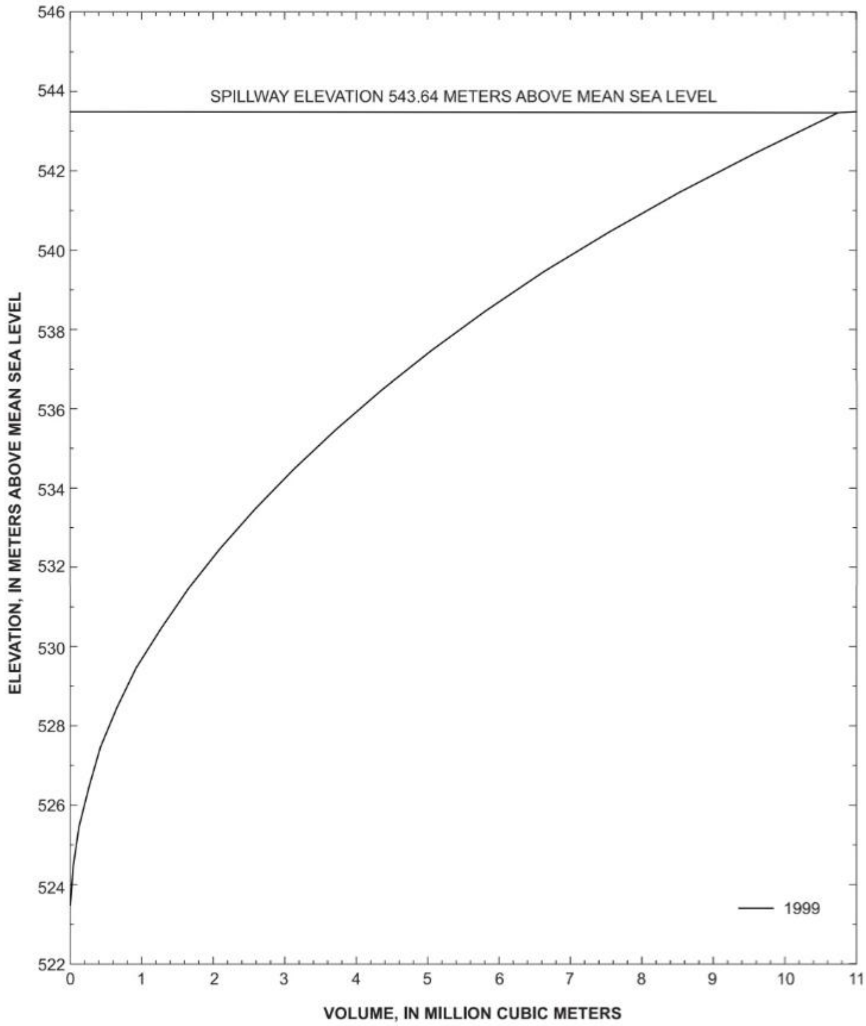


Figure 17: Water-storage Capacity and Pool Elevation of Lago Carite, Puerto Rico, for October 1999 (Soler-López & Carrasquillo-Nieves, 2001)

In general, three of the four graphs show a decrease in volume, which results from the sedimentation accumulating in the storage pools.

4.2.2 Trapping Efficiency and Sediment Yield

The world's most respected empirical study that expresses and correlates the trapping efficiency of a reservoir to its inflow and capacity is Brune's Curve (Soler-López & Gómez-Gómez, 2005, p. 22).

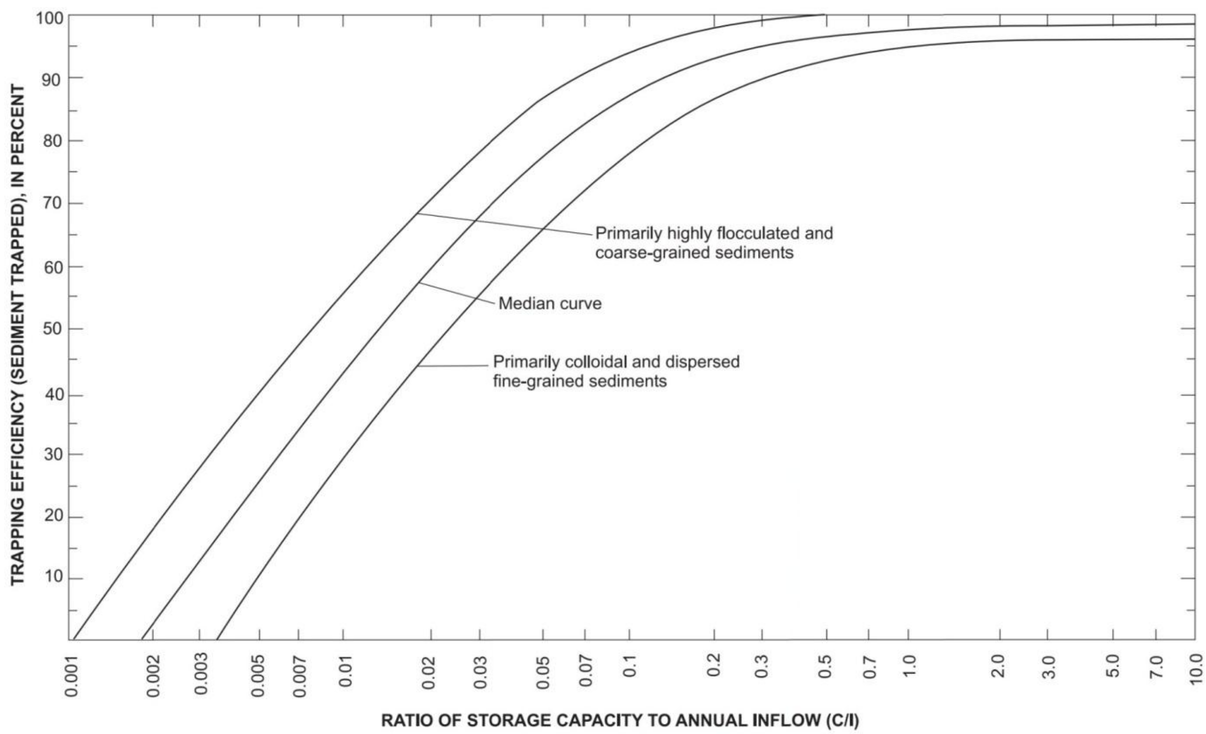


Figure 18: Brune's 1953 Curve

(Soler-López & Carrasquillo-Nieves, 2001)

Brune's Curve provides an estimation of the trapping efficiency of a reservoir based on the capacity-inflow value of a reservoir. Brune's Curve is illustrated in Figure 18.

The trapping efficiency depends on many parameters such as the reservoir's geometry, location, in-flow rates and times, outlet position, and the variety of distributed sediment-particle size curve (Soler-López & Gómez-Gómez, 2005, p. 22). A decrease in trapping efficiency is the result of more sediment accumulating in a reservoir and vice-versa for an increase. If the total sediment accumulated in the reservoir is divided by its long-term trapping efficiency, the amount of sediment that has eroded from the drainage area is found. Then if this number is divided by the drainage area and by the time span of sedimentation culmination, the sediment yield per year is found.

In Soler-López and Gómez-Gómez's (2005) Lago Loíza Sedimentation Survey the trapping efficiency was estimated using Brune's Curve (p. 22). As seen in Figure 19, the trapping efficiency was estimated to be 72%, 78%, and 76% for years 1994, 1999, and 2004, respectively. The dredging operation executed in 1997 and 1999 resulted in the increase from 72% to 78%, but in 2004 a decrease

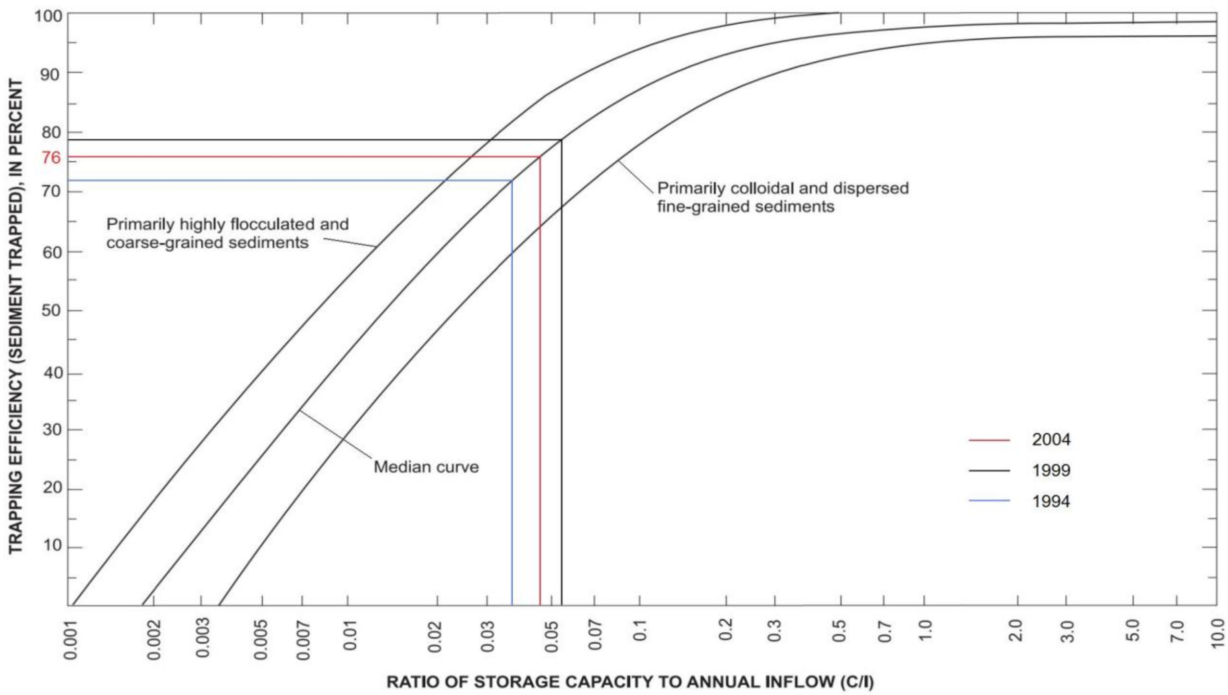


Figure 19: Lago Loíza Reservoir Trapping Efficiency

(Adapted from Soler-López & Carrasquillo-Nieves, 2001)

occurred. The capacity inflow value was derived from dividing the storage capacity of Lago Loíza of 17.53 million m^3 in 2004 by its annual drainage area runoff of 363 million $m^{3,}$ equaling 0.048 (p. 22). Lago Loíza experienced an average drainage area sediment yield of 859 $m^3/km^2/yr$ from 1994-2004 (p. 22).

For Lago Carite, Soler-López and Carrasquillo-Nieves (2001) estimated the long-term average trapping efficiency to be 96% (p. 1). They averaged the trapping efficiency percentages for Lago Carite as: 97%, 95%, and 95% for years 1913, 1986, and 1999, respectively (p. 1). In Figure 20, the calculated trapping efficiency numbers from Brune's Curve are shown. The decrease from 97% to 95% reflects more sedimentation accumulating in the reservoir. The annual sediment yield estimate from 1913 to 1999 was 1,938 $m^3/km^2/yr$ (p. 21). There was a decrease in the sediment yield to approximately 1,559

$m^3/km^2/yr$ from 1986 to 1999 (p. 21). The decrease occurred in spite of hurricanes Georges and

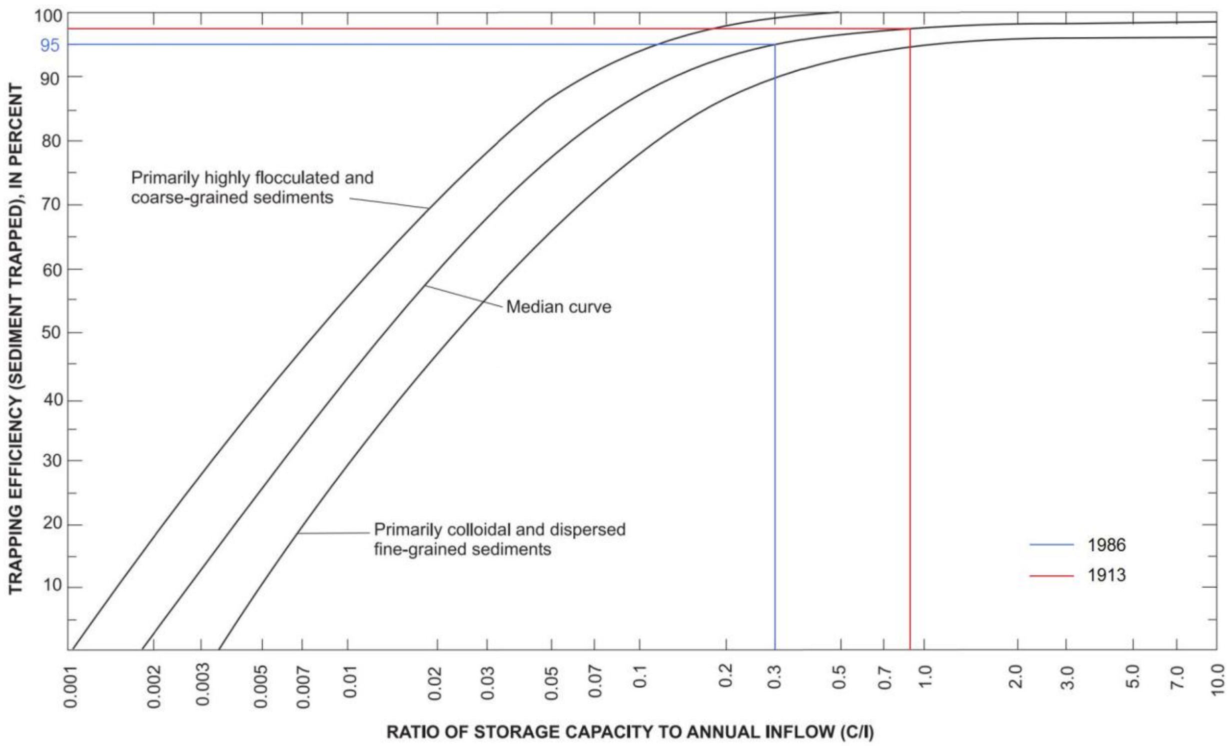


Figure 20: Lago Carite Reservoir Trapping Efficiency

(Adapted from Soler-López & Carrasquillo-Nieves, 2001)

Hortense, which caused great increases in sedimentation deposits in many other reservoirs.

Lago de Cidra has an average trapping efficiency of approximately 98%, which was averaged from its 1997 estimated value of 96% and its initial 100% trapping efficiency in 1946, when it was constructed (Soler-López, 1999, p. 18). To calculate the trapping efficiency for 1997, the storage capacity of 5,764,000 cubic meters was divided by its 1993 runoff inflow of 14,500,000 cubic meters, which is considered an average annual runoff value for Lago de Cidra (p. 18). The capacity inflow value was approximately 0.4. Figure 21 displays the value from 1997 on Brune's Curve. The estimated sediment yield calculated from the average trapping efficiency was 768 megagrams per square kilometer per year (p. 19).

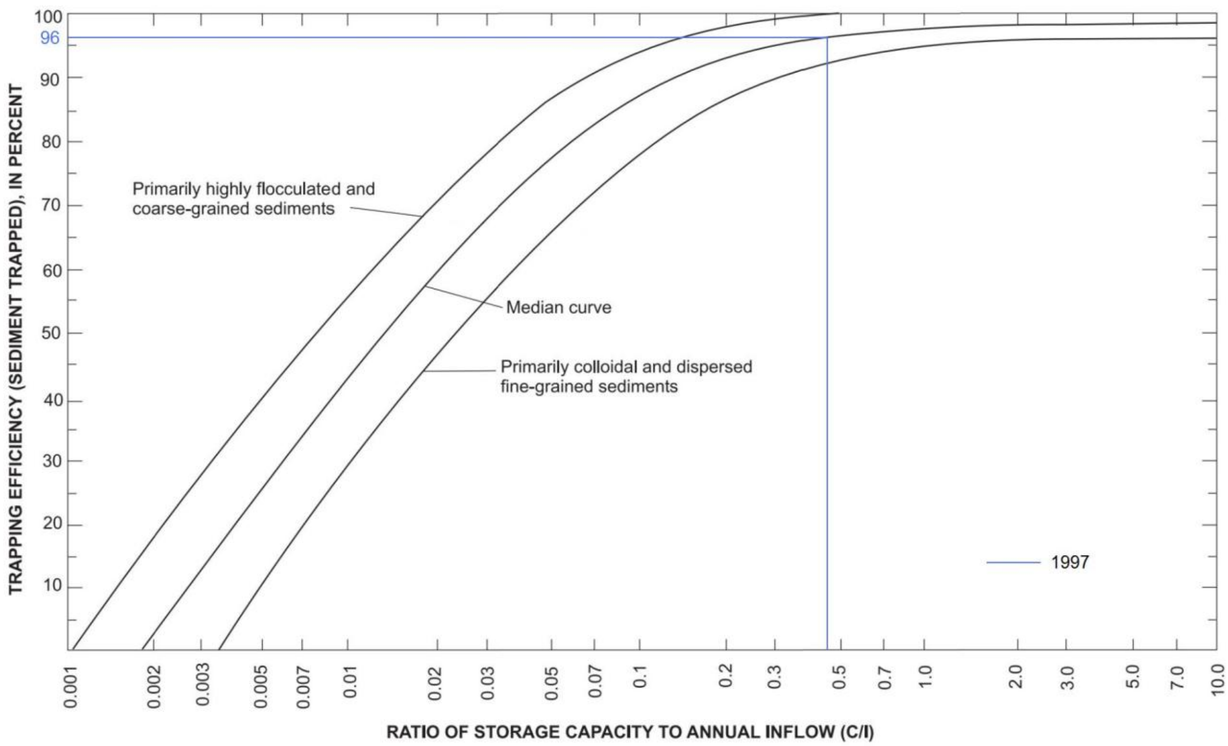


Figure 21: Lago de Cidra Reservoir Trapping Efficiency

(Adapted from Soler-López & Carrasquillo-Nieves, 2001)

As seen in Figure 22, Lago La Plata had estimated trapping efficiency values of 90% in 1974 and 85% in 1998 (Soler-López, Webb, & Carrasquillo, 2000, p. 23). For a long-term average of the 24-year period, Lago La Plata had a trapping efficiency of 88%. To calculate the sediment yield, Soler-López divided the sediment deposited in the reservoir which was 4.75 million cubic meters by the trapping efficiency of 0.88 to obtain 5.4 million cubic meters of material eroded from the drainage basin (p. 23). This value divided by the area of the drainage basin for La Plata and the 24-year period resulted in the sediment yield of 483 megagrams per square kilometer per year (p. 23). A 5% decrease in trapping efficiency illustrates a large increase in sedimentation depositing in the reservoir.

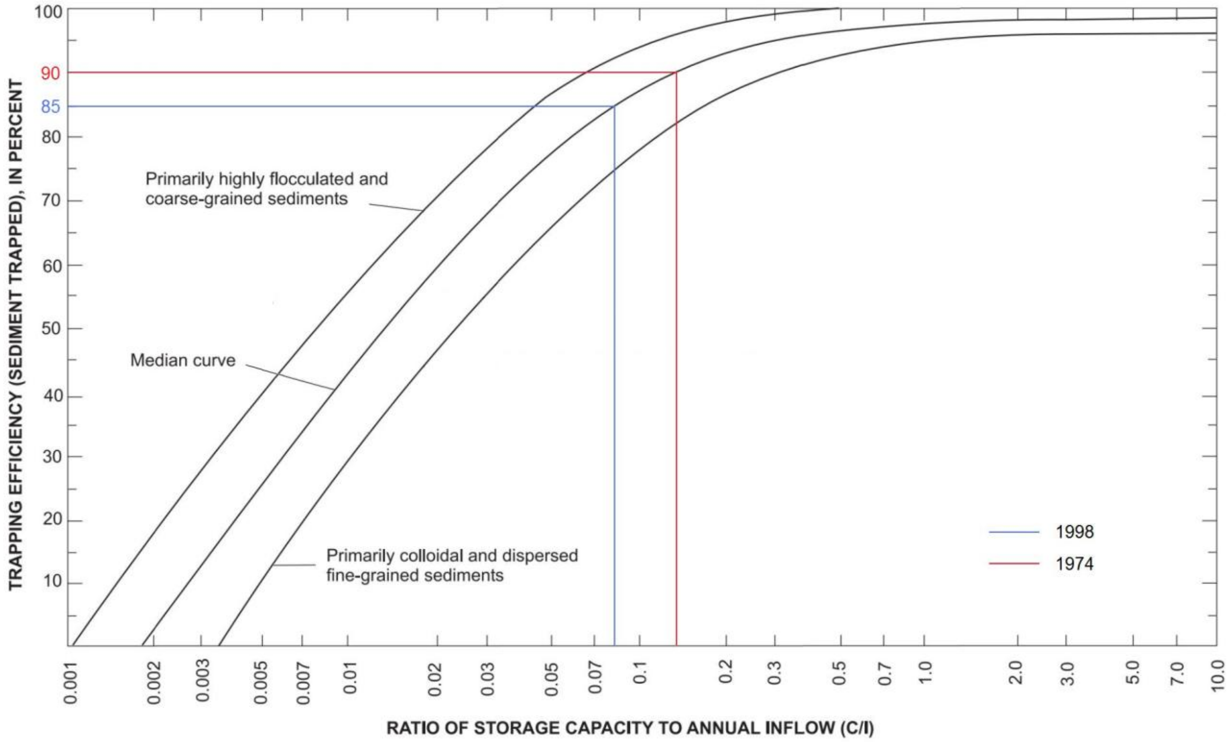


Figure 22: Lago La Plata Reservoir Trapping Efficiency

(Adapted from Soler-López & Carrasquillo-Nieves, 2001)

4.2.3 Sedimentation Summary

The life expectancy of a reservoir can be approximated "by dividing the remaining storage capacity by the annual storage capacity loss" (Soler-López & Gómez-Gómez, 2005, p. 24). Lago Loíza, from 1953 to 1997, experienced a rate of storage loss of 310,000 m^3/yr and as a result it will be completely filled by 2060 (p. 24). A reservoir will reach the end of its project life typically before half of the reservoir is filled with sediment. Lago Loíza in 2015 will be reduced to the same storage volume in 1994 that brought severe drought conditions (p. 24). Figure 23 displays the past and future storage capacity losses from sedimentation in the Lago Loíza reservoir.

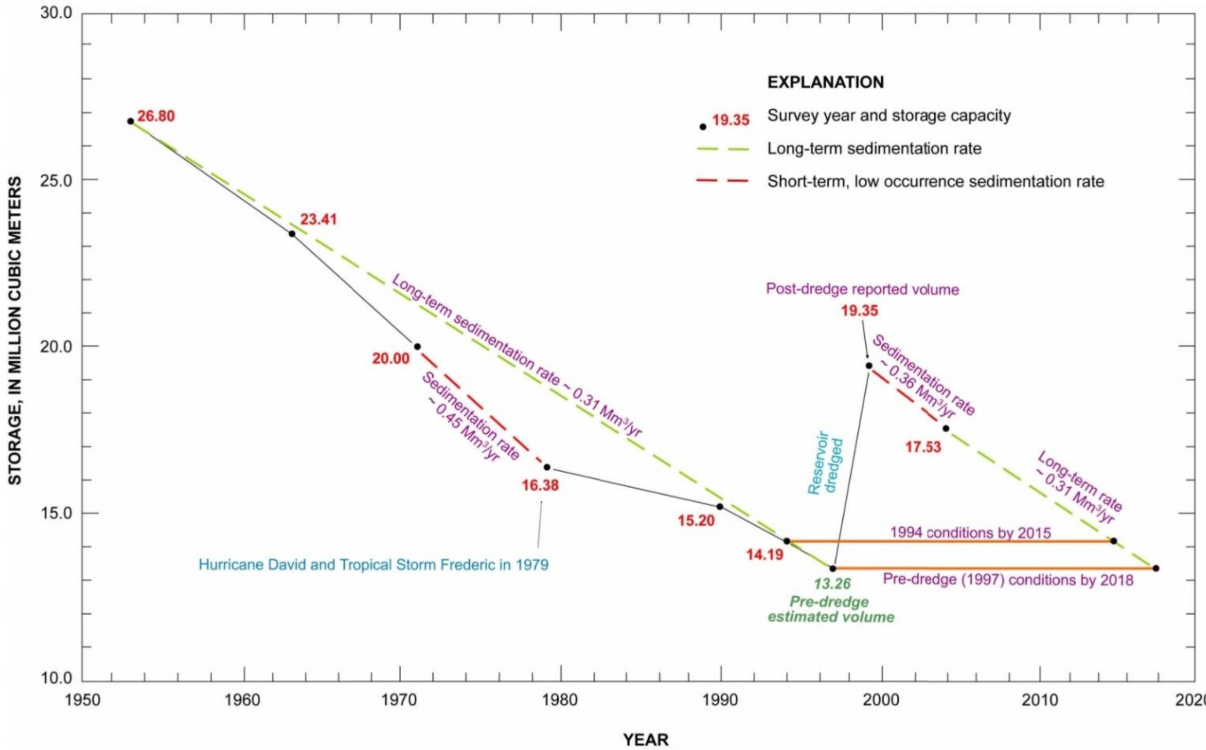


Figure 23: Lago Loíza Sediment Accumulation and Storage Capacity from 1953 to 2004 (Soler-López & Gómez-Gómez, 2005)

The project life of Lago de Cidra is not available but it will be completely filled with sediment in the year 2440 if the estimated sedimentation rate of 13,000 cubic meters per year from 1997-2007 is used (Soler-López, 2010, para. 13). A great amount of sediment has been depositing and accumulating closer to the dam, so it is possible it will reach its project life soon.

Lago Carite will be completely filled with sediment by the year 2289 (Soler-López, 2001, p. 1). If the sedimentation it experiences is distributed and deposited by its power outlet, it could be "rendered useless" quite earlier than anticipated (p. 1).

Lago La Plata faces a very similar situation in regards to sediment accumulation hindering its function. The critical issue with Lago La Plata is sedimentation depositing next to its water intake structures. The water intake structure of Lago La Plata is at a mean of 25.00 meters above sea level and the 2006 data revealed that the bottom of the reservoir by the structure is at 27 meters above mean sea level (Soler-López, 2008, para. 12). This could disable the reservoir if it is not operated on regularly (para. 12). Lago La Plata had a life expectancy of 112 years, but the project life, from 1998 to 2006, decreased by approximately 60 years (para. 11). In 1998 to 2006, the sedimentation rate doubled and, as a result, by 2066 the reservoir could reach its project life (para. 11). The effects of sedimentation on Lagos Loíza, Carite, de Cidra, and La Plata have been adapted and summarized in Table 2. Table 2 was compiled from Table 1 in Soler-López's *Sedimentation Survey Results of the Principle Water-Supply Reservoirs of Puerto Rico*. On average these four reservoirs in Region 2 face a storage loss of 882 $m^3/km^2/yr$ and a sediment yield of 985 $m^3/km^2/yr$.

Table 2: Bathymetric Survey Results (Adapted from Soler-López, 2001)

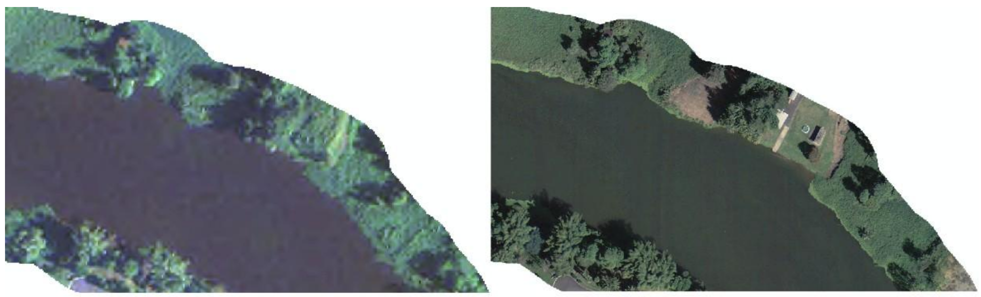
Reservoir	Original Capacity in Mm^3	Const. Year	Study Year	Storage Capacity in Mm^3	Total Volume Loss in Mm^3	Long-term volume loss in m^3/yr	Long-term storage loss per year in percent	Deposition rate in cm/yr	Sediment Yield in $m^3/km^2/yr$	Storage Loss in $m^3/km^2/yr$
Carite	13.95	1913	1999	10.74	3.21	37,326	0.3	3.1	1,938	1,820
De Cidra	6.54	1946	1997	5.76	0.78	15,294	0.2	1.4	768	715
La Plata	40.21	1974	1998	35.46	4.75	197,917	0.5	6.4	483	422
Loíza	26.81	1953	1994	14.20	12.61	307,561	1.1	11.5	750	572
Average	21.88			16.54	5.34	139,525	0.5	5.6	985	882

4.3 Land Use in Watersheds

By performing the land use analysis for Río Grande de Loíza we were able to determine that in the past 7 years there has been extensive development inside the riparian zone of the river. There has been construction of buildings as well as roads in the area. This expansion can pose serious problems because development can greatly increase sedimentation rates.

The riparian zone of Río Grande de Loíza under study spans approximately 9.9 miles along the river bank. Widthwise, the riparian zone was identified as the area located less than 150 feet away from the water bank. Overall the total area for which land use analysis was performed was approximately 0.9 square miles.

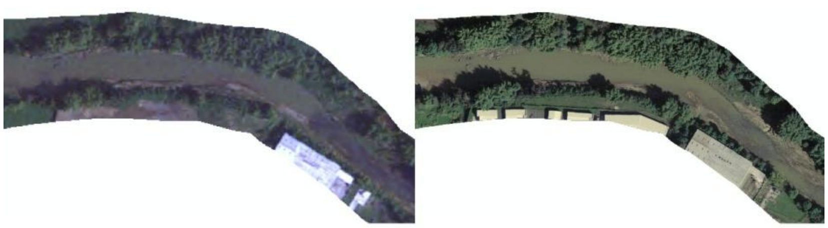
From the 2004 aerial photographs we were able to estimate the developed areas to be roughly 592,512 square feet. In 2010, this area increased to 691,750 square feet. This constitutes a 16.75% increase of land development in a 6-year timeframe. This number is very alarming considering that impervious surfaces such as buildings and paved roads can greatly increase surface water runoff, which in turn increases stream flow and erosive forces in downstream areas. As a result, more sediment gets transported downstream which fills up water reservoirs, potentially reducing their storage capacities by a significant amount. Figure 24 is a clear example of a change in land use. The 2004 aerial photo on the left clearly shows no development on one of the sides of the river, yet the image on the right side from 2010 shows construction of two buildings, cutting of grass as well as exposed soil.



(a) (b)

Figure 24: Example of Land Development between (a) 2004 Aerial Photo and (b) 2010 Aerial Photo

Although there are a number of remote undeveloped areas that were developed over the years, we found that development occurred mostly near previously developed area (Figure 25). This most likely happened due to easy access to the sites because of previously built roads. These areas can be classified as problematic as they attract more development than completely untouched areas.



(a) (b)

Figure 25: Example of Land Development near Previously Developed Areas between (a) 2004 Aerial Photo and (b) 2010 Aerial Photo

During our analysis we were not able to find any sites where buildings were demolished or paved surfaces were turned to either grassland or forest. From this we can conclude that sedimentation rates will continue to increase if development does not stop or if reforestation measures are not taken.

4.4 Effectiveness of Reforestation to Reduce Sedimentation in a Watershed

We obtained important information on reforestation from Dr. Ariel E. Lugo of the International Institute of Tropical Forestry (IITF). Dr. Lugo has a Ph.D. in ecology from the University of North Carolina at Chapel Hill and has done research on the forests of Puerto Rico since 1963. He has been involved in multiple reforestation efforts with the U.S. Department of Agriculture, so the information he was able to provide us was very valuable.

Our main points of interest in the interview with Dr. Lugo were to find out information on the plausibility of reforestation, the effectiveness of forests to prevent sedimentation, what types of trees should be used in reforestation and other solutions to reduce sediment yield. He was very knowledgeable in every area and was a major help in focusing our project.

We began by asking him about the correlation of forested areas in a watershed to the health of the watershed and sedimentation rates. He told us that because watersheds are naturally covered by forests, that is the best way to preserve water quality and prevent sedimentation. Dr. Lugo also mentioned pastures as a fairly effective land use when preventing sedimentation.

We followed up that discussion by asking Dr. Lugo about the plausibility of reforestation, and he let us know that it is much more difficult than we previously believed. In order to plant a forest area, a lot of money and time must be invested to nurture the trees past their younger stages. He suggested using exotic trees for reforestation if we attempt to do it because the exotic trees establish themselves faster and grow more easily. An example of exotic trees that he gave to us was pine trees. He said that by growing exotic trees it can rejuvenate the soil and make it easier to grow endemic trees in the area.

When we asked Dr. Lugo about solutions besides reforestation to reduce sedimentation, he talked about reducing feeding stream velocity so that the sediment does not make it to the reservoir. By reducing stream velocity, the sediment that would travel all the way to the reservoir is deposited in the stream. Sediment in streams is not a problem for treatment plants, but could become a problem in the future if too much sediment accumulates there. Dr. Lugo also suggested using a fence to allow the secondary forest to establish itself naturally. By using a fence, the sapling trees are not eaten by cows or other animals in the area, and the trees are also slightly more protected from human activity than without a fence.

Additionally, the librarian Gisel Reyes that works with the IITF gave us links to helpful documents about reforestation and sedimentation. In particular, a sedimentation handbook she recommended had a lot of useful information. In the handbook there is a chart that shows rates of erosion of different land uses relative to forests. An adaptation of this chart is shown below in Table 3.

Table 3: Rates of Erosion of Different Land Uses Relative to Forests (Adapted from Fan & Morris, 2010)

Land Use	Erosion rate		Relative erosion rate
	Short tons/mi^2/yr	t/km^2/yr	(forest = 1)
Forest	24	8	1
Grassland	240	84	10
Abandoned surface mines	2,400	840	100
Cropland	4,800	1,680	200
Harvested forest	12,000	4,200	500
Active surface mines	48,000	16,800	2,000
Construction sites	48,000	16,800	2,000

4.5 Counter-Arguments to Reforestation as a Solution to Sedimentation

Dr. Gregory Morris provided some counter-arguments to our results in our interview with him. He emphasized how complex watersheds are, and that there is much more than land use that impacts the sedimentation rates. He has done research in various watersheds in Puerto Rico, and told us reforestation is not as effective to decrease sedimentation as we originally thought. The following section summarizes what Dr. Morris discussed in his interview.

Dr. Morris focused his research and work on preventative measures to sedimentation. Overall sedimentation can be greatly reduced by decreasing sedimentation during major storm events. Allowing the sediment to pass through reservoirs by opening gates in the reservoir can prevent sediment deposition, which would only be used during major storms. By opening these gates, the sediment-containing water passes through the reservoir and does not deposit the sediment it contains until it gets further downstream.

The most effective way to reduce the strain on water resources is to implement loss prevention projects in the water distribution system in Puerto Rico. With losses of up to 43% between water withdrawal and final destinations, something needs to be done to reduce these losses. Replacing pipes, improving water meters at consumers' residences and decreasing water pressure in the pipes are but a few of the things that can be done to reduce losses.

Reforestation is not the best way to decrease overall sedimentation because there are too many factors that influence sedimentation. Changing land use in a watershed can reduce sedimentation, but in a short-term situation it will not be very effective. In the 1940s farms in Dos Bocas reservoir in Puerto Rico were abandoned. This farmland had forests grow and develop on it, and is currently covered by a forest. Despite these changes, the sedimentation rate has stayed fairly constant in the reservoir. These findings contradict our findings that forests in a watershed will reduce sedimentation when the forests replace any other type of land use.

Although Dr. Morris cited a counter-example, our research still shows that forest cover reduces sedimentation in a watershed. We also have a table (Table 3 above) from a book that Dr. Morris co-authored in which forest cover is shown to yield at least ten times less sediment than any other type of land use. We received much insight from Dr. Morris about how each watershed is unique and the solution to sedimentation in each watershed must be specific to that watershed. However, our project did not have the time required to research each watershed and we have established general guidelines for watershed management to begin to reduce sedimentation.

Chapter 5: Conclusions and Recommendations

This chapter contains our conclusions and recommendations based on our results. It includes the expectations of the lifespans for the reservoirs we studied based on analysis and recommendations for land use in the riparian zones of the feeding streams in Puerto Rico.

5.1 Lifespans of Reservoirs

Lagos Loíza, Carite, de Cidra, and La Plata have long life expectancies in terms of being completely filled, but they face the serious possibility of being rendered useless before half their storage volume is filled. Lago Loíza will need to be dredged once again by 2018 and Lago La Plata will reach its project life in 2066. Lago Carite and Lago de Cidra will be completely filled by the years 2289 and 2440 respectively, but will reach their project lives soon before those dates.

The reservoirs in Region 2 and all of Puerto Rico are major suppliers of freshwater for the island. The U.S. Geological Survey has conducted numerous bathymetric surveys on a total of 14 principal suppliers on the island. Figure 26 displays the storage loss of 14 principal reservoirs on the island. Looking at the graph, it is evident that efforts in extending the lifespans of reservoirs have not been “sufficient at a long-term scale” (Soler-López, 2001).

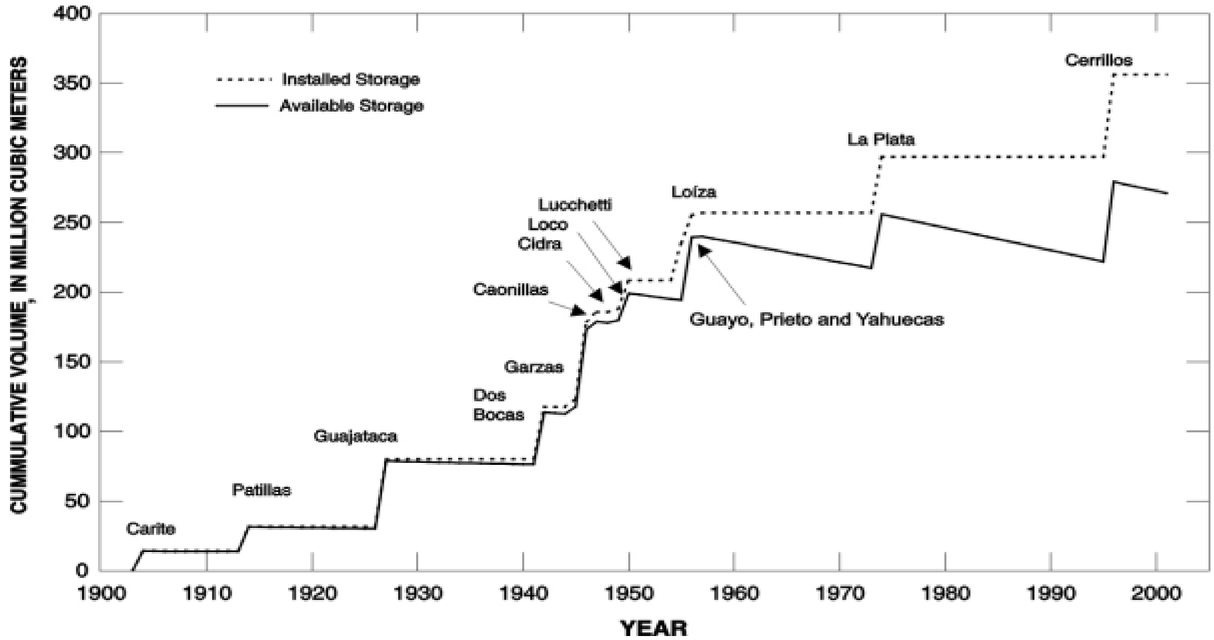


Figure 26: Cumulative Water Resources and Sedimentation Trends for the 14 Principal Reservoirs and Lago Cerrillos (Soler-López, 2001)

Our project focused on reservoirs in Region 2 but in order to fully understand the impeding strain on these water sources, a broader knowledge of all reservoirs on the island must be obtained. According to the U.S. Geological Survey, the eight major water supply reservoirs in Puerto Rico are Lago Guajataca, Lago Loíza, Lago La Plata, Lago de Cidra, Lago Toa Vaca, Lago Cerrillos, Lago Caonillas, and Lago Dos Bocas (U.S. Geological Survey, 2008c). Our recommendation is, if a future study is conducted regarding the lifespans of reservoirs on the island, a focus should be put on Lago Guajataca, Lago Toa Vaca, Lago Cerrillos, Lago Caonillas and Lago Dos Bocas.

5.2 Reforestation Recommendations

Dredging is an unfortunate necessity in Puerto Rico, but any avenue that can reduce the frequency of it should be taken. There have been numerous methods that we have come across to reduce the erosion/sedimentation rates for the major reservoirs in Puerto Rico. Primarily, reforestation has been our focus to reduce sedimentation as it correlates with the work of the Conservation Trust of Puerto Rico so well. Our recommendation is to use forested areas in the riparian zone for 150 ft. on either side of a stream/river to reduce sedimentation rates and lessen the frequency of dredging. The method to create a secondary forest in the area depends on the degradation the area has gone through.

If an area has been deemed to have fairly low sedimentation rates but is not forested, our recommendation is to put up a fence 150 ft. from the stream. Putting up a fence prevents grazing animals from eating any vegetation that may grow there and helps prevent people from causing erosion. The forest can then regrow naturally and will be as healthy as a primary forest in forty years.

Areas that have moderate sedimentation rates and are not forested should also have a fence put up 150 ft. from the stream, but with grass planted in the area between the fence and stream. Grassland gives ten times the sedimentation of a forest, but it establishes quickly and improves the health of the soil in preparation for the growth of a forest. The forest can again grow naturally in this situation, with the grass being the short-term solution until the forest has grown in as the long-term solution.

Severe sedimentation rates are usually the result of unhealthy soil and poor land use. Therefore, a reforestation program can be implemented, using exotic trees as Dr. Lugo suggested. Grass should be planted in this situation as well, serving as a quick and easy short-term solution. The exotic trees, such as pine trees, will establish themselves quickly and help to improve the health of the soil while providing the shade and soil stability required for the endemic trees. The endemic trees can either be planted by people if the sedimentation demands an immediate fix or they can grow naturally over time.

In many areas there are buildings and roads next to the streams, and it would be too costly to try to move these to another location to reduce sedimentation. One thing that can be done is to implement incentives for the owners of the land to plant trees or establish preservation measures to protect the areas of the riparian zone that can be helped. These incentives should be sustainable for the government, and can include non-cash rewards such as no-till technology for farmers.

By expanding on the research we have done, a more complete understanding of the sedimentation in each watershed can be developed. Our research included the riparian zone of only one river, thus there is much more research to be done in all the drainage basins of Puerto Rico. Researching other reservoirs in Puerto Rico would also assist in the overall assessment of surface water on the island. By using our methodology this can be accomplished. We hope our report can be used to expand and continue with this research to conduct a more complete assessment of all the reservoirs in Puerto Rico.

The Conservation Trust of Puerto Rico can use the recommendations in this report to begin the reduction of sedimentation rates in reservoirs. Using the program Árboles…Más Árboles, the Trust can focus its reforestation efforts in the areas that necessitate a change in land use. A collective program between the Trust and the IITF could also be established with the focus of increasing plant life in the riparian zone.

WPI teams can expand this research to include studies on the land development of other watersheds in Region 2 and eventually all of Puerto Rico. With step-by-step instructions, our methodology shows how to accomplish this in the ArcGIS program. These land use studies can be combined with the sedimentation surveys already done for the major reservoirs in Puerto Rico to determine where the most problematic areas lie. The problematic areas can then be prioritized by need for intervention to reduce sedimentation. PRASA could also become involved with the project, as it would be to their economic benefit to reduce sedimentation.

The future of sustainable incentives is a bright one; the government just needs to be shown the benefits for such a program. PRASA is a government agency, so by decreasing the amount of dredging that needs to be done the government could actually save money by providing incentives. A cost-benefit analysis would need to be done, possibly by WPI, and presented to the government. Suggestions should include no-till agriculture technology instead of money as incentives. This creates a sustainable incentive for the government, and makes the farmers receiving the incentives happy as well.

The freshwater resources of Puerto Rico are slowly dwindling, and without intervention they will cause problems in the near future. By implementing our suggestions, millions of dollars can be saved by the government and the Puerto Rican people. This money can go towards more important things such as education, instead of being used to patch up a flawed system. Our report provides recommendations that will improve the lives of people who live in Puerto Rico; all that needs to be done is the implementation of these recommendations.

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Appendices

Appendix A: Sponsor Description

The Conservation Trust of Puerto Rico (2010) is a private, non-profit organization that was founded in 1970 by the United States and Puerto Rican governments. This organization's sole mission is to educate and improve the natural ecosystems of Puerto Rico. The Trust encourages citizens to contribute to the protection of the natural areas of the island by educating them with the necessary information. Programs such as Árboles... Más Árboles have been created to provide the citizens of Puerto Rico with information about the protection and conservation of the land. The Trust's driving motivation is to benefit the people of Puerto Rico.

Until 1980, the petrochemical companies in Puerto Rico paid tariffs to the government, which were previously used to fund the Trust (The Conservation Trust of Puerto Rico, 2010). In addition, the Trust also received funding from companies operating under Section 936 of the U.S. Internal Revenue Code until the section expired. To expand their financial resources the Trust began to invest in the stock market and created its own funding, helped by federal tax returns from the government. Their final source of income is the AMIGOS, a group comprised of individuals and companies, who donate money and land to further aid its cause.

One of the Trust's most successful programs is Árboles... Más Árboles, which addresses reforestation. Its mission is to promote the protection and conservation of native tree species exclusively (The Conservation Trust of Puerto Rico, 2010). The four main components of this proposal are as follows: Propagation, Reforestation, Research and Education. The program holds an annual fair that includes educational activities such as tree planting workshops, ecological walks, environmental games, storytelling and creative activities for children. The Trust has four nurseries: the Experimental Station of the University of Puerto Rico in Río Piedras, the San Cristóbal Canyon protected natural area between Barranquitas and Aibonito, Hacienda Buena Vista in Ponce and Las Cabezas de San Juan Nature Reserve in Fajardo.

The Land Acquisitions, Donations and Conservation Easements Program is the heart of the Conservation Trust (2010). With the aid of this program the Trust has been able to protect 23,000 acres of land (The Conservation Trust of Puerto Rico, 2010). The Trust uses numerous means such as direct land acquisition, donations, and the establishment of conservation easements to protect lands of ecological and historic value on the island.

The Conservation Trust (2010) has three trustees, an executive director and an advisory council. The three trustees, who essentially lead the company, include Kate Romero, Mack Mattingly and María Lorenza Ferré Rangel. Also in charge of the Trust is the executive director, Fernando Lloveras San Miguel, who is known to have expanded and improved the Trust since his instatement. Completing the executive level of administration at the Trust is the advisory council, which includes professors, scientists, businessmen, and lawyers.

Appendix B: Glossary

AAA - Autoridad de Acueductos y Alcantarillados

Agricultural water-use – includes water used for irrigation and livestock

Capacity In-flow- is the ratio of total reservoir volume to mean annual inflow

Design Life- is the planning period used for designing the reservoir project

Domestic water-use – includes water used for drinking, food preparing, bathing, laundry, cleaning dishes, flushing toilets, cleaning vehicles, and maintaining lawns and gardens

Dredging - the relocation of underwater sediments and soils for the construction and maintenance of waterways, dikes, and transportation infrastructures and for reclamation and soil improvements

Endemic Species – a species that is only found in one area, such as an island. An example of an endemic species is the lemur, which is found only on Madagascar

Exotic Species – a species that is not native to an area but is now living there. Exotic species are not necessarily invasive species. An example of an exotic species is the pine tree in Puerto Rico, not native to the island but can be found there now

Freshwater – water without salt

Grass – an annual to perennial herb, generally with round erect stems and swollen nodes; leaves are alternate and two-ranked; flowers are in spikelets each subtended by two bracts

Hydrology – the study of the properties, distribution, and effects of water on the Earth's surface, soil, and atmosphere

IITF- International Institute of Tropical Forestry

Industrial water-use – includes industrial uses: manufacturing processes (fabrication, processing, washing and cooling), commercial uses: hotels, restaurants, office buildings, commercial facilities, and civilian and military institutions, and mining use: extraction of sand and gravel

PRASA- Puerto Rico Aqueduct and Sewer Authority

Project Life- is the period during which a reservoir can reliably serve the purpose for which it was constructed

Reservoir yield-the function of available storage volume in the conservation pool

Riparian – the zone adjacent to a stream or any other waterbody (from the Latin word ripa, pertaining to the bank of a river, pond, or lake)

Saline water – salt water

Sediment Yield- amount of eroded sediment discharged by a stream at any given point

Turbidity – murkiness or cloudiness of water caused by particles, such as fine sediment (silts, clays) and algae

Trapping Efficiency-a ratio describing the mean annual sediment yield that is deposited or trapped in a reservoir

Unaccounted water-use – includes public water use: non-individual consumption activities such as firefighting, street washing, and/or recreational activities at municipal parks, conveyance loss: water lost in transit from a pipe or canal system due to leakage or evaporation, and apparent loss: water that is delivered to customers but is not metered due to errors in water accounting or unauthorized use of water

USGS- United States Geological Survey

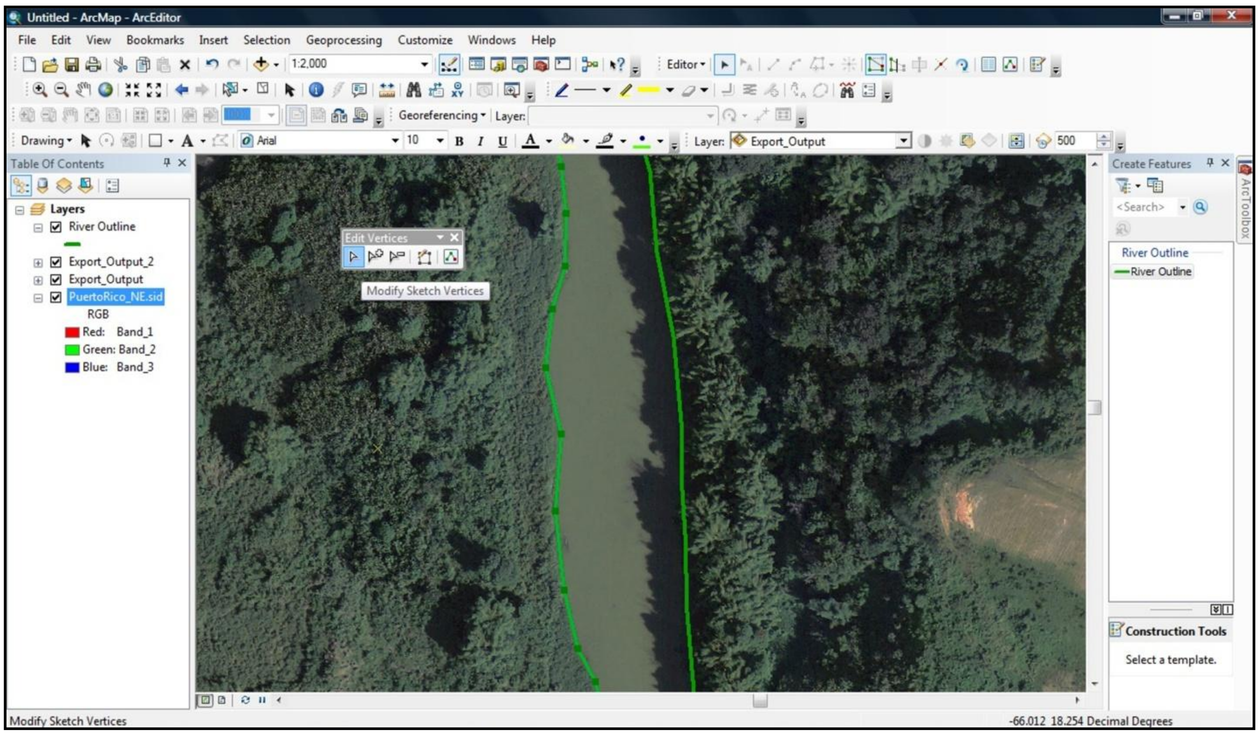
Watershed – the land area that drains into a particular river system, including its tributaries

Appendix C: Land Use Classification Guide

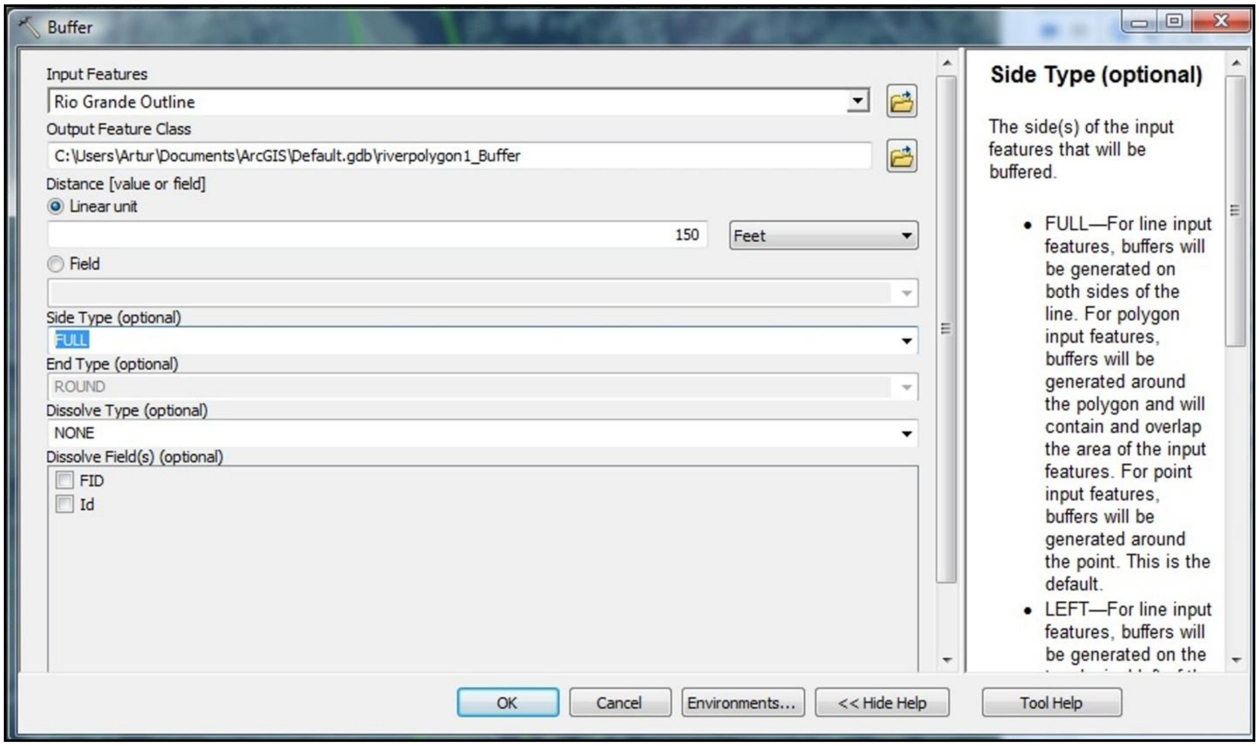
The following is a Land Use Classification Guide which shows step-by-step instructions that were used to identify developed areas along the riparian zone of Río Grande de Loíza.

Steps:

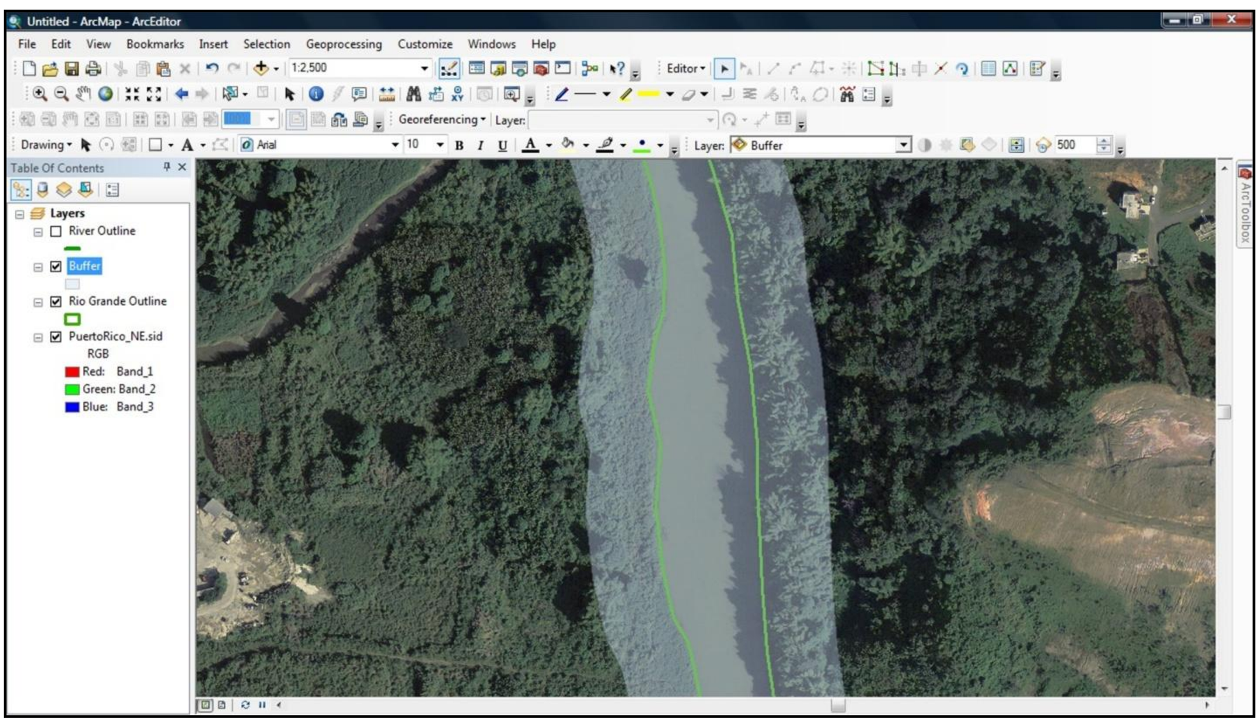
1. Edit the River Outline shape file in order to make it more accurate according to 2010 aerial photographs. Use the “Editor” tool to edit the river borders. Add, delete, and move vertices as needed.



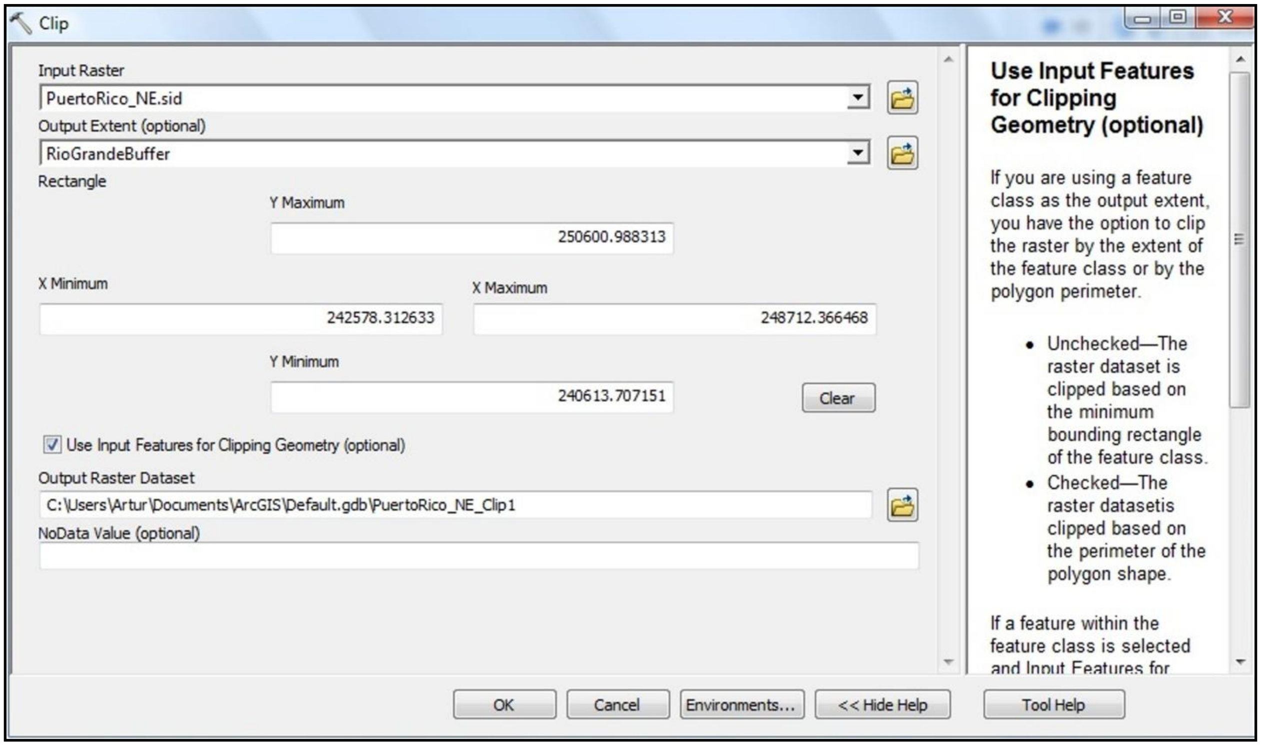
2. Use “Buffer” tool to create 150 foot buffer around the edited river outline to represent the riparian zone of the river.



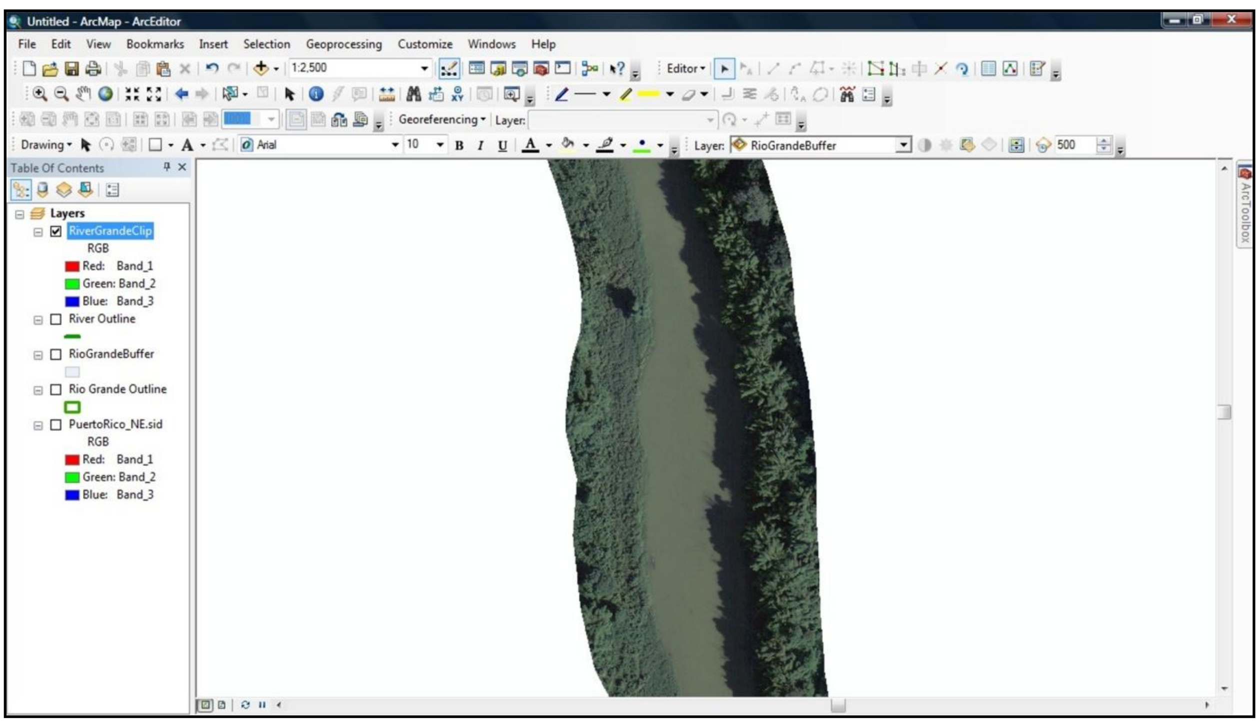
The result should look similar to the following image:



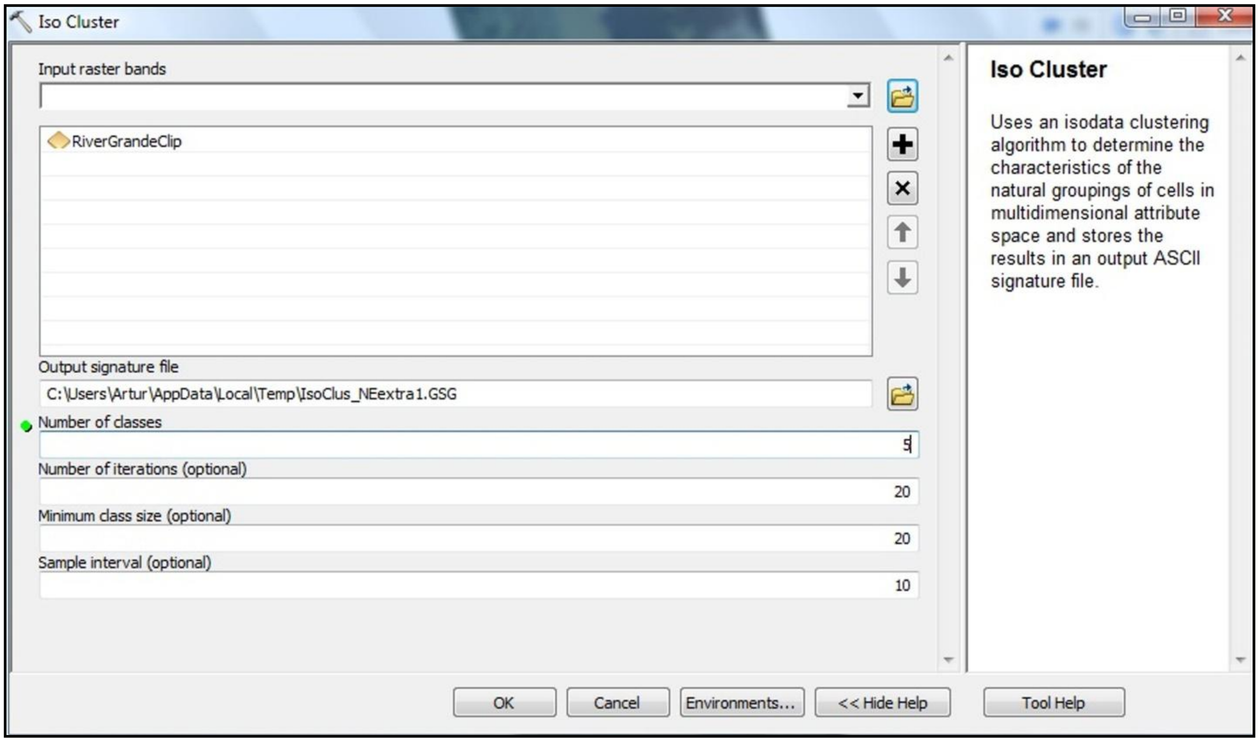
3. Use “Clip” tool to clip the aerial photograph by using the geometry of the newly created buffer file. Check off the “Use Input Feature for Clipping Geometry” checkbox.



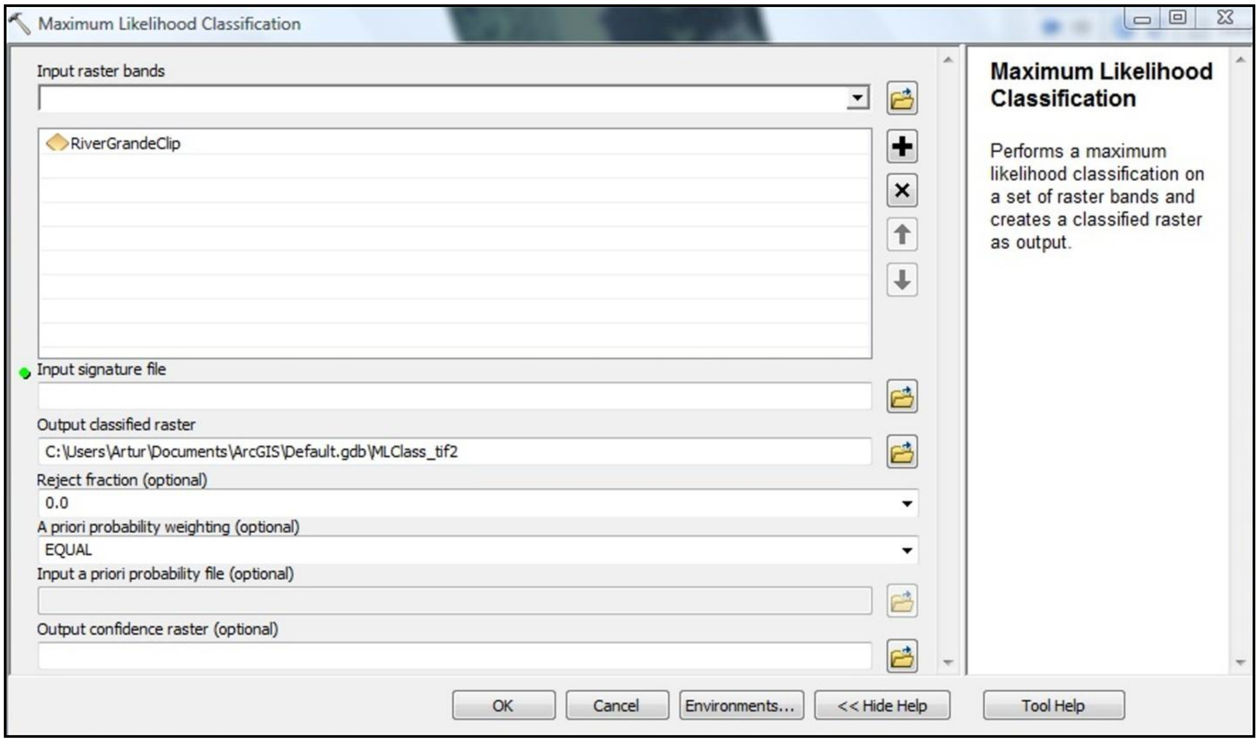
The resulting image should have the river along with the riparian zone cropped:



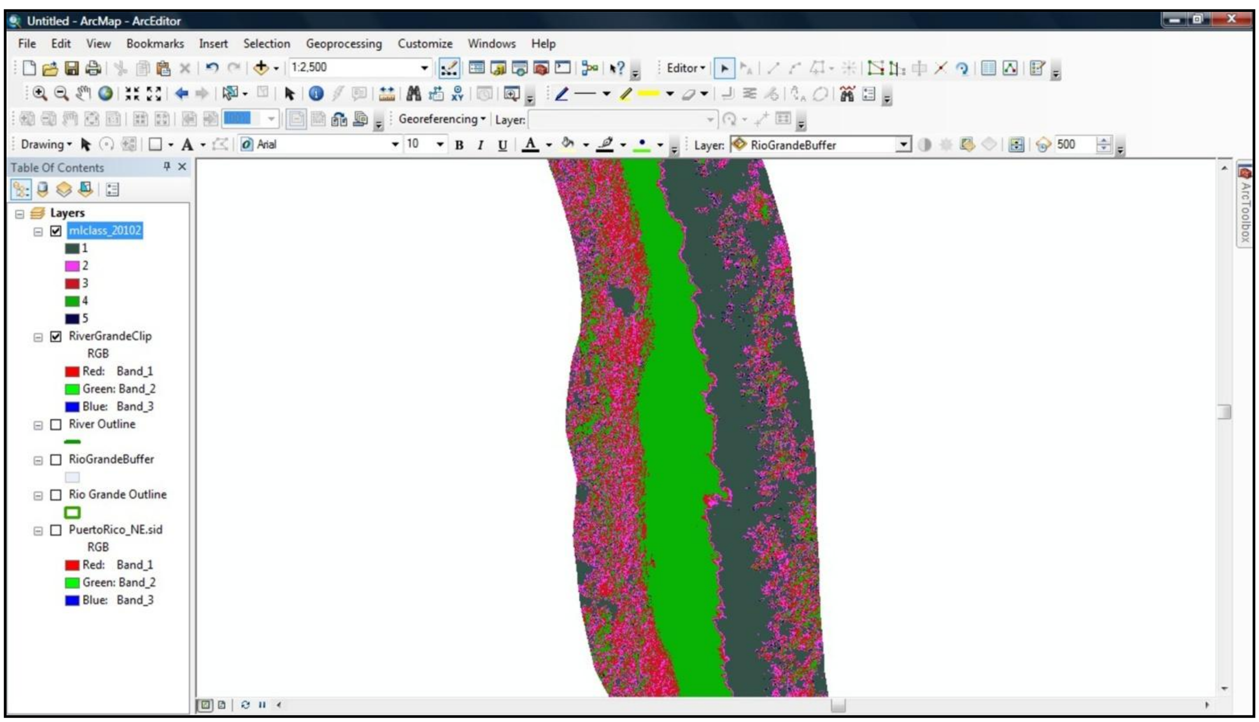
4. In order to use classification tools in ArcGIS, a signature file must first be created. Use the "Iso Cluster" tool to do so. Create 5 classes.



5. Create a supervised classification with "Maximum Likelihood Classification" tool using the signature from the previous step.

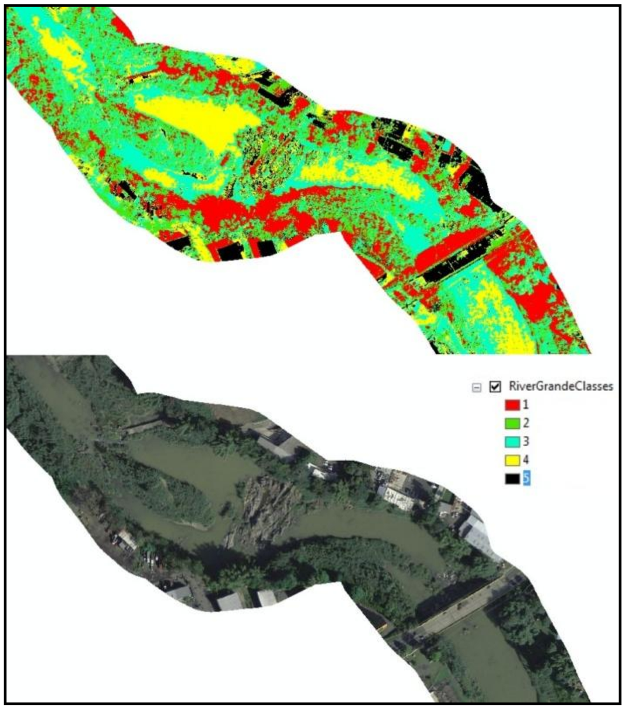


“Maximum Likelihood Classification” tool will generate a raster file with 5 different classifications:



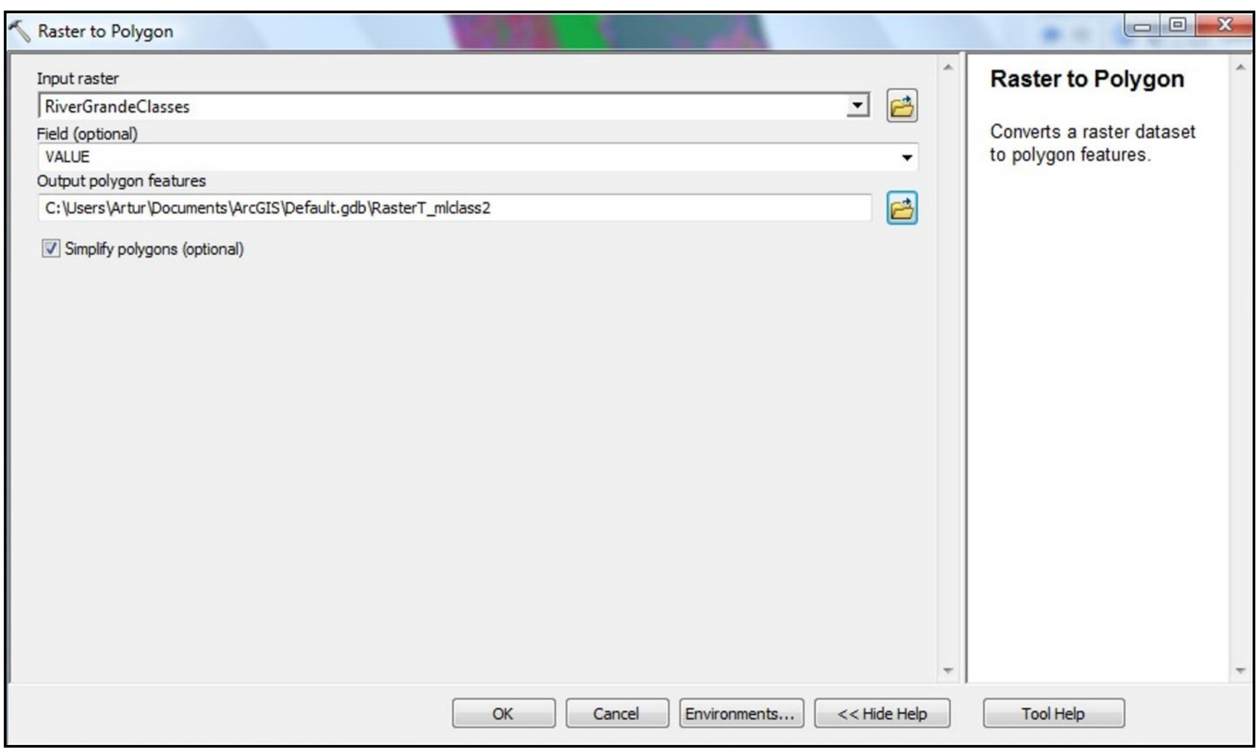
Each classification will represent a different type of land. 5 classes were used to generate a signature file and thus the classified raster file will not be very accurate and will require manual reclassification.

6. Identify which class best identifies developed land. In this example this is class 5.

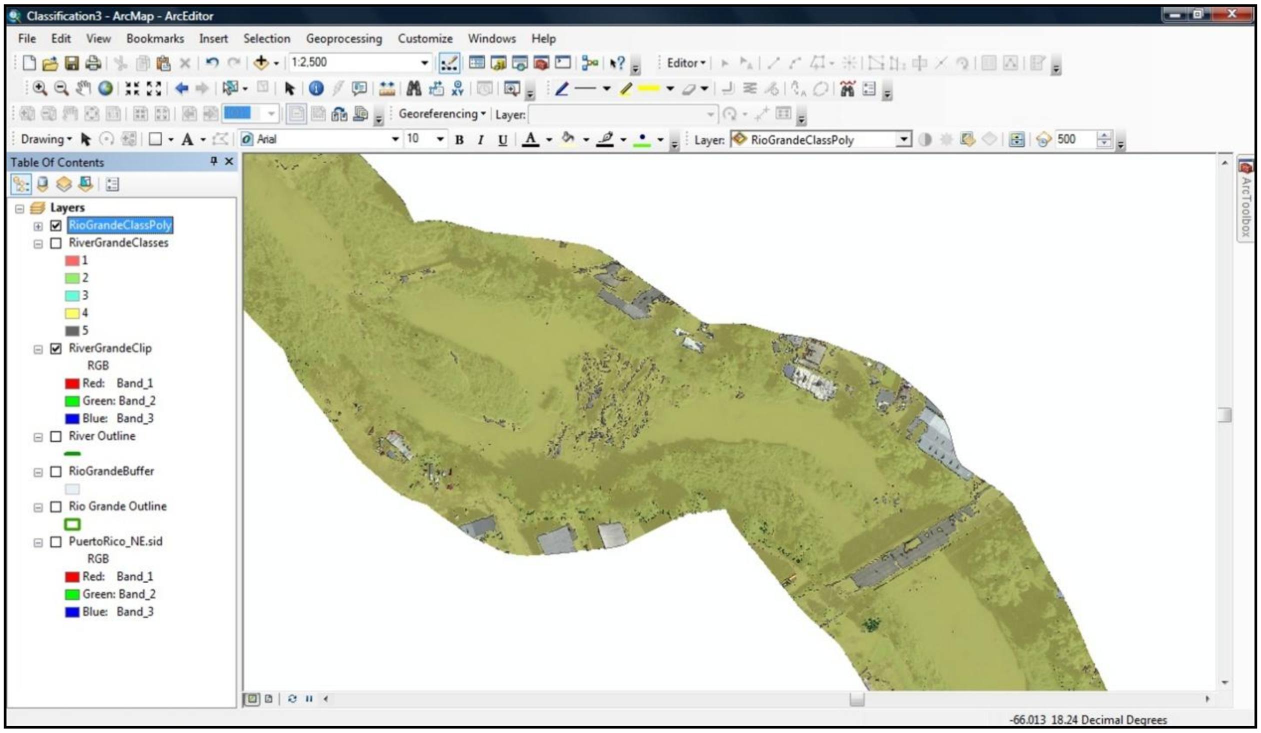


At the bottom right corner of the image there is a bridge that was not completely classified as class 5. Areas such as this will have to be manually reclassified.

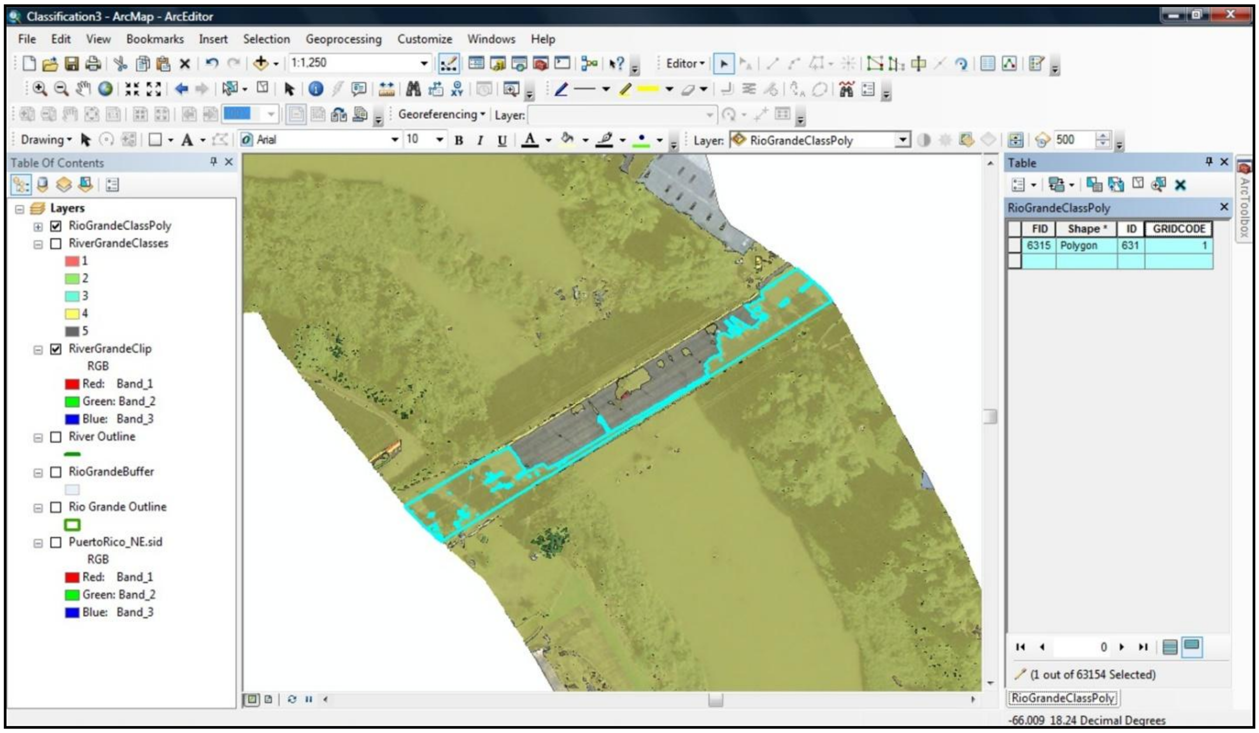
7. To manually edit the classified raster file, first use the "Raster to Polygon" tool.

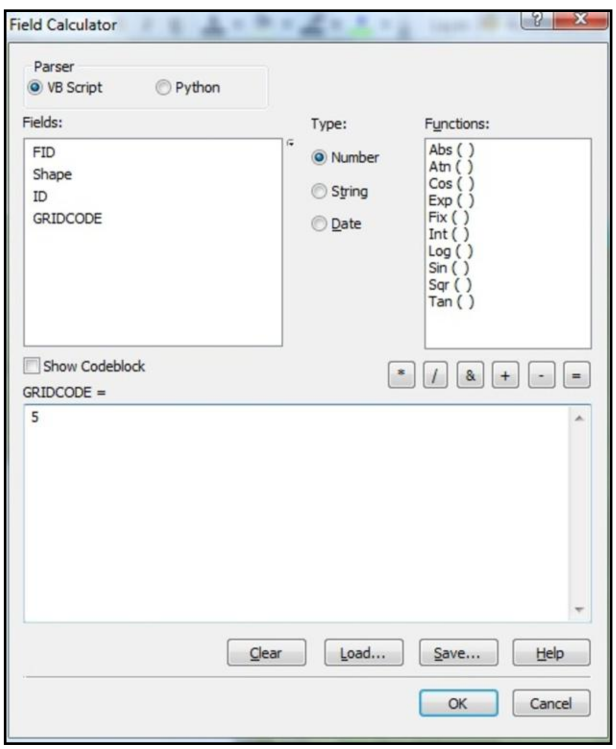


8. Adjust the transparency of the layer that was created in the previous step in order to see which parts of the map need to be reclassified:

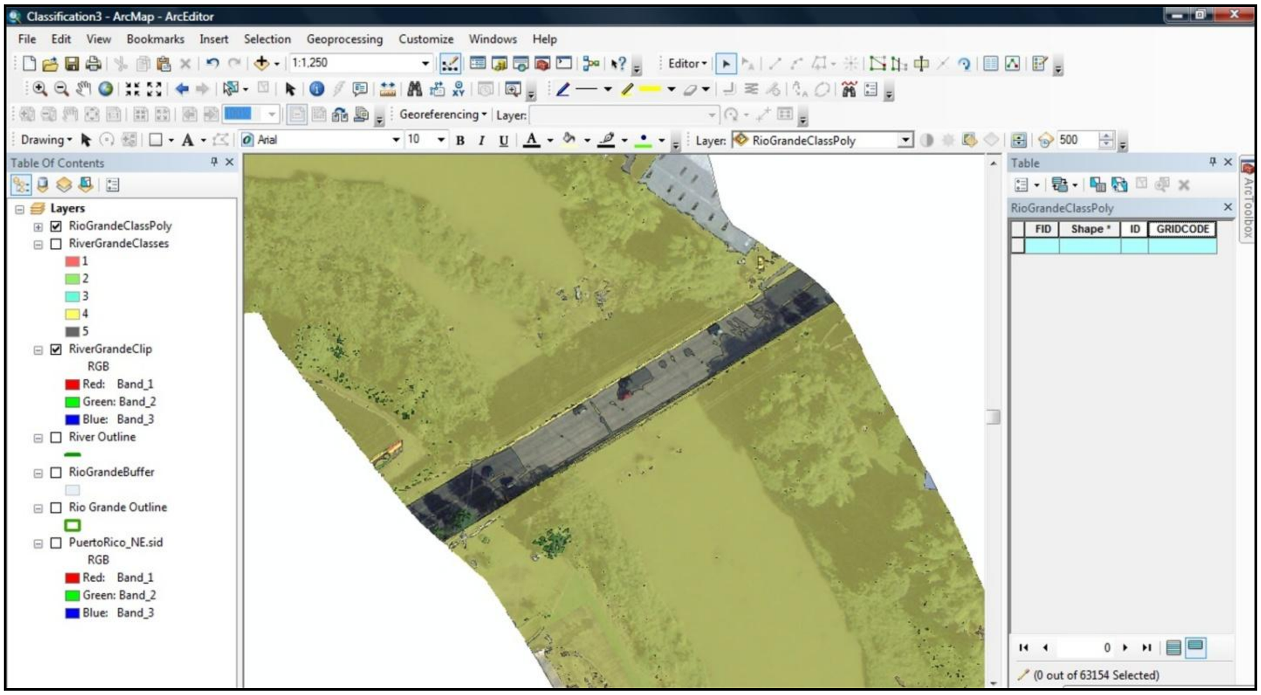


9. After selecting a polygon which needs to be reclassified, use the “field calculator” tool change the classification in the “GRIDCODE” window.

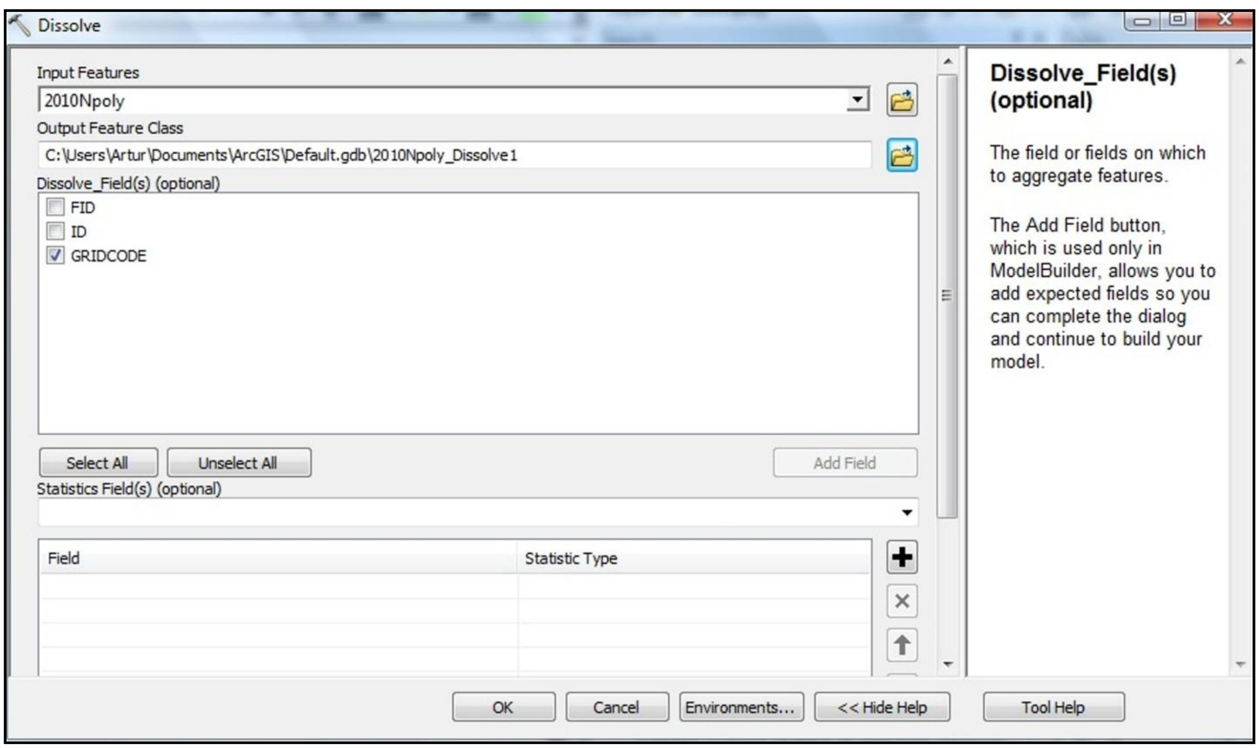




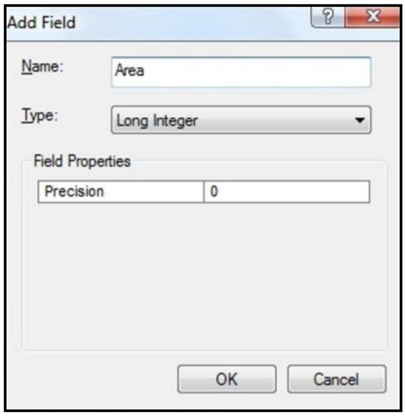
Values 1 through 4 are assigned to polygons which do not fall into the developed land category while value 5 is assigned for those that do. After reclassification, the polygon that was being reclassified should change its color:



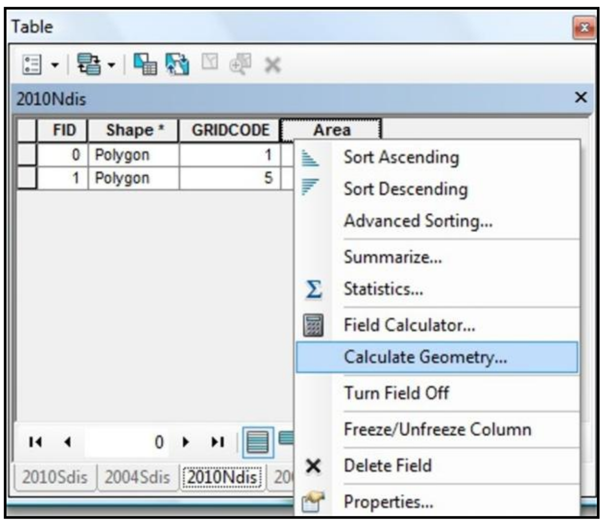
10. Repeat step 9 until all portions of the map are classified correctly.
11. “Dissolve” the polygons with filed “grid code”.



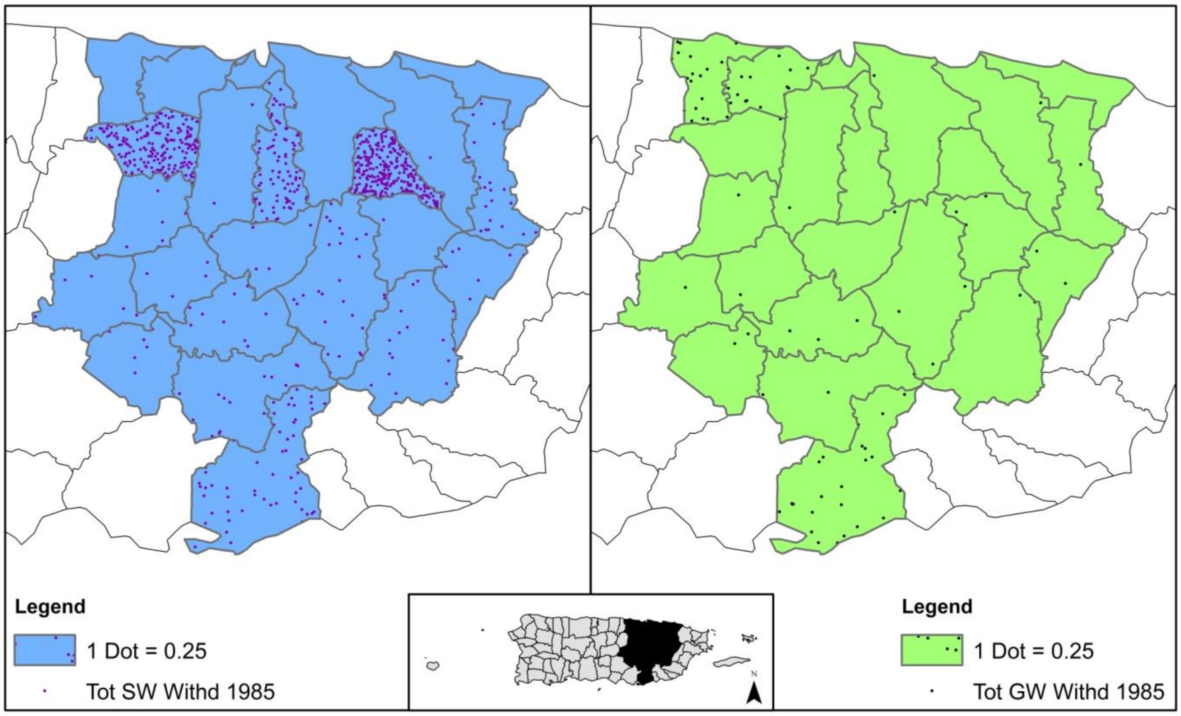
12. Create a new field in order to calculate areas of



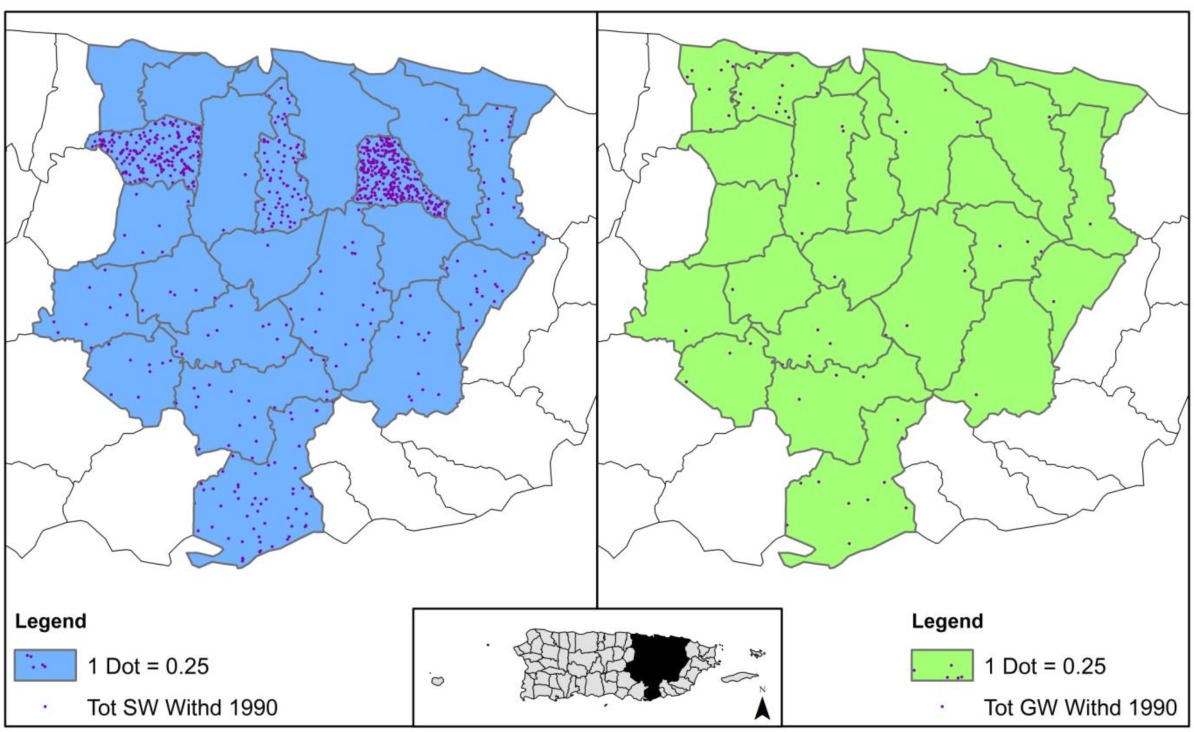
13. Calculate area of the developed land by using “Calculate Geometry” tool.



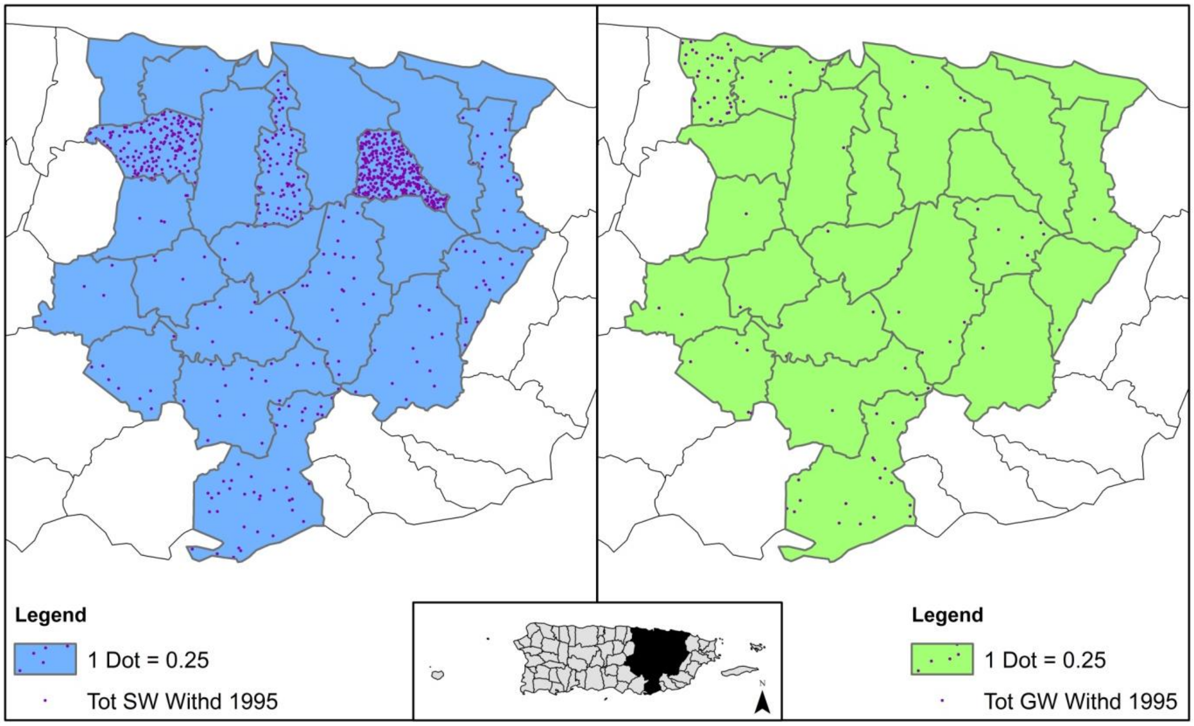
Appendix D: Maps of Surface Water vs. Ground Water Withdrawal Rates in Region 2



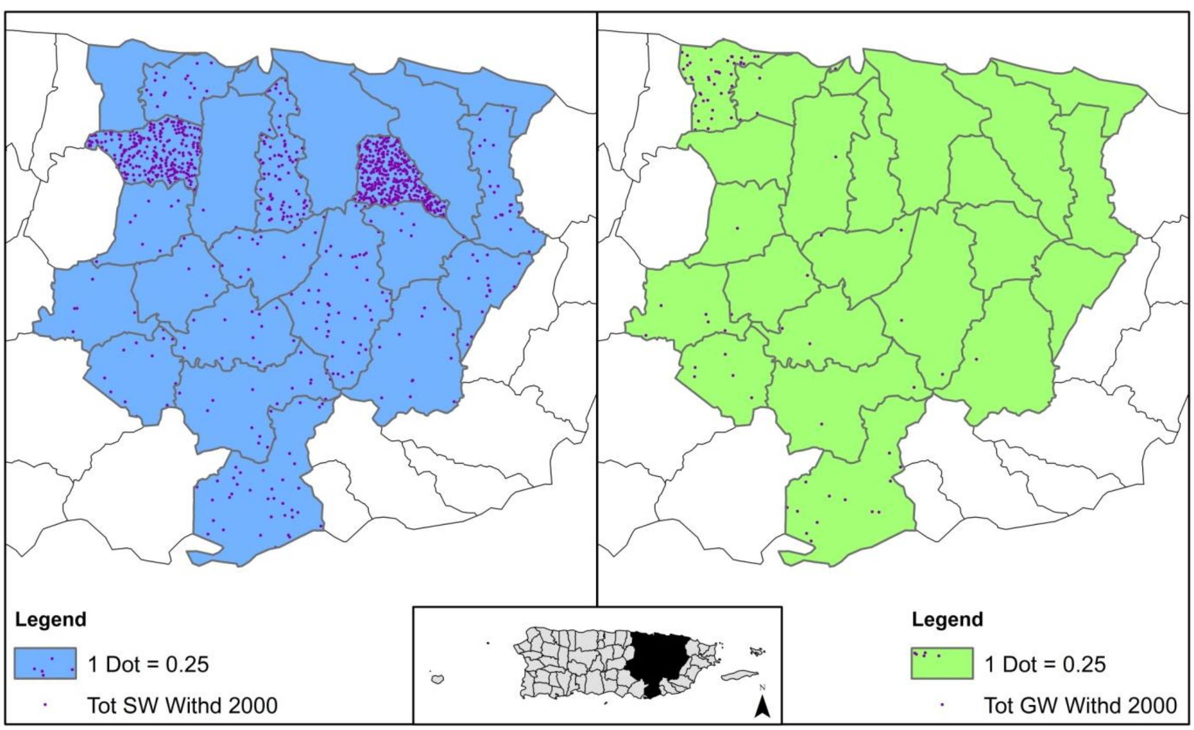
(a) (b)



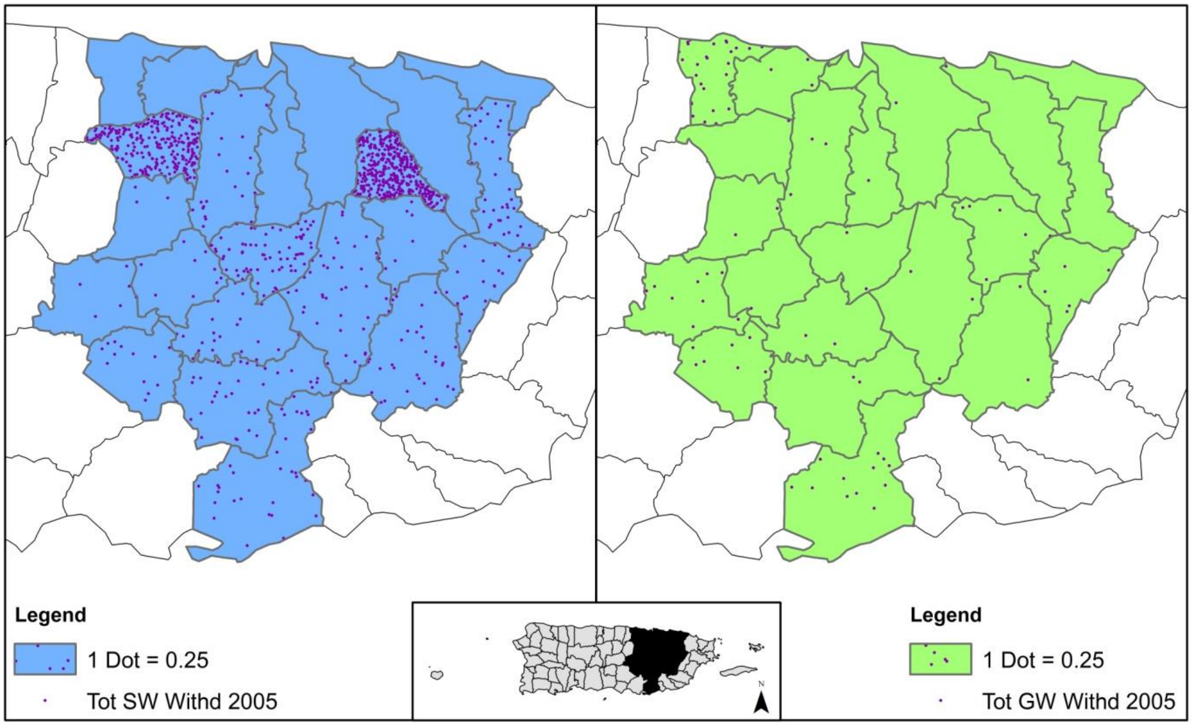
(a) (b)


Legend
1 Dot = 0.25
Tot SW Withd 1995
N
Legend
1 Dot = 0.25
Tot GW Withd 1995

(a) (b)

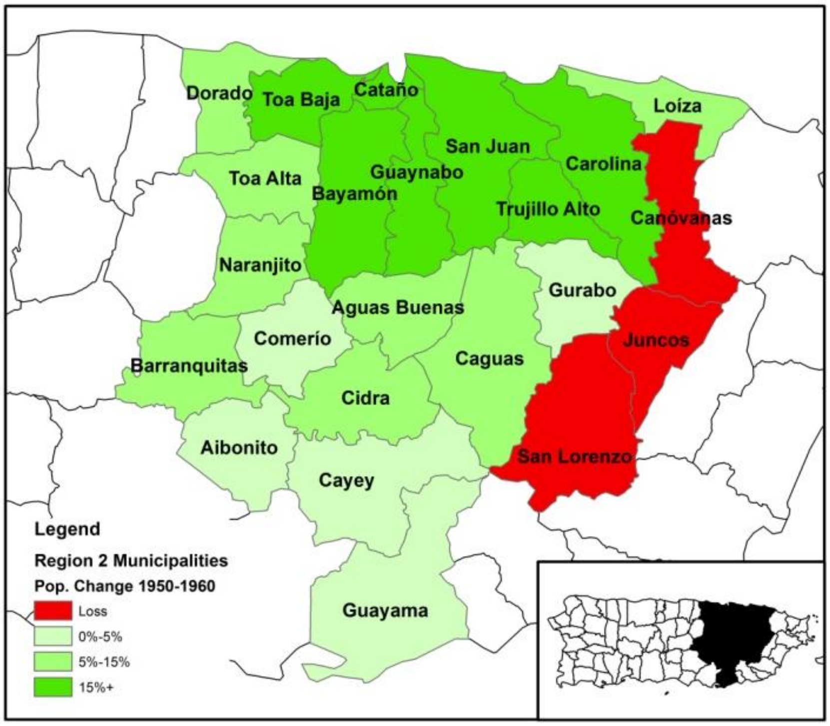

Legend
1 Dot = 0.25
Tot SW Withd 2000
N
Legend
1 Dot = 0.25
Tot GW Withd 2000

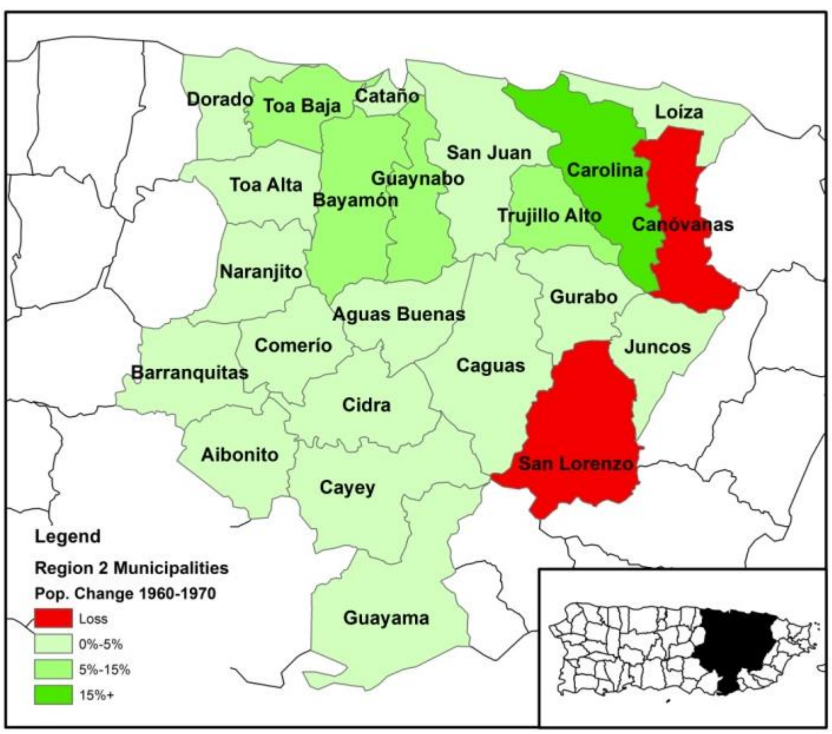
(a) (b)

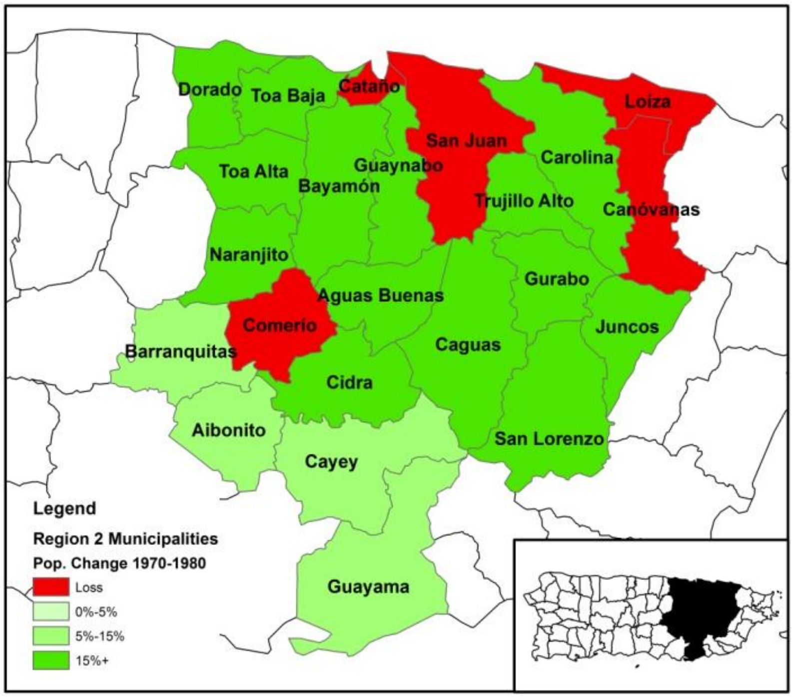

Legend
1 Dot = 0.25
Tot SW Withd 2005
Legend
1 Dot = 0.25
Tot GW Withd 2005

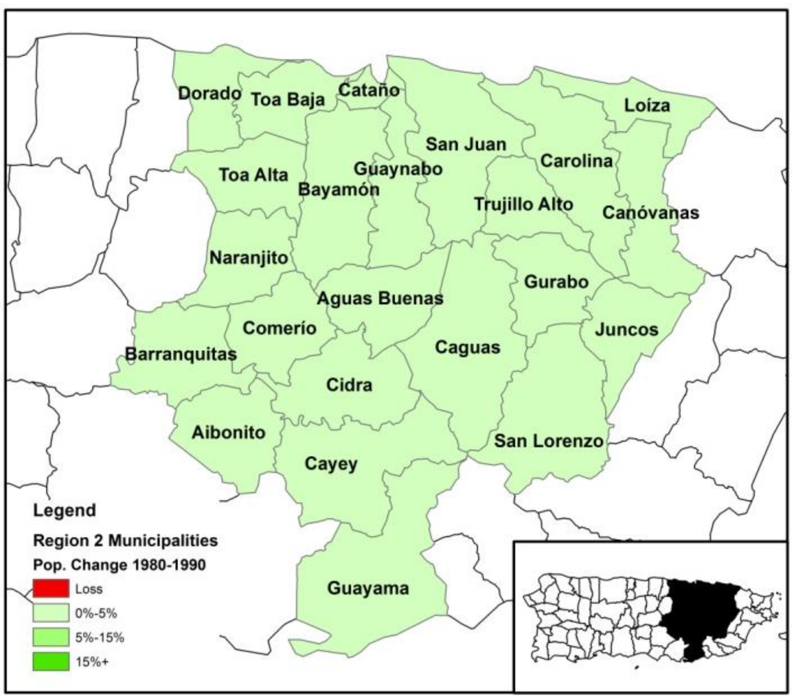
(a) (b)

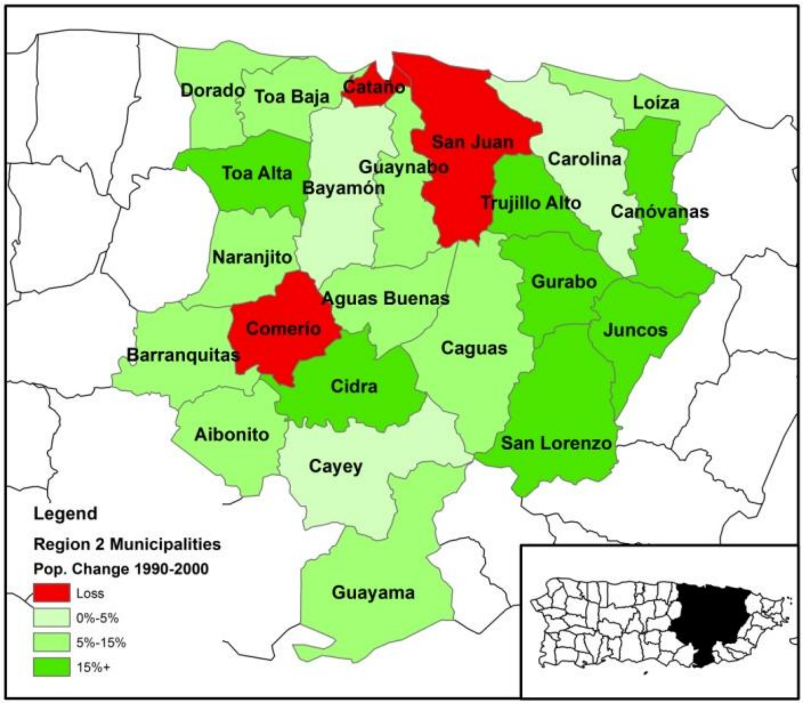
Appendix E: Maps of Population Change Rates in Region 2

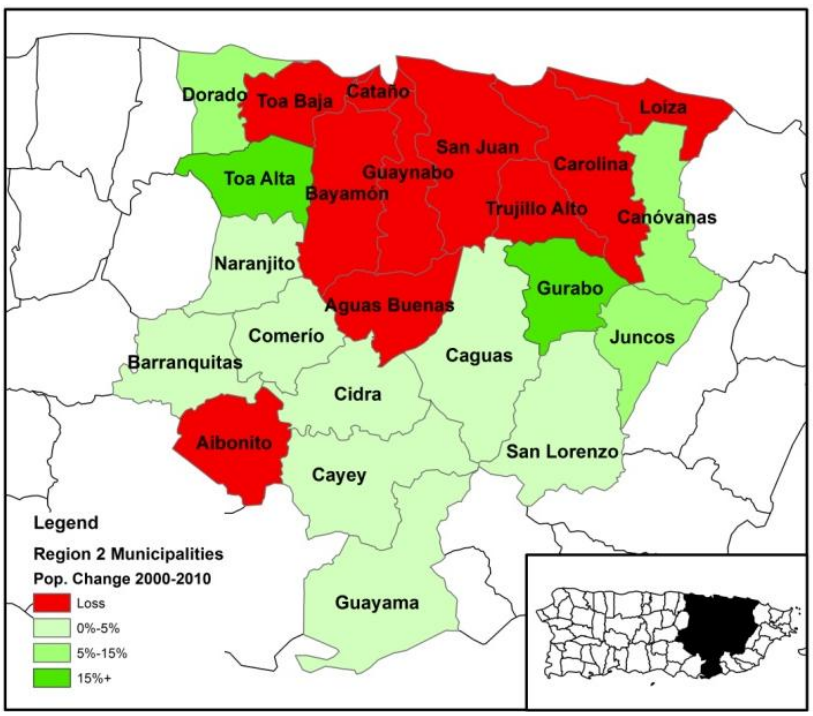





Dorado
Toa Baja
Cataño
Loíza
San Juan
Toa Alta
Guaynabo
Carolina
Bayamón
Trujillo Alto
Canóvanas
Naranjito
Gurabo
Aguas Buenas
Comerío
Juncos
Caguas
Barranquitas
Cidra
Aibonito
San Lorenzo
Cayey
Guayama
Legend
Region 2 Municipalities
Pop. Change 1970-1980
Loss
0%-5%
5%-15%
15%+


Dorado
Toa Baja
Cataño
Loíza
San Juan
Toa Alta
Guaynabo
Carolina
Bayamón
Trujillo Alto
Canóvanas
Naranjito
Gurabo
Aguas Buenas
Comerío
Juncos
Caguas
Barranquitas
Cidra
Aibonito
San Lorenzo
Cayey
Guayama
Legend
Region 2 Municipalities
Pop. Change 1980-1990
Loss
0%-5%
5%-15%
15%+


Dorado
Toa Baja
Cataño
San Juan
Loíza
Carolina
Toa Alta
Guaynabo
Bayamón
Trujillo Alto
Canóvanas
Naranjito
Gurabo
Aguas Buenas
Comerío
Juncos
Caguas
Barranquitas
Cidra
Aibonito
San Lorenzo
Cayey
Legend
Region 2 Municipalities
Pop. Change 1990-2000
Loss
0%-5%
5%-15%
15%+
Guayama


Dorado
Toa Baja
Cataño
Loíza
San Juan
Carolina
Toa Alta
Guaynabo
Bayamón
Trujillo Alto
Canóvanas
Naranjito
Gurabo
Aguas Buenas
Comerío
Juncos
Caguas
Barranquitas
Cidra
Aibonito
San Lorenzo
Cayey
Legend
Region 2 Municipalities
Pop. Change 2000-2010
Loss
0%-5%
5%-15%
15%+
Guayama