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The Panama Canal Expansion Impacts: Connecting Us to the Future

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Abstract

Since 2007, the Panama Canal Authority (ACP) has been carrying out an expansion project in order to accommodate larger vessels and increased traffic through the Panama Canal. This report addresses the following project goals: 1) provide land management reports for areas surrounding Lake Gatun; 2) suggest an alternative range structure for navigation; 3) improve the water quality stored on ACP tugboats; and, 4) provide preliminary designs for a new spillway. Collectively, the results from these projects have positive impacts on the environment, sustainability, efficiency, and safe transit of the Panama Canal to assure global operations.

Authorship

In general, all members of the team contributed to this report equally. Sections other than chapters 1, 2, 3, and 4 were written and edited as a team. Below, the specific chapter and their corresponding primary author are listed.

Chapter 1: Reclamation of Lake Gatun and Surrounding Areas – Abigail Brakenwagen

Chapter 2: Alternative Design for Range Towers used as Navigational Aids – Brigitte Perera

Chapter 3: Assurance of Drinking Water Quality on Tugboats – Adrienne Weishaar

Chapter 4: New BEC Spillway Design – Carly Giannini

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Licensure Statement

Professional licensure laws and requirements for civil engineering vary internationally. In Europe, an engineering student must apply to become a member of European Federation of National Engineering Associations. In some countries, such as Germany and India, graduating from an accredited university with a diploma in engineering is recognized as engineering licensure. In order to work for the Panama Canal Authority, an individual must register their university diploma and pay for a certificate and seal to be recognized as an engineer. Other countries have varying testing standards or requirements to become a professional engineer.

In the United States, each state has different requirements for becoming a licensed civil engineer. These requirements and laws are controlled by the National Council of Examiners for Engineering and Surveying (NCEES). Licensure in the engineering profession is critical to fully advance one's career and is a symbol of prestige and honor. A professional licensure signifies that an engineer understands the technical and ethical obligations in their field of engineering and the protection of public health and safety in society (ASCE, 2015; ABET, 2015). Only professionally licensed engineers are legally able to sign and seal plans or offer services (NSPE, 2015). Additionally, only licensed engineers can bid for government contracts or lead private firms. It is much easier for licensed engineers to advance further in their career and become more marketable as professionals when searching for a job (NCEES, 2015).

In order to be officially recognized as a Professional Engineer in the United States, the first step is to graduate from an Accreditation Board for Engineers and Technology accredited program with a Bachelor of Science degree. Around the time of graduation, the aspiring engineer must pass the Fundamentals of Engineering (FE) exam administered by NCEES with a score that is dependent on the state where the license is sought. When an individual passes the FE exam, they become an Engineer in Training (E.I.T). Four years of experience practiced in civil engineering must be completed under supervision of a licensed engineer. After the required years of work are completed, an E.I.T can take the Principles of Practice of Engineering (PE) exam. An application of all the engineer's work and responsibilities can be submitted after passing the PE exam and a PE license for the state they will work in can be obtained. The license must be continually renewed and maintained as the engineer improves their skills throughout their career (NSPE, 2015).

A professional engineering license ensures that the work of an individual is representative of the codes regulated by the state for the production of safe and sustainable projects. Professional engineering licensure is quality assurance and a safeguard for the public that educated professionals are conducting projects on the infrastructure they use daily. The NCEES, company, and public know that the work that an engineer performs is based on their knowledge of civil engineering. Professional engineers take pride in knowing their work meets a state-authorized engineering seal of approval. Obtaining a license is not an easy task and by doing so, the individual has put much time and effort into their work, and have gone above the minimum requirements for being an engineer.

Professional Engineers maintain a reputable position in the respectable and commended profession of engineering (NCEES, 2015). All engineers have a responsibility to themselves, their company, and the public to do the best work they can. The engineer is seen as a truthful, independent, and competent individual who will make the appropriate ethical choices in their career. Society relies on civil engineers daily, whether it is on their commute to work, the building they sleep in at night, or even for the water they drink. People depend on these engineers to provide services that emphasize safety as the top priority. Additionally, a professional engineer is responsible for advising engineering students on the licensure process, their experiences, and the expectations associated with the license. Professional licensure allows engineers to develop and improve the engineering practice over time.

Executive Summary

The Panama Canal began operations in 1914 to connect the Atlantic and Pacific Oceans, revolutionizing world trade. At the time of construction, it was the largest civil engineering undertaking in the world, and in 1997 the American Society of Civil Engineers named it as one of the Seven Wonders of the Modern World (ASCE, 1997). To accommodate larger vessels and increase the number of transits through the Canal, the Panama Canal Authority (ACP) began a $5 billion expansion project in 2007, expected to be completed in early 2016. This project increases the capacity of the existing Canal by adding two new passages for larger Post-Panamax vessels. The expansion project has economic, environmental, health, and social impacts throughout the Canal. This report addresses four projects based on these impacts relating to land use, navigation, water quality, and spillways in the Panama Canal.

Reclamation of Lake Gatun and Surrounding Areas

The first project studied the use of land surrounding the Canal, specifically around Lake Gatun. Since 1999, when the Canal Zone was returned by the United States to the Panamanian government, the occupants of this land have remained. Most of the residents around Lake Gatun and other Canal Zone areas were workers from the U.S. and decided to stay in Panama. The ACP is attempting to reclaim this land and implement measures to protect and manage it, primarily because of its proximity to the Canal. This project sought to assist in the management of this land by meeting the following objectives:

- Study land areas, current use, and existing policies and regulations;
- Investigate similar types of land management reports;
- Develop a framework for a carrying capacity study of Lake Gatun; and,
- Design a shoreline management plan for Lake Gatun.

In 2013, the ACP formed the Project for Conservation and Recuperation of Areas of the Canal (CORA for its name in Spanish), under the Vice President of Corporate Affairs. This initiative was primarily focused on the land surrounding Lakes Gatun and Alajuela up to a sea level elevation of 100 feet and 260 feet (30.8 meters and 79.2 meters), respectively. These land areas are called the Cota 100 and 260. The land around Lake Gatun was of greater concern, and due to the increased water level from the expansion project, 14 residences had to be displaced. Currently, 1% of the Cota 100 is occupied, both by authorized and unauthorized users.

This project created a framework for a carrying capacity study as well as a shoreline management plan for Lake Gatun. These reports were written following extensive research on land management reports, and compiling information about the lake and its surrounding land. The land immediately surrounding the Canal is known as Type 1 Land under Panama's Agreement No. 102, which states that it can only be used by the ACP for Canal purposes. However, there are unauthorized cases of occupation, and the CORA Project team aims to cause as little disruption as possible. It is also important for the ACP to look at how these occupations, as well as other uses, are affecting the lake environment. The shoreline management plan details the current state of Lake Gatun.

The goals of the CORA Project are to implement taxes and required certifications for users of the land. This has already begun with the tourism presence around the lake and the next step is to create taxes for residences, which is the recommended course of action in terms of unauthorized occupation in the Cota 100. Additionally, it is recommended that the ACP uses the carrying capacity scope of work as a bid package and hire a subcontractor to complete the study. At this time, the shore is being managed in the areas of occupation, and if that is the main concern of the CORA Project, a complete shoreline management plan does not need to be implemented. However, it may become important to manage this area more closely after the Canal Expansion becomes operational and traffic increases in Lake Gatun.

Alternative Design for Range Towers Used as Navigational Aids

The second project regarded an alternative design for range towers used for navigation in the Panama Canal. Mariners use navigational aids for safe transits on and through bodies of water. Visual aids to navigation are dependable and often preferred by mariners. The most common visual aids at the Panama Canal are buoys and ranges. This project focused on range towers because they are fixed structures. Range towers are visual aids that help ships navigate through narrow channels by aligning them with the centerline of a body of water. With the widening of the Canal, the centerlines have shifted, requiring new range towers to be constructed. The ACP is currently replacing and updating all of the ranges in the Canal with latticed steel structures. These skeletal structures are located throughout Lake Gatun, aiding ship navigation through a series of Reaches (narrow straightaways in the Canal). Reaches are difficult to navigate and challenging to access, making construction of towers tedious. To improve efficiency, the purpose of this project was to evaluate the potential use of an alternative structure for the range towers. In doing so, the project addressed the three following objectives:

- Determine the benefits and limitations of existing range tower designs;
- Select an alternative tower design for ranges; and,
- Evaluate the feasibility of the selected range tower.

The existing range towers in the canal are latticed and composed of galvanized and stainless steel. These materials are highly durable and do not require special coatings, so maintenance costs are low. These towers are open to the harsh Panamanian environment with high temperatures and heavy thunderstorms. Some towers are unprotected, have been looted for parts or defaced, and are exposed to environmental damage. This project researched an alternative structure with similar capabilities that is easily constructed and has protection.

The alternative structures considered in this project were concrete lighthouses and glass reinforced plastic (GRP) towers. Both structures are used worldwide in ranges and to mark inland waterways. However, GRP towers were chosen for their modular design and shape to increase efficiency and reduce potential damage. The GRP towers were compared to the existing latticed steel structures to evaluate their feasibility in the Canal. It was concluded that GRP towers are likely the most suitable replacement for latticed steel towers; however, these preliminary results were based on product descriptions from GRP manufacturing companies. This project recommends a further analysis be completed to compare the two structures pertaining to costs and structural capabilities. The GRP towers are considered a viable alternative structure and the ACP should replace the existing structures with GRP towers as necessary.

Assurance of Drinking Water Quality on Tugboats

The third project assessed the potable water provided to and aboard the Panama Canal tugboats and designed a Drinking Water Management Plan to improve the current drinking water quality. Once the Canal expansion is completed, tugboats will not only guide vessels through narrow channels of the Canal, but also through the new locks. In early 2015, tugboat engineers and crews expressed concerns regarding the quality of the water supplied on the vessels. This project was conducted alongside the ACP Water Quality Division and addressed the following three objectives to improve the water quality stored on the Panama Canal tugboats:

- Establish the quality of water at intakes where tugs receive fresh water along the Panama Canal;
- Launch a diagnosis of potable water in each tug; and,
- Prepare a safe drinking water management plan to improve the current water quality.

To assess the potable drinking water quality supplied to and stored on the Panama Canal tugboats, this project adapted the framework for safe drinking water quality established by the World Health Organization in the *Guideline to Safe Drinking-Water Quality* (2008). This framework is composed of five main parts; health targets, system assessment, monitoring, management, and surveillance. Health targets are the established water characteristics and guideline values that represent the desired water quality. A system assessment determines whether the drinking water supply system from the source to the point of consumption can deliver water of a quality that meets the established health targets. After a system assessment, the project must identify control measures that, when effectively implemented, regulate and minimize deviation from the health targets. Management pertains to the procedures that will result in the ability of the drinking water system to effectively and routinely meet health targets. Surveillance is the continuous action of assessing the drinking water system to ensure effectiveness and further improve the drinking water quality.

This project established health based targets regarding turbidity, residual chlorine, total coliforms, and *Escherichia coli*. Water was collected and analyzed from five tugboat landings and two Panama Canal tugboats. Results suggested that water provided at the landings met the targets, but water stored on tugboats failed to meet turbidity and residual chlorine standards. After inspecting the potable water tanks on the tugboats, the presence of rust was identified, which would contribute to the high turbidity and low residual chlorine levels in the water. In conclusion, this project recommended the cleaning and epoxy painting of the interior walls of the water storage tanks. Additionally, the project designed a Drinking Water Management Plan, outlining methods, scheduling, and documentation to improve the current drinking water quality on tugboats.

New BEC Spillway Design

The fourth project detailed the preliminary phases and design of a new spillway for the Lake Gatun region. If a lake or reservoir created by a dam contains excess water, this surplus is typically released through a spillway which is a passageway that carries the water to a downstream location. Due to the rise the water level of Lake Gatun, the existing Gatun Spillway was deemed insufficient to be able to discharge the amount of water necessary in the case of a probable maximum flood. Because Gatun Spillway does not have enough hydraulic capacity to release water safely, the ACP began the BEC Spillway project in 2014 by hiring a Colombian firm, INGETEC, to provide preliminary designs, schedules, and cost estimates for the project. In order to assist in the planning of the new spillway, the project objectives are:

- Research different types of spillways to ensure the best design is chosen;
- Revise INGETEC's technical drawings sent to the ACP for approval and check for points of conflict; and,
- Devise possible routes for excavated material to travel from the spillway site to offshore disposal sites.

When considering the construction of a spillway, there are several factors involved such as location, type, and soil erosion. The location of a spillway is determined by environmental considerations of how the spillway will affect people and ecosystems in the area, as well as soil types and seismicity. If the proper type of spillway is not chosen for the area based on geological features, then the structural integrity of the dam and spillway are in jeopardy. Erosion is a major hazard for spillways because the high velocity of the released water can cause damage to the surrounding area.

After researching various types of spillways, the ACP and INGETEC decided that a stepped chute spillway is the best option for the BEC Spillway due to geological constraints. In order to confirm the soils present within the proposed site for the spillway, INGETEC drafted AutoCAD drawings of borehole locations. Revisions were made to these drawings when borehole locations conflicted with an existing building or road. Once corrections were completed, the ACP requested the examination of excavation methods and techniques. Since the spillway site is an island created by the existing Gatun Locks and the new Third Set of Locks, construction vehicles are unable to be utilized for excavation and transportation of materials. After studying drawings of the site, it is recommended that the best excavation routes to the disposal sites are to sink large, steel pipelines in Lake Gatun to carry the material to its destination. Moreover, it is recommended that the ACP conduct more research on how to transport concrete and other materials to the site. Currently scheduled to begin in 2017 and reach completion in 2019, the new BEC Spillway will help to ensure that Lake Gatun remains the safe, sustainable water source for the Panama Canal locks.

Conclusion

These four projects provided the ACP with additional information and recommendations suggesting improvements on projects created as a result of the Panama Canal Expansion Project. Each individual project encompassed social, economic, environmental, and other design constraints that helped to conceptualize their future impacts. The projects intend to impact and ensure the sustainability, efficiency, and continuation of safe transit through the Panama Canal.

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Preface

This project fulfills the Major Qualifying Project (MQP) requirements for the Civil Engineering Bachelors of Science Degree at Worcester Polytechnic Institute (WPI). With challenging research and design elements, the MQP places students in a professional environment, working on real-world problems to advance their careers. This project team consisted of four WPI students, each completing individual projects related to the Panama Canal Expansion Project.

This project was conducted as a result of the National Science Foundation International Research Experience for Students Grant 1357667, titled "Environmental Impact of the Panama Canal Expansion Project". The Grant was awarded to WPI in August 2014 to send students to work at the Panama Canal Authority (ACP) on civil engineering projects for three months. The ACP is an entity of the Panamanian government responsible for overseeing the Panama Canal, and employs over 10,000 individuals in all of its facets.

The following report is structured with an introduction to the Panama Canal and individual chapters detailing each of the four projects completed with the ACP. The projects cover topics related to the expansion project including land use, canal navigation, water quality, and spillway design. The goal of these projects is to aid the ACP in expansion efforts of the Panama Canal to benefit its users locally and worldwide.

Introduction

Engineering Canals

Over 90% of the world's trade is carried by the sea. Maritime transportation is the most cost-effective mode of moving large quantities of goods and raw material around the world. Maritime routes are strategically planned based on capacity, physical constraints, and political borders. Primary passage routes link the most important shipping markets and without them, cost-effective shipping would be challenging. Bottlenecks such as canals are the most strategic maritime passages, since they connect people, places, and goods. One of the world's most important passages is the Panama Canal (Rodrigue, Comtois, & Slack, 2013).

History

The history of canal building dates back to ancient Egyptians in 4,000 BC. Canal historians credit man's desire to control and use water for technology as the motivator in the rise of canal building (Clarke, 2015). Since the construction of the first canal in Egypt, canals have been erected all over the world. The oldest canal used for industrial purposes was a waterway in Great Britain built in 1700. Not only were canals used to move goods, but they also facilitated the movement of people to settle new lands and areas (U.S. History, 2014). From 1817-1825, the United States constructed the Erie Canal, joining the Great Lakes to the Hudson River. Industrial development, land settlement, and a connection between the northern states and Midwest territories were benefits of this canal in the United States.

Construction

The Canal Era occurred before the age of the railroad, totaling over 3,000 miles (4,830 km) of canals built in the United States by 1840 (U.S. History, 2014). These canals were designed and constructed by canal engineers, who were considered the first type of professional engineers. In 1816 in the United States, there were two canal engineers per state, totaling 30 engineers. These men had received canal building training from Europe and the majority were immigrants. A shovel and wheelbarrow were the only tools given to canal laborers. In some cases, horses with scrapers helped to reduce the digging, as well as giant wheels with pulleys for removing large tree stumps (Figure 1). Workers excavated canals with shovels and dynamite (Figure 2). Many workers were rendered deaf from blasts or killed by falling rocks and timber (Shaw, 1990).

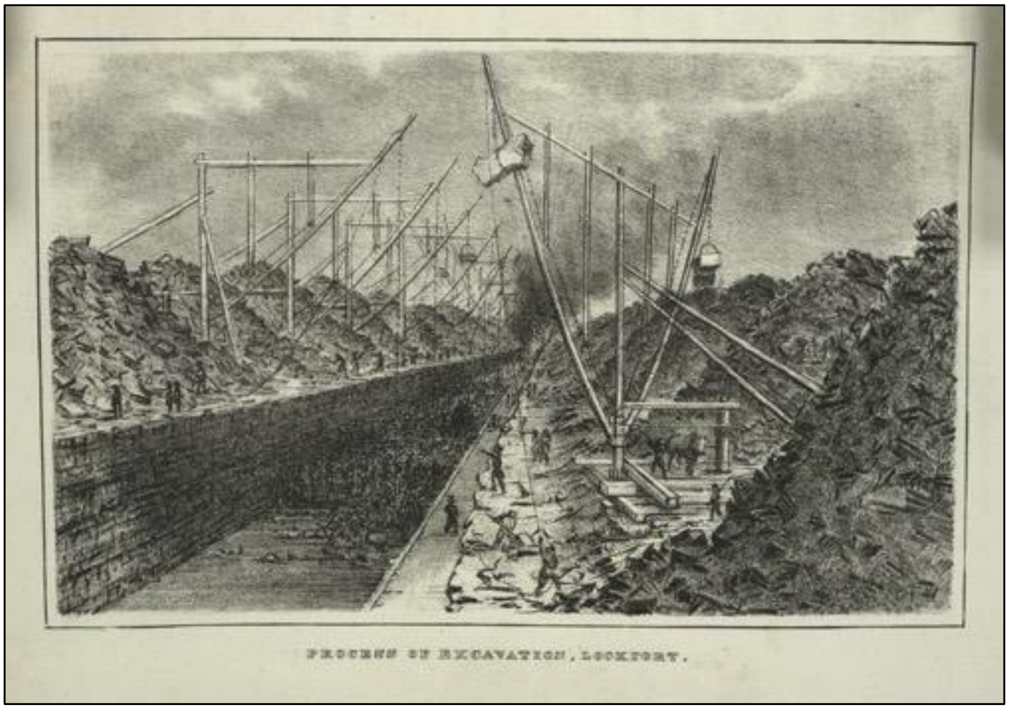

Figure 1: Makeshift pulleys and early machinery involved in 1800s canal building (Root, 2015)

Figure 2: Early canal building with dynamite and shovels (Everett, 2011)

Depending on the contours of the land, either a straight right-of-way canal or a lock system canal was built. A straight right-of-way canal is a level passageway and does not have elevation changes throughout its course. An example of a right-of-way canal is the first canal built in Egypt, today known as the Suez Canal. A lock system canal has different levels controlled by lift locks that raise or lower a vessel by a few feet depending on the land elevation. Although the concept sounds simple, constructing a lock system takes a lot of time and manpower, as well as planning. Canal engineers had to calculate the available water supply and estimate where other sources of water the in case of shortages. Often, the answer was watersheds or man-made feeders to nourish the canal water source. Another popular approach to supply the canal with water was to construct aqueducts. An example of a canal with aqueducts is the Lichfield Canal in Great Britain (Inland Waterways Association, 2013). Engineers had to determine the pitch of a waterway to provide a current as well as the number of locks needed to reach the final elevation (Shaw, 1990).

Environmental and Social Impacts

Early canal building took a toll on the environment. Not only was the land excavated, moved, and reshaped, but noise pollution was also present. The blasts of dynamite from canal construction caused extensive noise and habitat destruction. Consequently, many people and animals fled the area. Some remaining species posed a threat to canal construction; one example was burrowing animals digging holes in canal banks and causing the water to lower (Shaw, 1990). Plant and tree species were not as resilient. Deforestation and destruction of wild vegetation were a major factor in canal construction. Because records were scarcely kept in the early age of canal building, to this day, historians and environmental protection agencies still do not know exactly which species went extinct during this period.

While canals were unfavorable to the environment, they resulted in social and economic benefits. The United States prospered during the Canal Era, as citizens began to spread to other parts of the country. The new trade routes that canals brought created a unified network of goods that could be delivered nationally and globally (US History, 2014). Citizens of the United States felt as though their country was well connected at this point in history. During the time when railroads did not exist, canals were commended for being a source of unity.

Panama Canal

The Panama Canal began operations in 1914, and at its time of construction, was the largest engineering undertaking in the world. It was built by the United States and transferred to Panamanian ownership in 1999. It is currently operating under an autonomous branch of the Panamanian government known as the Panama Canal Authority (ACP)[1]. The canal is known as one of the Seven Wonders of the Modern World (ASCE, 1997).

[1] ACP for Autoridad del Canal de Panamá, in Spanish

History and Construction

In 1513, Spanish explorer Vasco Núñez de Balboa traveled from the Atlantic Ocean across the Isthmus of Panama to the Pacific Ocean. At this time, the shortest route between the Atlantic to Pacific Oceans was traveling around Cape Horn, the southernmost point of South America (Figure 3). After Balboa's discovery, the Spanish, Dutch, French, British, and eventually the Americans became interested in creating a path to shorten this common route (Longley, 2003).

Figure 3: Panama Canal Route and Cape Horn Route (Mohit, 2010)

Throughout the 1800s, the Americans and British sought a cheap and efficient way to export goods between the Atlantic and Pacific coasts (U.S. Department of State, 2014). In 1855, a New York-based company completed the world's first transcontinental railroad across the Isthmus of Panama. The railroad cost $8 million, took five years to construct, and profited in excess of $7 million in its first six years of operation. At one point, the Panama Railroad was the highest-priced stock listed on the New York Exchange. The Panama Railroad demonstrated the value an ocean connection could serve for Panama (McCullough, 1977).

Construction of the Panama Canal began in 1881 by Frenchman Ferdinand de Lesseps (ACP, 2015b). De Lesseps, from 1859 to 1869, led the construction of the Suez Canal in Egypt that connected the Mediterranean and Red Seas. The success of the Suez Canal made Lesseps a "celebrity" and in 1879, the French appointed Lesseps the leader of the construction of the Panama Canal (BBC, 2014). However, unlike the flat desert terrain of the Suez Canal, Panama was a mountainous jungle with snakes, mosquitoes, and other dangers. After only six years of construction, the Panama Canal project came to a halt in 1887 due to disease and accidents. Eventually, the project went bankrupt and was abandoned in 1889 (McCullough, 1977). De Lesseps failed at building the Canal and Panama became known as a “sinkhole” (Pollack & Ives, 2011).

During this time, the United States was the number one industrial power in the world and President Theodore Roosevelt believed completing the Panama Canal was the "obvious path to the future.” Roosevelt was determined to build the canal in what was then known as the Colombian Province. The United States tried to reach an agreement with Colombia to complete construction of the Panama Canal; however, the offer was rejected (ACP, 2015b; Pollack & Ives, 2011). In 1903, Panama, with the help of the United States, declared independence from Colombia (Figure 4). The Hay-Bunau-Varilla Treaty was signed by Panama and the United States, giving the United States the right to construct the Panama Canal for an annual payment of $250,000 (ACP, 2015b; Pollack & Ives, 2011).

Figure 4: Newspaper Cartoon Regarding U.S. Support of Panamanian Rebellion (Rogers, 1903)

On May 4, 1904, the United States began construction of the Panama Canal led by 51-year old John Findley Wallace (ACP, 2015b). The mindset of the United States, inspired by President Roosevelt, was to "make the dirt fly.” Wallace did not establish a plan to build the canal other than resuming the work of the French, and Roosevelt did not allow the time to develop a plan. During the first year of construction, many employees contracted yellow fever and other workers fled the project in fear. In January 1905, John Findley Wallace resigned as Chief Engineer of the Panama Canal. In the first year of construction $78 million was spent, and hundreds of millions of tons of spoil remained (Pollack & Ives, 2011).

Global concerns arose that the United States attempt to construct the Panama Canal would fail, similarly to the French attempt. The health of the workers became the largest setback. Chief Medical Officer Colonel William Gorges theorized that yellow fever and malaria were being contracted through mosquitoes (ACP, 2015b). In July 1905, Roosevelt backed Gorges, increased the sanitation workforce, and the attempt to eradicate mosquitoes began. On November 11, 1905, Gorges reported the last case of yellow fever (ACP, 2015b; Pollack & Ives, 2011).

At the same time as the eradication of mosquitoes, John Stevens became the new Chief Engineer of the Panama Canal project. Stevens believed the project required improvement of the living accommodations and the development of a plan. Stevens' first order of action was replacing old equipment and repairing the railroad to increase the spoil removal efficiency to one that would match the digging rate from the canal. Ideally, the railroad was to act as a conveyor belt and needed to be able to move depending on the location of digging. Initially, digging was to begin at either end of the Panamanian Isthmus and work towards the middle, where there was a mountain. Stevens realized that building a canal at sea level would condemn the project to failure. He suggested building a lock system at Gatun that would raise ships above sea level to a man-made lake, and back down through a lock system (ACP, 2015b). However, after two years as Chief Engineer of the Panama Canal, John Stevens resigned in a letter to President Roosevelt stating that the Panama Canal was, in his opinion, "a big ditch" (Pollack & Ives, 2011).

In February 1907, Lieutenant Colonel George Goethals was selected by President Roosevelt as the third Chief Engineer of the Panama Canal (ACP, 2015b). In his first month as Chief Engineer, Goethals' crew excavated 800,000 yd^3 (612,000 m^3) of material. In December of the same year, excavation began for the construction of the Miraflores Locks and 600 acres (2.43 km^2) of jungle were cleared to begin constructing the Gatun Dam. By the end of December, the major excavation work of the Panama Canal was wrapping up and men were being laid off due to the low demand for workers. By the end of his first year as Chief Engineer of the Panama Canal, Goethals' workforce had excavated over 37 million yd^3 (28.3 million m^3). This was more than half the spoil removed by the French during their 17 years of construction on the Canal. Throughout the next seven years, the Pedro Miguel and Miraflores Locks, excavation at the Gaillard Cut (previously known as Culebra Cut), and the Gatun Dam was completed. On December 10, 1913, the Panama Canal officially connected the Atlantic and Pacific Oceans, and on January 7, 1914, the *Alexandre La Valley* became the first vessel to transit the Panama Canal. The Panama Canal was officially completed and opened to the public on August 15, 1914 (ACP, 2015b; Pollack & Ives, 2011). After 10 years of construction under United States authority, the Canal spans 50 miles (80.5 km) at a width of 10 miles (16.1 km) (Boyer, 2004).

The United States took ten years and spent $375 million to construct the Panama Canal. Between 1881 and 1914, more than 75,000 workers were employed and roughly 25,000 died during construction (ACP, 2015b). The Panama Canal Zone was a 553 square mile (1,430 km^2) piece of land that extended 5 miles (8.05 km) on either side of the Canal. It was administered by the United States as an unorganized territory from 1903 until the Torrijos-Carter Treaties negotiations ended and were signed in 1977. The first treaty, called *The Treaty Concerning the Permanent Neutrality and Operation of the Panama Canal (Neutrality Treaty),* declared that the United States military would intervene in the case of threatened neutrality to the Canal. In doing so, the *Neutrality Treaty* also ensured the perpetual use of the canal by the United States as needed. The second treaty, *The Panama Canal Treaty*, went into effect on October 1, 1979, with the dissolution of the Canal Zone. It was important to the Panamanian people because it would turn the Canal over to Panama on December 31, 1999 (U.S. Department of State, 2013).

The Panama Canal has been operating for over 100 years, and tens of thousands of ships transit the Panama Canal each year (Figure 5). In 2014, there were approximately 12,000 transits of traffic through the Panama Canal with a total of $1.91 billion paid from tolls. Approximately 8% of maritime trade transits the Panama Canal (ACP, 2015k). As of 2007, 37% of ships worldwide are too large to travel through the Panama Canal (ACP, 2015g; Allianz, 2013; Pollack & Ives, 2011). In response, Panama began construction to expand the Canal, adding two new sets of locks, widening the passage and doubling its capacity. The expansion of the Panama Canal is expected to be completed in 2016.

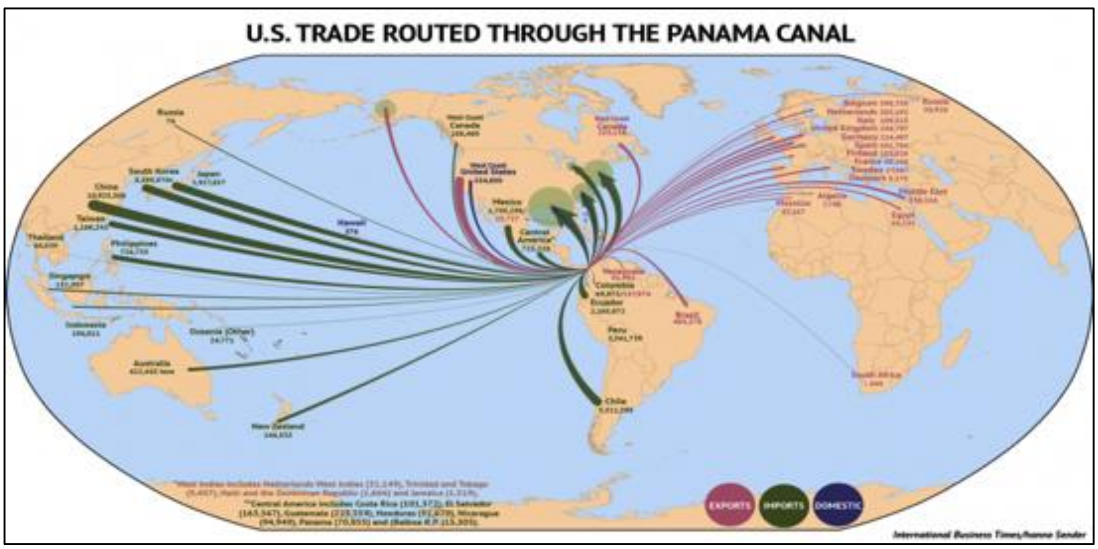

Figure 5: Trade routes through the Panama Canal (Caulderwood, 2015)

Panama Canal Authority

The ACP was founded under Title XIV of the National Constitution of Panama in 1999 as a government agency, and operates under the management of a board of 11 directors (ACP, 2015a). Originally, when the Panama Canal was a United States territory, it was operated under the supervision of a nine-person Board of Directors. Five of the directors were from the United States and four were Panamanian, all appointed by the President of the United States. In 1977, 75% of on-site operation staff were Panamanian and the rest were American (Augelli, 1985). Today, 11 Board of Directors oversee every aspect of the Panama Canal. Each member serves a term of nine years and offers a different area of expertise, forming a well-rounded Canal management team. These areas include law, engineering, Canal affairs, economy, marketing, investment, government representation, manufacturing, transportation, development, local business representation, relations, and interpretation. Having a Board of Directors with diverse education and experience is beneficial for the productivity and overall atmosphere of the Canal.

The Panama Canal operates 365 days a year, 24 hours a day. Currently, over 10,000 people work for the ACP. One of the ACP's missions is to "encourage teamwork and collaboration for Canal workers" (ACP, 2015h). Operation of the canal takes a tremendous amount of manpower because there are so many aspects to oversee. From the engineers to the administrative individuals, working together is essential to maintain the integrity of the Canal.

Another of the ACP's missions is to "produce the maximum sustainable benefit from [the Canal’s] geological location." The Panama Canal's prime location brings wealth and prosperity to the country and in the process, improves the standard of living and progresses the country of Panama. From the ACP's 2014 Income Statement in the Financial Report, the Panama Canal averaged an income of $1.4 billion. Approximately $700 million of this income goes to the Panamanian treasury for reserved funds; the Canal is vital for Panama's economic stability and progress. For this reason, Title XIV in the National Constitution states that the Canal cannot be sold, mortgaged, or transferred under any circumstance. Since the United States turned over the Canal in 1999, the ACP has contributed more than $80 billion to the Panamanian economy, both directly and indirectly. In 2014, the Canal operations and other resulting activities contributed $2.72 billion to the economy, which was almost 6% of the gross domestic product (ACP, 2015h).

The ACP emphasizes safety and precautionary measures for the transit systems of the Canal and aims to provide maximum efficiency and quality to all their customers and consumers that transit the Canal. In 2005, the standard for safety increased and the ACP implemented new regulations. Every employee undergoes significant and intensive training on how to avoid maritime accidents. The ACP implements many extensive prevention programs that are updated annually. Since this began, the number of accidents among vessels has decreased steadily each year (ACP, 2015h).

The last of the ACP's missions is to manage and preserve the water resources, sustainable development of the Canal watershed, and environmental protection. Lake Gatun, part of the Canal watershed, is replenished by rainwater and supplies the water that fills the locks. On average, 35-45 vessels travel through the Canal daily. For each of these vessels, over 52 million gallons (197 million liters) of water is needed to complete the transit between the Atlantic and Pacific Oceans. Following a potential water scarcity discussion in the late 1970s, the Panamanian government implemented policies to use the Canal watershed only for sustainable development. These policies stated that the watershed would only be used for

Canal purposes, but their implementation was unsuccessful potentially due to irresponsible water resource management (Carse, 2012). The government believed that this resource needed to be managed, and after the proper measures were taken, water scarcity would no longer be a concern.

Panama Canal Expansion Project

Soon after the Panama Canal opened, both authorities and suppliers saw the need for an increase in the Canal's capacity. In 2006, a majority of Panamanian citizens voted to "modernize" the Canal. This modernization is known as the Panama Canal Expansion Project, an endeavor that, according to then-President Martin Torrijos, would transform Panama into a first world country (Tulchin, 2013). The largest project undertaken by Panama, it was proposed to create an estimated 30,000 jobs, and improve the country economically and socially for many years to come (Lacey, 2006). The Panama Canal Expansion Project is expected to cost $5.25 billion. The project began in September 2007 and has an estimated completion date of early 2016.

Elements of the Expansion

The expansion includes the addition of a third channel which will more than double the current capacity of the canal, from ships of 5,000 TEU (Twenty foot Equivalent Units) to ships of 13,000 TEU (ACP, 2015f). The largest ships that can pass through the existing Canal are called Panamax ships. Ships too large to fit through the current Canal are known as Post-Panamax (Figure 6). Post-Panamax ships make up a mere 16% of the world's cargo fleet but their immense sizes hold nearly half of all cargo (Hricko, 2012). The expansion also includes improvements to the entrances and exits of the Canal as well as dredging the channel between the locks to accommodate Post-Panamax ships.

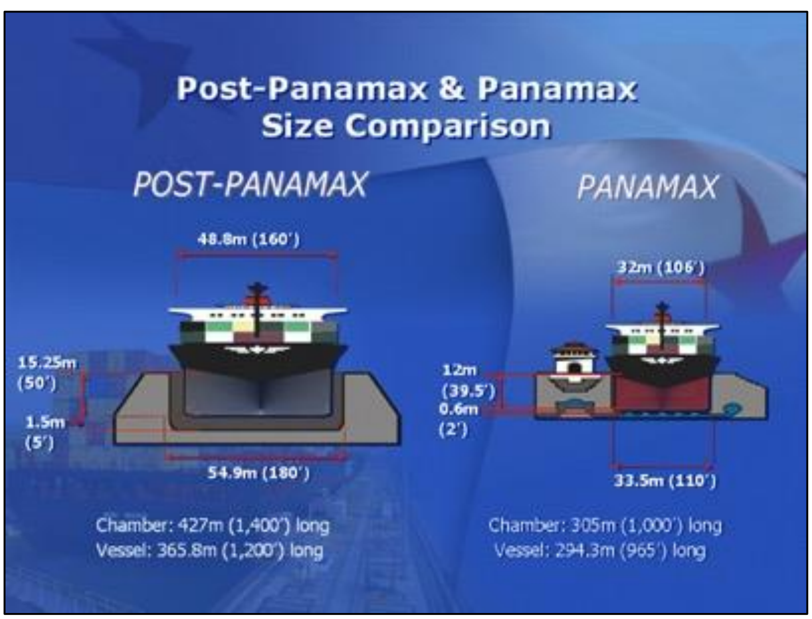

Figure 6: Comparing Post-Panamax and Panamax ships (Embassy of Panama in Japan, 2010)

The expansion project focuses around the accommodation of Post-Panamax ships and mainly the new installation of the locks on the Atlantic and Pacific sides, known as the Third Set of Locks. The contract for these locks was awarded to Grupo Unidos por el Canal, S.A. for $3.20 billion, and work on the new lock systems began on August 25, 2009. The Third Set of Locks has three water chambers, each with new features. These include a lateral filling and emptying system, saving water by using 7% less than the existing locks and reusing 60%, thereby decreasing fill and empty time (Figure 7). Other new features of these locks are the perpendicular gates, made in Italy and weighing 3,000 tons (2,720 tonnes) each. The new gates are a variation of the original gates, which swing open against the locks. Instead, the new gates slide in and out on wheeled tracks into recesses perpendicular to the direction of passage (ACP, 2015f).

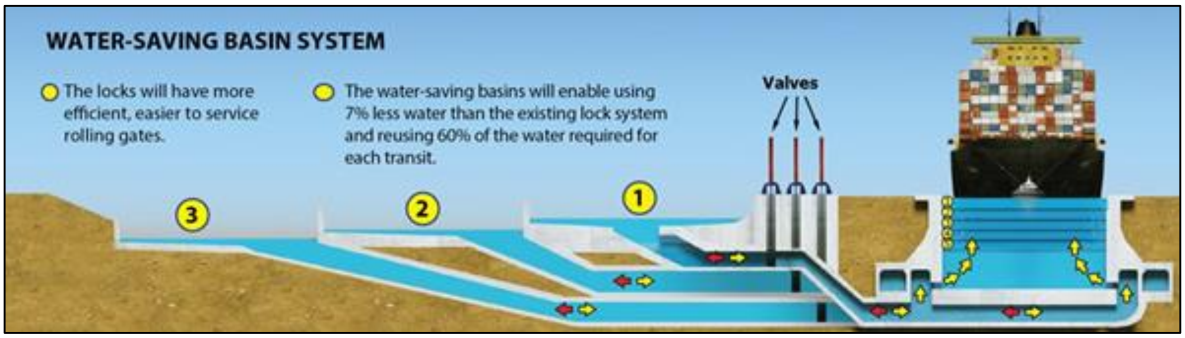

Figure 7: Water Saving Basin System (ACP, 2015f)

Another component of the expansion project is increasing the Canal capacity for safe passage of Post-Panamax ships. The Pacific Access Channel (PAC) consists of excavation for the Pacific North access, including the dry excavation of roughly 64.1 million yd^3 (49 million m^3). This is being completed in four phases, called PACs 1-4. Additionally, the ACP is making improvements to the Navigational Channels by dredging vertically 50.9 ft (15.5 m) on the Pacific entrance, 52.8 ft (16.1 m) on the Atlantic, and horizontally widening entrances to a minimum of 738 ft (225 m).

There will also be improvements made to the water supply in Lake Gatun. This portion of the project aims to "rais[e] maximum operating levels" which will improve water supply and deepen the lake, again for safe passage of the Post-Panamax ships (ACP, 2015f). The major aspects of the Panama Canal Expansion Project are summarized below (Figure 8).

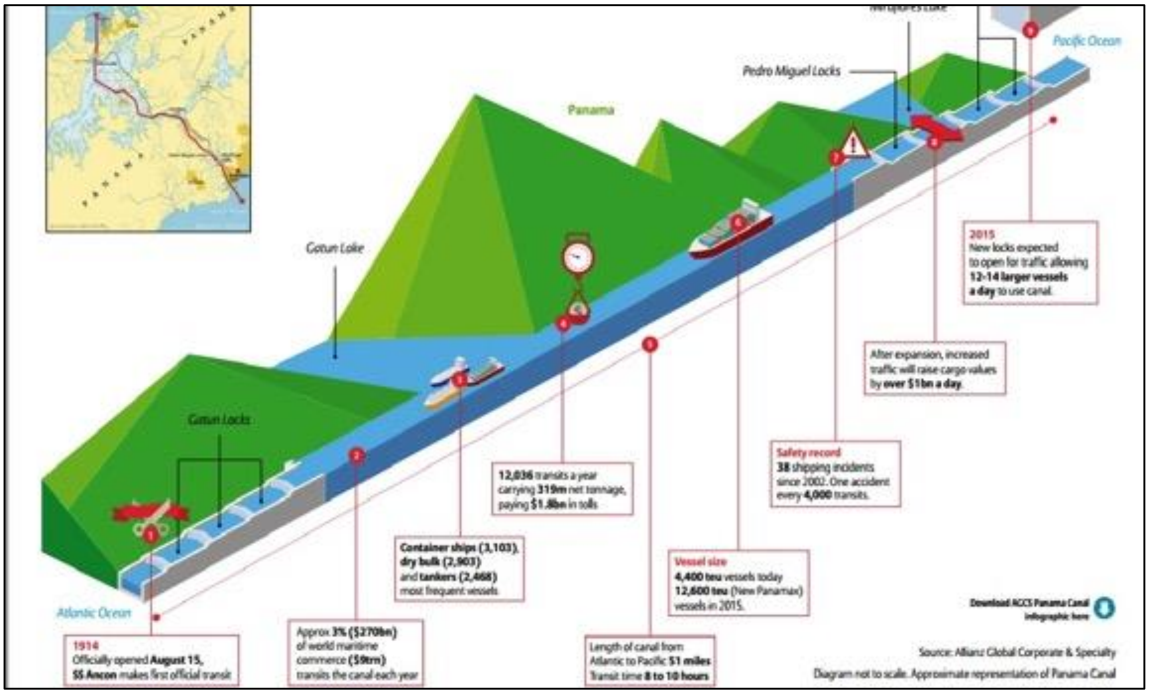

Figure 8: Panama Canal summary statistics (Allianz, 2013)

Current Status

As of August 31, 2015, 93% of the expansion project is complete and on track for an early 2016 opening. All of the dredging in the Atlantic and Pacific Access Channels is complete, and the dredging in Lake Gatun and the Gaillard Cut is 94% finished. The design and construction of the Third Set of Locks is 92% complete, with the gates in place and concrete poured. The raising of the maximum operating level of Lake Gatun is 95% finished, and only the dry excavation of PAC 4 remains (ACP, 2015f).

Local Environmental Impacts

Prior to the expansion, the ACP presented an environmental impact study to the National Environmental Authority. The largest impacts of the expansion construction are higher risks of landslides and soil erosion, which are both results of the immense excavations occurring and the removal of vegetation. Additionally, the ACP states that air and water quality will decrease as a result of dredging and excavation, because the turbidity of the water will increase from the addition of suspended solids. The air quality will also deteriorate due to the emissions from construction equipment, as well as the addition of particles in the air due to the disruption of the earth from excavation (ACP, 2007).

In terms of biological impacts, the Miraflores Lake will experience minor alterations, such as lake volume and area loss. The coastal marine ecosystems will experience an increase of sediments in suspension, which will increase turbidity. The lake bottoms will be altered as a result of the dredging (ACP, 2007).

Also included in the environmental impact study are the impacts during the operation phase of the Canal expansion. All of these impacts listed are of medium, low, or very low significance. The highest significance is the deterioration of the air quality, as the ship transits increase. Other notable impacts are the higher landslide risks, water quality deterioration, higher noise and vibration levels, higher odor perception, soil contamination, soil compaction, caving, and subsidence. Although only categorized as medium significance, the biological element that will experience the largest impact is the alteration of coastal marine ecosystems. Other biological impacts in Panama are the higher risk of wildlife road kill, the alteration of aquatic resources in rivers and creeks, terrestrial habitat loss, vegetation cover loss, wildlife perturbation, direct injury to fauna, damage to protected area, and rise of illegal hunting practices (ACP, 2007).

Although there are many negative environmental impacts of expanding the Panama Canal, Líder Sucre, an individual from the National Association for the Conservation of Nature in Panama City, argues that the expansion of the Canal could bring environmental benefits. Sucre states that "[t]he importance of protecting the [C]anal's water supply will oblige us to manage the watershed in an environmentally responsible manner" (Orellana, 2005). Since the early 2000s, Panama's conservation organization has taken responsibility for the Canal watershed, instead of forest guards and military representatives. Under their new supervision, deforestation has reduced from 7,410 acres (30 km^2) to 74.1 acres (0.30 km^2) per year (Orellana, 2005). The conservation organization predicts that this number will continue to decrease with the new expansion project.

Global Environmental Impacts

One of the more important environmental impacts of the expansion project is the need for ports in North America to expand. The majority of the impacted ports are on the East Coast of the United States (Figure 9).

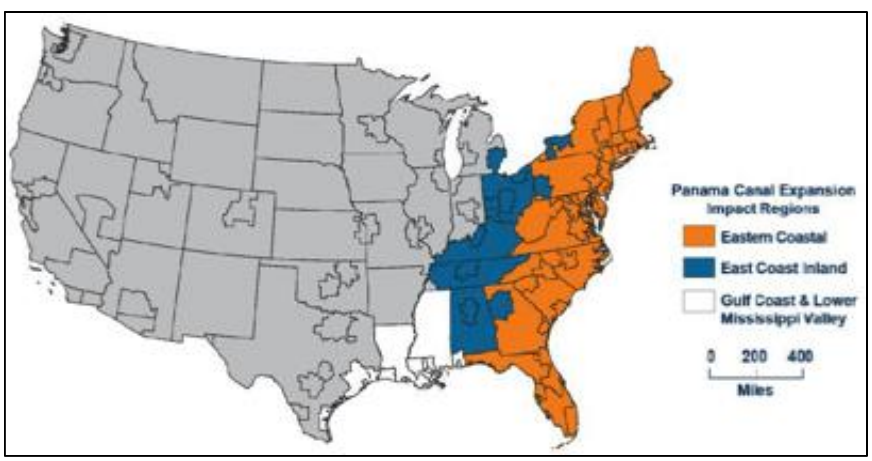

Figure 9: Impacted Regions by the Panama Canal Expansion in the United States (Parsons Brinckerhoff, 2012)

The only ports currently equipped to harbor these larger vessels are in Baltimore, Maryland, and Norfolk, Virginia (Allianz, 2013). Many of the East Coast and Gulf Coast port authorities have realized the need for extensive dredging by 45 ft (13.7 m) or more in order to accommodate the larger ships to stay competitive with the Pacific Coast ports (Allianz, 2013; Hricko, 2012). Currently the Port Authority of New York and New Jersey is undergoing a $6 billion construction effort to receive the Post-Panamax ships and their cargo, which is expected to be completed in 2016, in time for the opening of the widened locks in Panama. As part of this construction, the Bayonne Bridge is being raised 64 ft (19.5 m) to a total height of 215 ft (65.5 m) (Jervis, 2015; PANYNJ, 2015). Additionally, the Port Authority of New York and New Jersey is partnering with the U.S. Army Corps of Engineers to dredge New York Harbor (Figure 10).

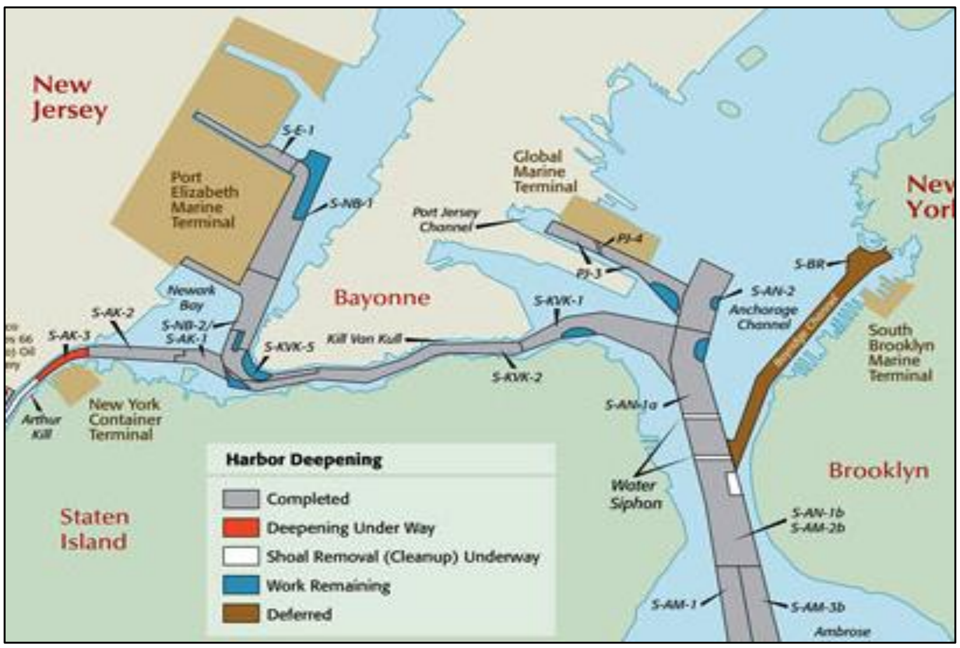

Figure 10: New York Harbor Dredging Plan (PANYNJ, 2015)

Other major United States ports are being expanded to accommodate Post-Panamax ships. These include the Ports of Miami, Mobile, Long Beach, and Seattle/Tacoma. These ports are spending anywhere between $400 million and $4.50 billion on expansion efforts. For example, the Port of Long Beach is spending $4.50 billion to construct a 0.475 square miles (1.23 km^2) “mega-terminal” as well as a 205 ft (62.5 m) tall bridge that will connect the port to the mainland, and improvements to the roadway and nearby railway (Jervis, 2015).

Accommodating the larger ships is not restricted to dredging; the bridges, tunnels, rail lines, and highways must also be expanded to carry the larger cargo loads. For example, the railroad company Norfolk Southern blasted through two dozen Appalachian Mountains to build the Heartland Corridor that will accommodate double-stacked container trains (Hricko, 2012).

As a result of ports enlarging to accommodate larger ships, exhaust from more fuel will be emitted into the environment in the water and air. Additionally, the cargo containers will be transported by diesel fueled trucks or trains, thereby contributing to more air pollution. Larger cranes will also be needed to lift cargo items from the ships and move them to storage. These cranes create additional emissions (Allianz, 2013). With the expansion of the Panama Canal, there will be a significant rise in emissions as the amount of cargo passing through ports increases (Hricko, 2012).

Not only does the fuel from the vessels themselves cause pollution, but with larger ships traveling through the Canal, there is greater risk of collisions. Larger vessels accommodate more goods and if these goods are hazardous, a collision or accident could cause pollution spills in the water (Allianz, 2013). This increased risk of a spill is both local and global, and would have impacts as such. However, the ACP has prevention plans in place for events from natural disasters to oil spills. They have also taken the initiative to send their operatives to conferences and other training on how to properly handle larger cargo vessels. The Panama Canal pilots are the group of individuals responsible for making sure there are limited causes for accidents during transit. In order to prepare, these pilots practice situations and maneuvers in the case of an accident. Since the new set of locks operates differently, there will be a learning curve to how the pilots respond to incidents and reduce the likelihood of an environmental hazard.

Conclusion

This year, the Panama Canal celebrated its 101st anniversary. Throughout these years, the Canal has made world trade more efficient and cost-effective. Currently, the Panama Canal is undergoing an expansion project to increase its capacity by making the Canal accessible to Post-Panamax ships. Although the Panama Canal has benefited the world in many ways, including shortening travel distances across the globe, the current expansion project has many local and global environmental effects.

In August 2014, Worcester Polytechnic Institute received a grant from the National Science Foundation to work with the Panama Canal Authority to evaluate the impacts of the Panama Canal Expansion Project. In July 2015, the inaugural team traveled to Panama to carry out projects regarding impacts of the expansion project to fulfill their Major Qualifying Project requirements. The following chapters outline each of the projects, their methodologies, results, and recommendations for the evolution of the Panama Canal.

Chapter 1: Reclamation of Lake Gatun and Surrounding Areas

1.1 Design Statement

This project worked with the Project for Conservation and Recuperation of Areas of the Canal (CORA[2]) team in moving forward with their efforts. In order to meet the capstone requirements for the Major Qualifying Project at Worcester Polytechnic Institute, a carrying capacity scope of work and shoreline management plan for Lake Gatun were designed. Lake Gatun's changing geography has not been studied in depth. In response, the CORA project team determined that now is the time to have a carrying capacity study performed to determine the maximum amount of activity that can be supported by the lake. A carrying capacity study for Lake Gatun would be beneficial as the Lake accounts for more than half of the transit length and is the water supplier for the Panama Canal.

A shoreline management plan facilitates management of an important land area. Because of this, it is a valuable resource that may be useful to the ACP. Currently, the shoreline of Lake Gatun is being monitored by biweekly site visits for instances of unauthorized occupation that are primarily residences. Since the shoreline is so extensive, with different land use in various areas, a shoreline management plan is a good option for ensuring the proper site visits are performed and the shore remains in its current state.

Current uses and occupations of the land surrounding Lake Gatun need to be addressed in the design of these reports, which detail the framework for a carrying capacity study and a shoreline management plan, as well as the consultation of ACP and national policies that dictate proper land usage. These reports were written following the compilation of extensive research. As with all engineering projects, many global engineering design constraints had to be considered throughout the course of this project, and are outlined in more detail below.

This project relates primarily to land use, which is a field dictated by environmental constraints. Keeping the natural environment in its current state is one of the main goals of the CORA project. A carrying capacity study was performed so the environment is not harmed by human activities. A shoreline management plan is concerned with maintaining the natural shore of a body of water and protecting the surrounding environment. The goal of the CORA project team is to revert the land back to its previous state so that the patrimonial lands of Panama can remain untouched and healthy.

The CORA project is primarily concerned with unauthorized land use around Lake Gatun. Residents and other occupants may be displaced as a result of the CORA project's efforts to

[2] CORA for Conservación y Recuperación de Áreas Patrimoniales del Canal, in Spanish

reclaim the land. This social impact was largely considered in the development of the scope of work for a carrying capacity study.

Politics and laws play a large role in land use regulations. One of the CORA project’s main objectives is determining the unauthorized use of the land that is owned by Panama but regulated by the ACP. The design of these reports considered the Panamanian Constitution as well as the Organic Law of the ACP.

Engineering reports and management plans consider ethics when making recommendations for future actions. Similarly, the reports, research, and site visits for this project were conducted in an ethical manner.

This project and the CORA project aim to regulate unauthorized use of lands so that the quality of the lake and its surroundings are preserved. Additionally, changes are being made to Lake Gatun and its surrounding areas as a result of the expansion project, and the safety of residents is a priority for the ACP. Since Lake Gatun is used by many people each day, this directly relates to public health and safety.

1.2 Introduction

The land surrounding the Panama Canal played a large role in the construction of the Canal and continues to be a vital part of Canal operations to this day. Because the land was managed by the United States until 1999, it was occupied by many people, the majority having to do with Canal operations. However, once the Canal and surrounding land changed ownership, the land was overlooked by the ACP under the new Canal administration; therefore, its current owners and inhabitants remained. The ACP is in the process of reclaiming this land since they are the rightful owner, as dictated in Article 3 of the ACP's organic law. These lands are known as patrimonial lands and the ownership cannot be transferred. The majority of the patrimonial land in question surrounds Lakes Gatun and Alajuela (drinking water reservoir to the east of the Canal). Lake Gatun in particular has been under scrutiny by the ACP due to a number of unauthorized residents along its shores, as well as its continuing evolution as the Canal expansion comes to a close. This project aims to offer guidance on potential future actions to preserve the lake and its surrounding land with the following objectives:

- Study land areas, current use, and existing policies and regulations;
- Investigate similar types of land management reports;
- Develop a framework for a carrying capacity study of Lake Gatun; and,
- Design a shoreline management plan for Lake Gatun.

1.3 Background

The ACP has owned and managed the land surrounding the Canal since 1999, when Panama was transferred ownership. This land is now under scrutiny as being occupied without authorization and the ACP is looking into reclaiming and managing the land and lakes with more definitive plans. Land and water management planning can be completed in various formats, including but not limited to carrying capacity studies and shoreline management plans.

1.3.1 Lake Gatun

Lake Gatun is the most important aspect of the Panama Canal. At the time of construction, it was the largest man-made lake, created by the largest dam, in the world. The lake spans 167 square miles (433 km^2) and contains about 1.4 billion gallons (5.2 billion liters) of water (Pabst, 2000). The Panama Canal Watershed feeds into the lake year round, ensuring a sufficient water level and ability to operate the Canal locks. Additionally, the lake accounts for more than half of the length of the Canal.

When the lake was filled between 1907 and 1913, it flooded many towns and many hills became islands (Price, 2013). This interrupted a lot of wildlife growth and during low water levels, the tops of petrified trees can still be seen. Currently, due to the particularly strong seasonal winds in the Pacific, rainfall has been significantly less than normal in Panama, and Lake Gatun is 6.50 ft (2 m) below its normal level. This has not yet become a problem for Canal operations, but if it were to lower more significantly, larger ships would have to be turned away from transiting the Canal for safety reasons.

The water quality reports of Lake Gatun indicate that the lake has remained in stable condition and nothing drastic has occurred in the past few years (ACP, 2014b). As part of the expansion project, the level of Lake Gatun was raised 1.50 ft (0.450 m) to accommodate larger ships. To plan for this water level change, reports were made to find any areas of occupation surrounding the lake, and 14 households were evicted to maintain the integrity of the shore. This began regular site visits to Lake Gatun by members of the CORA team and, upon the realization of the amount of unauthorized occupation around the lake, was a catalyst for the CORA project itself.

1.3.2 CORA Project

The land formerly known as the Canal Zone was used by the United States for many different purposes, including residences, offices typically for Canal operations, tourist attractions, and many others. Therefore, although this land was used for various purposes under United States governance, once the Canal was turned over to Panama, it became "patrimonial" land, meaning that it was now owned by the Panamanian government and could no longer be transferred. Article 315 under *Title 14: The Panama Canal* of Panama's Constitution states that the Panama Canal is made of inalienable patrimonial land, and Article 3 of the ACP's Organic Law states that this land cannot be sold, transferred, mortgaged, taxed, or alienated (República de Panamá, 1972; ACP, 1997).

The CORA project is an initiative under the Vice President of Corporate Affairs to reclaim patrimonial land owned by the ACP. The majority of the land covered in the CORA project is made up of river banks known as "compatibility areas". Compatibility areas are the land parcels that are currently or will eventually be used for Canal purposes such as water storage, container storage, ports, areas for future expansions, and similar activities (R. Munoz, personal communication, September, 2015). Patrimonial land is divided into two areas: economical and inalienable. Inalienable patrimonial land (light green in Figure 11) is owned by the country of Panama under the constitution and is administered privately by the ACP. Economic patrimonial land (dark green in Figure 12) is owned and managed by the ACP.

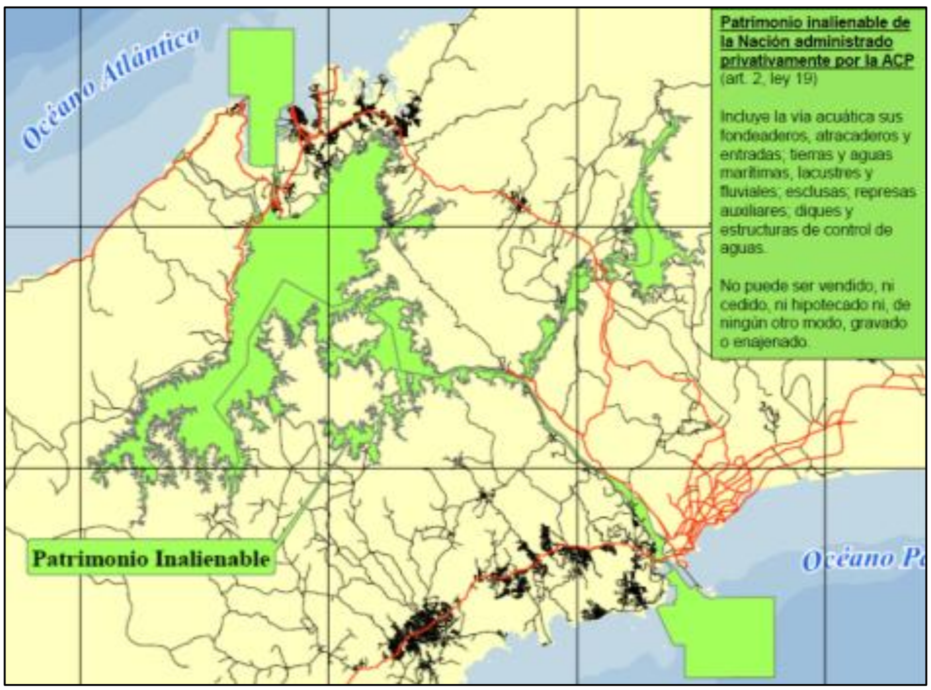

Figure 11: Inalienable Patrimonial Land (ACP, 2015i)

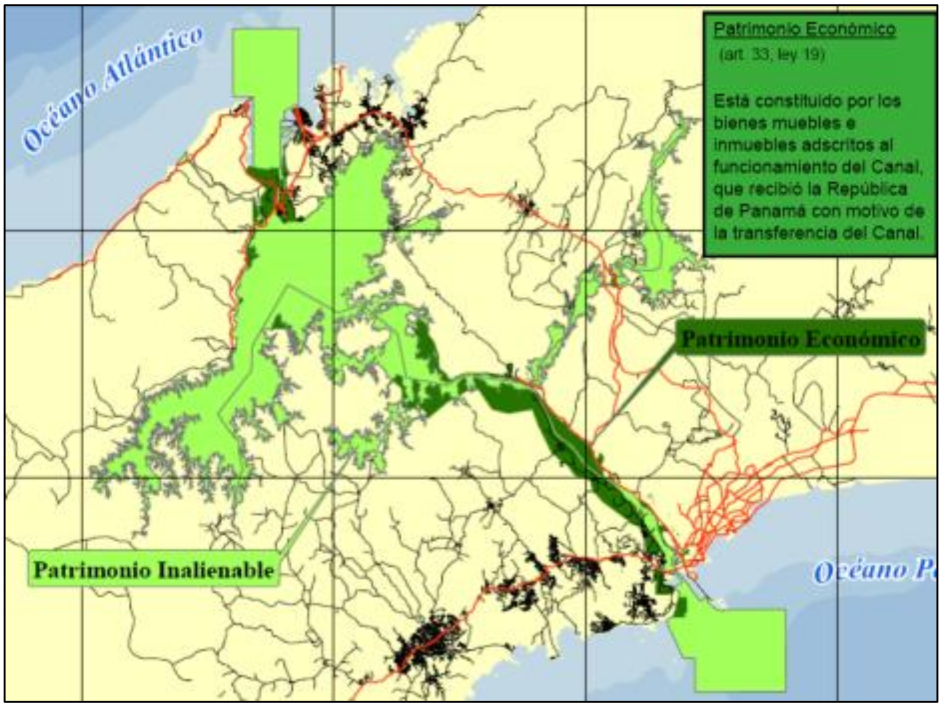

Figure 12: Economic Patrimonial Land (ACP, 2015i)

1.3.1.1 Cota 100 and 260

These two main patrimonial lands, that encompass the majority of the CORA project scope, surround Lakes Gatun and Alajuela. They extend to heights above sea level of 100 and 260 ft (30.8 and 79.2 m), respectively (Appendix A). These areas are called the Cota[3] 100 and 260, respectively, and need to remain regulated to guarantee their integrity since the lakes are used as reservoirs to supply water to Panama City, as well as operate the Canal. An objective of the CORA project includes the implementation of measures to regulate the land and prevent new occupation through means of surveillance, disclosure, and signage. To meet this objective, the ACP has been surveying adjacent land for any suspicious occupation. Currently, nearly 1% of the Cota 100 is illegally occupied. In July 2015, the CORA project team carried out eight site visits to Lakes Gatun and Alajuela to monitor public infrastructure constructed on the Cota land (E. Soto, Personal Communication, July 2015). The ACP partnered with the National Land Administration Authority (ANATI[4]) to establish the requirement of obtaining a certificate issued by the ACP before granting property titles.

Another potential measure to take regarding the Cota 100 and 260 initiatives is the implementation of taxes for land use up to these levels. However, the CORA project team is concerned that these taxes will increase the desirability of living there for those that can afford the additional fee. The team is also identifying areas of potential future use of the Canal (for

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[3] *Cota* is the Spanish word for level or altitude

[4] ANATI for Autoridad Nacional de Administración de Tierras, in Spanish

example, the efforts in Diablo as described below), and studying the carrying capacity of the Cota land (E. Soto, personal communication, July 2015).

One of the main priorities for the CORA project is the Cota 100 around Lake Gatun, which is privately owned and operated by the ACP. As previously mentioned, the lake is critical for Canal operations. However, Lake Gatun is also used as a reservoir for drinking water and is supplied to individuals in Panama City and other small suburbs. Due to its natural beauty and quiet location outside of the city, the lake is becoming more attractive to live near, for urbanization, and for tourism.

By protecting this land, the ACP can guarantee water supply for aqueducts, control potentially damaging erosion, prevent water contamination, conserve the scenery of the lake, and maintain the Canal operations effectively. These results will cause benefits to all of Panama, such as reducing the cost of making water potable, protecting communities from heavy water inundations, and maintaining the vegetative coverage of the lake's surrounding area. To do this, the ACP is installing signage to prevent the unauthorized occupation of islands and banks. Protecting the Cota 260 surrounding Lake Alajuela has the same benefits, with the addition of guaranteeing water supply to the nearby Federico Guardia Conte potable water plant (E. Soto, personal communication, July 2015).

1.3.1.2 Diablo Heights

The other area that has been the focus of the CORA project team is called Diablo Heights, located in the Diablo sector of Panama City. The main objective of the Diablo Heights initiative is to convert the area back to its original state to be used for maritime activities that benefit Panama, such as a container port. The area of concern is known as Property 196273, which consists of 114 hangars occupied for various reasons, including family residences, although none of this occupation is authorized. As of July 31, 2015, 100 of the hangars had been reclaimed by the ACP, with 99 as property of the ACP and one with an agreement to leave, for a total ACP ownership of 87% of the hangars. Two hangars are being used by the National Police and two others are under a government protective order. Seven of the hangars are currently owned by the Ministry of Economy and Finance and actions are being taken for negotiations of these properties. The remaining hangars are in the process of reclamation by the ACP (E. Soto, personal communication, July 2015).

1.3.3 Carrying Capacity Studies

Carrying capacity is typically referred to as the population or activities that are able to be supported by the resources of a certain region of land. When an area has reached carrying capacity, it means that a balance has been struck between the natural resources of the land and the number of people using these resources. Populations tend to increase if they are below carrying capacity, and resources become scarce if the opposite occurs (Huggett, 2009). Although most carrying capacity studies are based on physical features, they can also be studied from an environmental, social, and economical perspective.

1.3.3.1 Ecological Carrying Capacity

Ecological carrying capacity generally encompasses the use of resources in an area and how they can be used in a sustainable way as not to significantly affect the natural environment. Ecological carrying capacity is important to be aware of because the overuse or exploitation of resources could cause a “survival crisis” in that ecosystem (Wang, 2010). It is referred to as the proper relationship between ecosystem and species (including humans), in which each benefits equally from the other.

1.3.3.2 Social Carrying Capacity

A social carrying capacity analyzes the maximum amount of human activity that can occur in an area without the overuse of resources, and the tolerance level of native people with regards to tourism in their area. It also incorporates the interaction between humans and nature and how each is affected by the other. This is an important factor to consider with Lake Gatun because it is a large tourist attraction (Jaafar, Marzuki, & Mohamad, 2014). However, the tourism influences on the lake are incomparable to the impact traffic levels have on the Canal.

1.3.3.3 Economic Carrying Capacity

Economic carrying capacity is similar to the social carrying capacity in that it accounts for the tourism and attractions of a particular area. More specifically, the economic carrying capacity of an area describes the amount of change can be made for the full tourist potential without harming the natural environment or indigenous people. A community at its economic carrying capacity will have integrated tourism with the previous natural habitat and allowed residents and tourists to coexist, each benefiting from the presence of the other (Mathieson & Wall, 1982). Tourism infrastructure comes from human changes to the natural environment, which can impact many natural features of the surrounding area.

1.3.4 Shoreline Management Plans

As with most natural elements, a shoreline of a body of water is constantly evolving. This can be due to changing water levels, erosion, natural disasters, and anthropogenic effects, which vary greatly in reason and intensities (Walker, 1984). A shoreline management plan (SMP) can be established regarding a specific body of water in order to protect it from as much anthropogenic coastal change as possible. An SMP is a non-statutory document, so it is rather a guide for policies that should be followed to ensure the continued management of the given shoreline. Shoreline management plans are used by public and private companies worldwide (SE Coastal Group, 2010).

When creating a shoreline management plan, it is important to consider all factors that may be changing the face of the riverbanks – more specifically, what the area surrounding the water body is used for. A common practice is to divide the land into sectors such as agriculture, forest, parks, residences, industry, etc. Each of these sectors uses land and water differently and thus will contribute various elements to the environment – all of which are important to consider when discussing how the shoreline will evolve in the future. Land use regulations dictate what can and cannot be developed along a shoreline as well as the historical preservation of the area in some cases.

1.3.5 Summary

The Cota 100 and 260, as well as Lake Gatun, require monitoring and regulation. These lands are patrimonial; however, since the Canal and surrounding areas were transferred to Panama in 1999, use of the land had not been thoroughly investigated until the implementation of the CORA project in 2013.

Limits of land and water use, especially for large areas such as Lake Gatun, can be summarized most easily in a carrying capacity study, which outlines the extent of activity that can occur before the integrity of an area is sacrificed. In addition, the regulation of a shoreline is best described in a shoreline management plan, which can dictate the limits of future use of the shore in order to preserve it. This paper researches these two types of management plans and how they can be applied to the Panama Canal.

1.4 Research Topics

In order to produce the framework for a carrying capacity study and shoreline management plan for the ACP, four main objectives were identified:

- Study land areas, current use, and existing policies and regulations;
- Investigate similar types of land management reports;
- Develop a framework for a carrying capacity study of Lake Gatun; and,
- Design a shoreline management plan for Lake Gatun.

This section details the research and results obtained through personal communication with CORA team members as well as individual research regarding land use regulations and examples of land management reports.

1.4.1 Regulations of Land Use Surrounding the Panama Canal

On August 25, 2005, the ACP Board of Directors signed a land use plan in accordance with Agreement No. 102, outlining the proper use of the patrimonial land of Panama by the ACP, the Republic of Panama, or a third party. A third party may use the appropriately zoned land once they agree on a contract with the ACP. The objectives of the land use plan were to maximize the use of these areas in terms of tourism, recreation, commercial, education, science, and culture to guarantee continued, efficient, and secure function for the Canal. Preserving natural resources was a priority for the Canal. Additionally, the land use plan established the type, density, and intensity of the activities of a third party that are permitted on land owned by the ACP or under private administration (ACP, 2005).

The ACP has a series of maps showing the various land types in different locations along the Canal. An example of this can be found in Appendix B. The agreement divides the land into three types by the permitted use of each, as is illustrated in Figure 13, and detailed below.

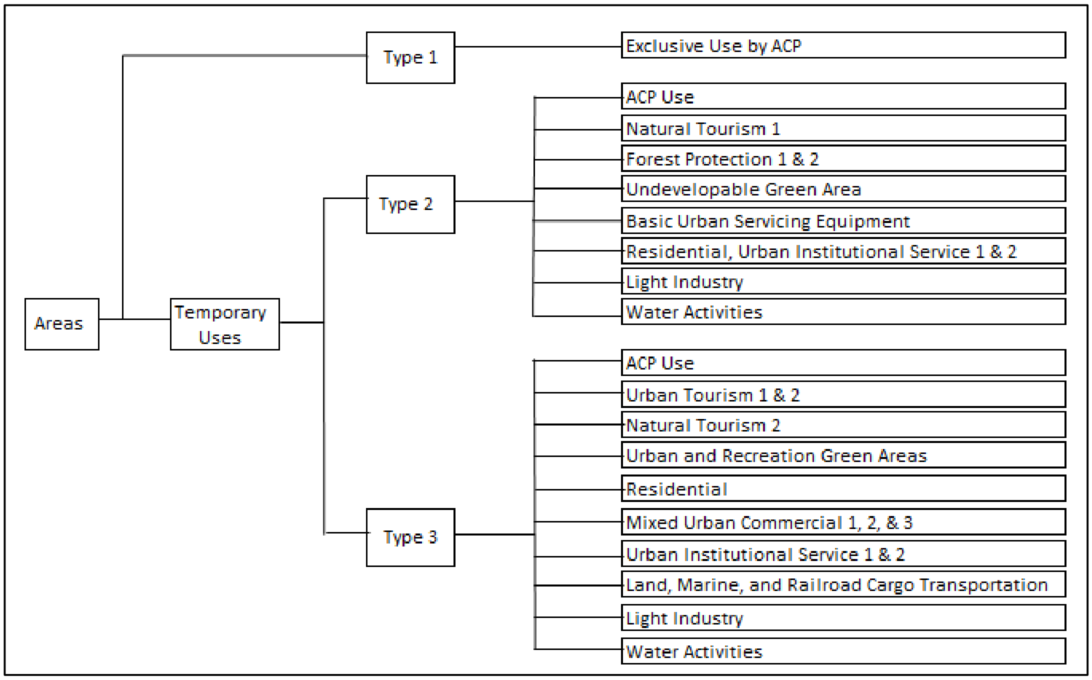

Figure 13: Permitted Use According to Area Type[5]

1.4.1.1 Type 1 Lands

Type 1 lands are those that are property of the ACP or are patrimonial inalienable land under private administration by the ACP. These lands are critical to the function and modernization of the Canal and for activities directly associated with these functions. General characteristics of Type 1 lands include the presence of locks, reservoirs, spillways, Canal operation-related infrastructure, maintenance and modernization of the Canal, and buildings and paved areas. In terms of natural elements, Type 1 lands are within a rainforest ecosystem with water and shores of the Canal. Type 1 lands are solely used by the ACP, however, permission can be granted for use by third parties under the following exceptions (ACP, 2005):

- If the activity is in support of ACP activities (for example, health related activities benefitting ACP employees);
- If the activity is under the patronage or supervision of the ACP;
- Scientific investigations;
- For the writing of official articles regarding the Canal;
- For international communication services or restaurant concessions/cafeterias (such as at the Miraflores visitor center);
- For observation of activities or landscape; and,
- To move to areas of Types 2 or 3 (ACP, 2005).

[5] Translated version taken from Agreement No. 102

1.4.1.2 Type 2 Lands

Type 2 land is also patrimonial land operated by the ACP, but can be used for activities that will not affect the function, infrastructure, critical system installations, or natural resources surrounding the Canal. Type 2 lands are also within the same rainforest ecosystem, but are home to many more buildings and infrastructure. The scope of use for Type 2 lands are as follows (ACP, 2005):

- Permit the ACP to approve third parties' activities or projects that make the most of the natural landscape, strategic location, infrastructure, waters, or buildings in the Canal area;
- Permit activities or projects that do not affect the function of the Canal nor the conservation of water in the watershed, and benefit the ACP;
- Permit activities under the patronage or supervision of the ACP; and,
- Permit the approval of use for the allowed activities, contracts, or authorization.

Type 2 land is prioritized for activities that help in the operation, maintenance, and modernization of the Canal. Other activities are permitted by third parties include camping areas, potabilizing water, bathroom facilities, single- and multi-family housing, and ecotourist activities in the water bodies (ACP, 2005).

1.4.1.3 Type 3 Lands

Activities permitted on Type 3 lands make up a much larger range than those previously described, as long as they do not affect the Canal or its operations in any way. The major differences in permitted activities include the approved use for light industry, mixed commercial use, urban recreation areas, institutional service, and cargo transportation. Type 3 lands include both natural and constructed environments. A general limitation for activities occurring on Type 3 lands is that they are in accordance with the characteristics of the land. For example, an urban recreation area should not be constructed in the rainforest area, but rather where there is space for it in the urban sectors of the Type 3 land (ACP, 2005).

1.4.2 Investigate Similar Reports

In order to prepare a framework for a carrying capacity study and shoreline management plan, several carrying capacity reports and SMPs were consulted to gather information about proper terminology, formatting, and methodology. Research of previously completed land management reports was beneficial to understand the expected final product and the methods needed to complete them.

1.4.2.1 Carrying Capacity Scope of Work

In 1974, the Florida Keys were named an Area of Critical State Concern, and therefore the State took several measures to protect it. In 2001, the U.S. Army Corps of Engineers hired the URS Corporation to perform a carrying capacity study for the archipelago. The Scope of Work began in 1996 with the formation of the Steering Committee and a Technical Advisory

Committee, which included 38 agencies and three individuals. The committee was made up of residents who were able to voice their experiences and concerns that they would like to be addressed in the study (URS Corporation, 2003).

The Florida Keys Carrying Capacity Study (FKCCS) was a considerable undertaking by the State of Florida and had heavy involvement from a wide range of citizens and companies alike. The study was broken into five main areas of importance: terrestrial and marine ecosystems and species, human infrastructure, socio-economics, fiscal, and water issues. The culmination of the study was the integration of the data, relationships, and carrying capacity research into an automated computer model using Geographic Information Systems (GIS) technology (URS Corporation, 2003).

The Ministry of Tourism for Uttarakhand, India, also found the need for a tourism (social) carrying capacity study in 2014. The request for a proposal began with a scope of work for the study, which outlined the necessary steps to complete it. These steps included background research on the part of the subcontractor, as well as forecasting for up to 30 years in the future. The scope of work was used as a bid package so the Ministry could hire an outside firm to complete the study (Ministry of Tourism, 2014).

1.4.2.2 Shoreline Management Plan

In 1995, the Ontario Ministry of Natural Resources decided to implement a shoreline management plan for the Great Lakes as written by Ontario conservation authorities. These plans were drafted to account for the increasing erosion due to higher water levels and storms that affected the area the previous year. The goals of the SMP were to reduce any risk to humans or property due to flooding or erosion, and to account for these possibilities when developing along the shore. The key components of the plans included “provisions for prevention, protection, emergency response, public information, environmental assessment, and monitoring” (Lawrence, 1995).

1.5 Presentation of Final Reports

Land use management has become important in many countries around the world, especially in those areas of high tourism or residences. Lake Gatun is of a different nature, given the traffic patterns due to the Panama Canal, and this type of management or monitoring may be beneficial for this particular area. This section details the final land management reports recommended to the ACP after the completion of the methods outlined in Section 1.4 Research Topics.

1.5.1 Carrying Capacity Scope of Work

Performing a carrying capacity study requires the collection of information and analysis, as well as predictions for the future use. To write a carrying capacity study, natural resource availability must be analyzed, along with patterns of their use. Additionally, it is important to study the current and forecasted trends of occupation, since this impacts natural resource depletion as well. The scope of work for the carrying capacity study of Lake Gatun is outlined below for use by the ACP:

- I. Review all existing information about lake
  - A. Water engineering office
  - B. Water resources office
  - C. Annual water quality reports
- II. Stakeholder workshops
  - A. Potential involvement: Canal administrators, Lake Gatun experts from ACP, water quality experts, board of directors, tour guides, Canal pilots
- III. Obtain maps from GIS/COAT department of occupations around lake
  - A. Determine type of occupation – authorized/unauthorized
  - B. Compliance with Agreement 102
- IV. Assess carrying capacity with regards to the following four characteristics:
  - A. Physical
    - 1. Physical features of lake
    - 2. Changes over time
  - B. Ecological
    - 1. Population size surrounding lake
      - a. Number of residences
      - b. Dependence on lake for resources
    - 2. Use as reservoir for cities
      - a. Estimated load of that + gallons per boat per canal transit should be equal with water coming in by watershed and rainfall
  - C. Social
    - 1. ACP use statistics
      - a. Current/expected transits per time
    - 2. Swimming
  - D. Economic
    - 1. Tourism statistics
      - a. Daily boat rides
      - b. Shore tourist areas
    - 2. Any other business on the shore

Figure 14: Framework for Carrying Capacity Study

1.5.2 Shoreline Management Plan of Lake Gatun

The purpose of the following SMP is to prevent damage to the shore of Lake Gatun, including by but not limited to erosion and increased unauthorized occupation. This SMP was created to manage any potential harm to the shoreline or its inhabitants as a result of Canal operations. Water quality management was also considered.

There are about 1,020 miles (1,640 km) of shoreline on Lake Gatun. Since all the land that makes up the shoreline of Lake Gatun is Type 1 (refer to Section details the research and results obtained through personal communication with CORA team members as well as individual research regarding land use regulations and examples of land management reports.

1.4.1 Regulations of Land Use Surrounding the Panama Canal), it is set aside for use solely by the ACP. However, 1% of the land (10.2 miles/16.4 km) is being used, with 50 cases being unauthorized. These cases are mostly residential, commercial, or tourism.

As previously mentioned, the management and monitoring of unauthorized occupation around Lake Gatun is under the scope of work of the CORA project. Certification and approval by the ACP is now required for use of land within the Cota 100. The implementation of taxes or fees for use of this area is a viable solution to regulate who is using the land. Currently, land in the Cota 100 occupied for commercial use is being taxed, and the ACP is working toward implementing a tax for private and residential use.

There are five locations along Lake Gatun that are set aside for ecotourist activities, each with specified allowable areas, ranging from 1,000 to 1,500 m^2 (10,800 to 16,100 ft^2). Only the following may be constructed or installed in these areas: structures covered with a biodegradable roof; wooden, removable docks; open air cafes; latrines; and paths. Contracts for ecotourism companies to construct on this land remain in effect for five years and can be renewed for an additional five years if desired (ACP, 2014c). At this time, contracts are not being drawn up for other uses of the Cota 100.

As part of the expansion project, the ACP and subcontractors dredged about 1 billion ft^3 (30 million m^3) from Lake Gatun and the Culebra Cut to accommodate for the larger ships that will be passing through. Lake Gatun increased in depth from 87.5 to 89.0 ft (26.7 to 27.1 m), which added almost 7 billion ft^3 (200 million m^3) of additional storage space for water. Dredging, however, can affect the shoreline, either directly or indirectly. The direct impact of dredging on a shoreline is the slow infill of the dredged area by sedimentation sloping from the shoreline to the area. The indirect effect of dredging is more likely to occur in an open water body location; dredging can change wave heights and directions which will create some changes along the shoreline over time (Demir, Otay, Work, & Börekçi, 2004). Due to the size of the lake, the potential for direct impact of dredging was low because only the passage for ships was dredged. Additionally, since Lake Gatun is a closed body of water, the shoreline was not affected by a changing wave pattern as a result of dredging.

The amount of traffic through the Panama Canal is important to consider when studying Lake Gatun, especially with the upcoming expected increase in transits as a result of the expansion. However, emissions from the ships do not affect the shoreline in a noticeable or harmful way. In the 2008 fiscal year (October-September), there were approximately 13,100 transits, for a total of 12.6 million TEU (ACP, 2008b).

The water quality over the past decade has improved in Lake Gatun – leading to the conclusion that the emissions from ships do not have a negative impact on the lake. The ACP conducts water quality tests of the lake monthly and at each testing location, and summarizes the results in a water quality index (WQI) calculated on the following criteria (ACP, 2006):

Table 1: Framework for Water Quality Index (ACP, 2006)

Characteristics	Percentage (%)
Dissolved Oxygen (%)	17
Fecal Coliforms	16
pH	11
BOD (Biochemical Oxygen Demand)	11
Temperature deviation	10
Phosphates (PO_4)	10
Nitrates (NO_3)	10
Turbidity	8
Total Dissolved Solids	7

This index is then categorized based on a scale of zero to 100 with the following ranks:

Table 2: Water Quality Index for Lake Gatun (ACP, 2006)

Range	Color	Description
91-100	Blue	Excellent
71-90	Green	Good
51-70	Yellow	Average
26-50	Orange	Bad
0-25	Red	Very Bad

In 2003, the average WQI was 84.8 based on the 181 indices. 3.70 % of the 191 data samples collected in that year were less than 71 (or “good”) (ACP, 2006). The water quality in 2013, however, improved, with 100% of the samples being at or above a “good” ranking (ACP, 2014b). This water quality improvement proves that Lake Gatun is a valuable and well-maintained part of the Panama Canal.

1.6 Discussion, Conclusions, and Recommendations

The CORA project team has a solid foundation and long term plan for the use of the lands described in this report. However, due to the immense size of Lake Gatun, the ACP would benefit from stricter management of the use of the lake and its surrounding area.

1.6.1 Carrying Capacity Study

For many organizations, a carrying capacity study has been a catalyst for better management of ecosystems. The ACP would benefit greatly from the completion of a carrying capacity study of Lake Gatun. This study could hold the ACP accountable for the proper use of the lake and its surrounding areas, and prevent further unauthorized occupation. It is recommended that the ACP utilize Section 1.5.1 Carrying Capacity Scope of Work as a bid package and hire an outside firm to complete the study. This study will be an important resource to the ACP as the expansion project wraps up and Post-Panamax ships begin transiting the lake.

1.6.2 Shoreline Management Plan

Shoreline management plans are very important for maintenance of changing shoreline environments such as ocean coasts. There has been no drastic change to Lake Gatun in the past 100 years except for the extensive dredging as part of the expansion. The shoreline and surrounding areas have also remained largely untouched, with only 1% of the land being occupied and the rest left naturally. Although it is a quiet area with few inhabitants and users, it is important to keep reports of use to monitor and predict future changes, especially with more traffic coming through the Canal. The ACP has begun this initiative with taxes put in place for commercial use only and are working toward the installation of taxes for residences.

Based on the findings of this report, it is recommended that the CORA project continue with their current plan and regular site visits to monitor unauthorized use of the lake. A shoreline management plan may be beneficial in terms of wildlife and natural habitat preservation, and should be explored in more detail through the hire of a subcontractor. At this time, it is unnecessary to implement a full shoreline management plan for regulation of land use since the current initiatives are fulfilling the needs of the ACP. Lake Gatun is an important resource to the ACP and Panama. Through the CORA project, managing Lake Gatun will preserve the environment for years to come.

Chapter 2: Alternative Design for Range Towers used as Navigational Aids

2.1 Design Statement

According to ABET criteria, students graduating from WPI must be prepared for the engineering practice upon completion of their capstone major design experience, or Major Qualifying Project (MQP). This project applies skills acquired in undergraduate coursework and knowledge in the field to investigate an alternative design for range structures for navigation in the Panama Canal. The existing range structures are unprotected, difficult to design, and are prone to looting. Choosing the design was an iterative process based on the realistic constraints including safety, economics, sustainability, environmental, and manufacturability.

Range towers are critical to the safe passage of vessels through the Canal. They must be accurately designed and constructed to emit their signals marking the centerline of the channel. Pilots, trained ACP mariners that navigate vessels through the Canal, rely on ranges as the most efficient mark in the Aids to Navigation System at the Panama Canal. It is imperative that the ranges are accurately designed for passenger, crew, and cargo safety aboard vessels as they transit the Canal.

The ACP recently finished updating the current range towers to accommodate the larger vessels transiting the Canal as a result of the expansion project. It is uneconomical to replace the current towers, but worthwhile to protect these new range towers from possible impacts or looters. This project addressed safeguarding the existing structures for immediate protection and suggests an efficient alternative structure to replace the towers as necessary.

Sustainability is important to incorporate into the design of the range towers. The existing latticed steel towers are equipped with sustainable light fixtures with LED lights and solar panels. This project analyzes the sustainability of the materials used to construct existing range towers as well as tower lighting elements.

Range towers need to be visible to all ships, meaning they may be constructed in or near communities. The aesthetics, lights, and construction of the towers should not be disruptive to local people living near the range towers. Protective measures from looters should be taken for towers located near communities. This project recognizes the social, political, and ethical implications and considers them in the selection of a new range tower structure.

Topography in the Panama Canal is very uneven, and range design can be difficult whether it is the height of the tower, the luminosity of the light, or the geographic range of the signal. Placement of range towers must be planned cautiously to make sure the centerline is marked accurately. Excavation and foundation construction have already been completed where the existing range towers are located. If the ACP erects alternative structures, it would be ideal to place them on an existing foundation for less environmental disruption.

Existing range towers in the Panama Canal are open to the atmosphere. When towers require maintenance, the weather may cause low visibility from fog or rain, increasing the likelihood of work-related accidents on the ladder or tower itself. To improve safety, an enclosed structure is more reliable to ascend during low visibility conditions. With health and safety as one of the top priorities of the ACP, this constraint was unquestionably considered while selecting an alternative range tower structure.

The ACP must pay for both parts and services to manufacture and construct the existing latticed steel towers. An ideal design is easy to manufacture and construct in order to save money. Many of the existing ranges are located in remote areas of Lake Gatun. A new design that can be easily transported and constructed with few tools would improve time and cost efficiency.

These parameters are discussed in the following report and led to the selection of an alternative range tower structure. The report compares the feasibility of these new proposed structures with the existing ones.

2.2 Introduction

The Panama Canal is a critical component to global trade being the only shortcut connecting the Atlantic and Pacific Oceans. With roughly 12,000 vessels passing through the Canal annually with about 327 million PC/UMS[6] net tonnage, it is important that all of these vessels undergo a safe and efficient transit. Mariners utilize a variety of Aids to Navigation (ATON) including visual and electronic aids to successfully navigate through the Canal. As technology progresses, many aids or their elements become outdated or unnecessary and many new aids are introduced. Ranges are the most popular element of the Panama Canal ATON system and are constantly being updated and improved. A range is a pair of towers used to mark the centerline of a channel. This project aims to investigate the feasibility of a new range structure in the Panama Canal through the following series of objectives:

- Determine the benefits and limitations of existing ranges;
- Select an alternative tower for ranges; and
- Evaluate the feasibility of the selected alternative tower.

[6] Panama Canal Universal Measurement System (ACP, 2014a)

2.3 Aids to Navigation in the Panama Canal

Aids to Navigation (ATON) are systems or devices, external to a vessel, that assist mariners during transit to help determine position and course of travel. They warn mariners of dangers or obstructions, and advise the preferred route or safest course to travel. ATON include a combination of physical, aural, and electronic aids that may be located in or out of the water. Mariners follow the ATON system established by the governing bodies near shores and through waterways where they are located.

According to Section 2, Article 9, of the Regulations on Navigation in Panama Canal Waters (ACP, 1999), the ACP has the authority and responsibility for coordinating the "prevention and control of any dangerous events, acts, and accidents which may occur during navigation in Canal waters." The ACP has developed an ATON system for mariners to safely navigate the challenging waters of the Panama Canal. Among other requirements, the ACP requires that vessels traveling through the Panama Canal must carry a copy of the regulations for navigation in Canal waters for a safe and efficient transit (ACP, 1999). The ACP's responsibility to design and maintain ATON and safe navigation through the Panama Canal is comparable to the roles of the United States Coast Guard (USCG) or the Canadian Coast Guard (CCG) in their respective countries.

While the Panama Canal does not use all of the same ATON as the USCG or CCG, many elements are similar. Before the ownership of the Panama Canal shifted to Panama, the United States oversaw its maritime operations, thus using the USCG ATON system to navigate the Canal. Elements of this system are still being used and many of the new ATON used in the Panama Canal continue to be modeled after the USCG ATON. The ACP has additionally developed new technologies specific to the navigation of the Panama Canal making it a unique case for studying maritime navigation.

2.3.1 Challenging Terrain

When entering the Panama Canal from the Atlantic side, a ship must navigate through the three sets of locks, around 15 Reaches (short straightaway sections in the Canal, seven of which are located in the Gaillard Cut), under the Centennial Bridge, through the next three sets of locks, and under the Bridge of the Americas before reaching the Pacific Ocean. Throughout this journey, the vessel travels approximately 51 miles (82 km) and reaches a maximum elevation of 85 ft (26 m) before returning back to sea level on the other side. Figure 15 is a detailed map of the Panama Canal labeling each of the elements mentioned with associated numbers.

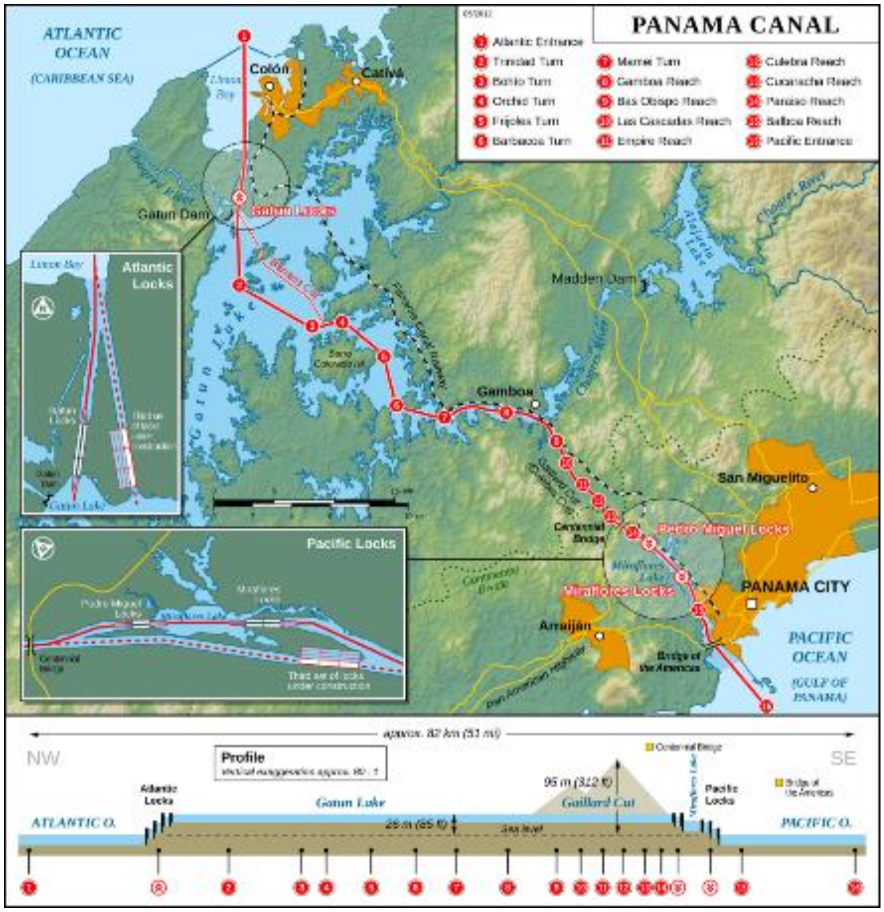

Figure 15: Map of the Panama Canal (USACE, 2013)

The series of 15 Reaches, numbered 2-15 on Figure 15 are narrow areas of the Canal that are difficult to maneuver. They span from the Atlantic Ocean over Lake Gatun to the Pedro Miguel Locks. Bas Obispo Reach to Paraiso Reach (numbers 9-14 on the map) are the narrowest reaches of the Canal known as the Gaillard Cut. Figure 16 is an image of the Gaillard Cut near the Centennial Bridge. In full length, the Gaillard Cut is 8.01 miles (13 km) long with 730 ft (222 m) width at its curves (ACP, 2008a; ACP, 2014a). The land surrounding some areas of the Canal is unstable and susceptible to landslides. During initial excavations of the Canal in the early 20th century, landslides poured millions of cubic yards of mud and dirt into the cut, which delayed further excavations and the opening of the Canal (ACP, 2008a; Gaillard Cut, 2015). Currently, hillsides have been terraced with smaller slopes to decrease the chance of these threatening landslides, but with the expansion underway, it is a constant threat to navigation through the Canal (Gaillard Cut, 2015).

Figure 16: Gaillard Cut near the Centennial Bridge[7]

The narrow Reaches like those at Gaillard Cut make navigation challenging through the Canal, but there are additional risks mariners must be aware of. The Panama Canal is constantly changing. Seasonal rains may reduce visibility and increase the risk of erosion and landslides. These risks and other environmental changes make the Canal difficult to navigate. In addition, mariners must be cautious of hydrodynamic effects like currents, suction, and surges throughout the Canal (Pilot's Handbook, 1996). The rivers that feed Lake Gatun and the Panama Canal originate in the rainforest. Erosion from deforestation of the rainforest carries sedimentation into the Canal during the rainy season (ACP, 2007). The sedimentation settles and builds up in the Canal, reducing the water depth.

Dredging is a continuous necessity to ensure vessel clearance through Gaillard Cut. As part of the Panama Canal Expansion Project, the ACP plans to dredge all areas essential for the Canal to accommodate the Post-Panamax ships. This includes the expansion of Gaillard Cut which the ACP must excavate, drill, blast, and dredge approximately 108 ft (33 m) to accommodate Post-Panamax ships (ACP, 2003; Gaillard Cut, 2015).

[7] Unless otherwise noted throughout the entirety of this report, all figures are photographs taken by the author.

2.3.2 Visual Aids

The most established and reliable aids to navigate through bodies of water are visual. Visual aids are physical signals that rely on light source, weather, position of the navigator, and background light of the element (Fang, Gong, Kim, Kim, & Park, 2015). Visual ATON are easily identifiable on navigational charts, but an experienced mariner will know to correlate the maps with the physical aids they see on the water. Examples of visual aids include buoys and ranges among others. They are designed for and placed where the mariner can best recognize the information provided by the device (Fang et al., 2015). Each visual ATON requires a light for nighttime navigation. Engineers choose the appropriate light fixture for best recognition by mariners depending on the aid and a variety of environmental factors.

2.3.3 Theory of Visual Signaling

When a mariner is traveling through a body of water and needs to check that he is in safe water, he looks for visual signals to keep his bearing, identify his location, and ensure he is on the correct route. The theory behind noticing these visual signals involves three phases: production, transmission, and detection of the signal. Signals are then evaluated by the mariner and can be estimated using Allard's Law (U.S. Coast Guard, 1997; U.S. Coast Guard, 2002). Allard's Law evaluates how the phases interact and the adequacy of a signal. This section describes the theory of visual signaling based on the three signal phases and their evaluation.

SIGNAL PRODUCTION: A signal uses optics to generate ATON lights. This signal may include color and/or rhythm characteristics to convey information to the mariner.

SIGNAL TRANSMISSION: After the signal is produced, it is transmitted through the atmosphere. While traveling through the atmosphere the signal or light is absorbed, scattered, and spread. The visibility or transmissivity of the light is caused by the amount of light exiting and entering the atmosphere.

SIGNAL DETECTION: Next, the mariner can detect the signal. Factors that play a role in determining the signal include background lighting and the psychological state of the mariner. The threshold of illuminance is a physiological quantity varying from person to person based on the size of the light viewed, its color, degree, and the state of dark adaptation of the observer. The USCG uses three different values for the threshold of illuminance. The first value is 0.67 sea-mile candela[8] for no background lighting, the second value is 6.7 sea-mile candela for low background lighting, and the final value is 67.0 sea-mile candela for high background lighting (U.S. Coast Guard, 2002).

These three phases determine if a mariner can adequately see a light provided by the visual signal. Allard's Law is used to evaluate the illuminance and physical height of the light. The nominal range is the range written on nautical charts so a mariner will know when to see a

[8] The SI unit for luminous intensity where one candela is equivalent to one lumen.

light in clear conditions without background light. The luminous range is the maximum distance a light signal can be seen by a mariner. The geographic range is the length that a signal can be detected disregarding the luminous intensity of the light. This range is the sum of the horizontal distances of the light and the observer and is the tangent from the light and observer to the earth.

2.3.4 Buoys

Buoys, which are floating, buoyant aids, are the most common visual ATON. They mark channels of transit through waterways and along shorelines. They are also used to mark shallow areas, rocks, and other obstructions in the water. Buoys have a variety of characteristics that are easily identifiable by an experienced mariner. Information and specifications of buoys are readily available in literature and online. This paper will briefly describe general information about buoys.

2.3.4.1 International Association of Lighthouse Authorities (IALA)

In 1976, there were more than 30 different buoyage systems in the world with conflicting rules that confused mariners traveling at sea. To unite the systems, IALA began establishing rules for two individual systems. When writing the rules based on the preferences of different regions, IALA realized the two systems were nearly identical. In 1980, IALA created the Maritime Buoyage System with help from representatives of 50 countries and nine international organizations and subdivided it into System A and System B (IALA, 1983). The standardization of a marine buoyage system lowered risks at sea and improved safety for mariners and their properties.

Like the rest of the Western Hemisphere, Panama follows the International Association of Lighthouse Authorities Maritime Buoyage System B, or IALA-B (Maloney, 1996). Figure 17 shows both IALA systems with System B, colored light blue, and System A, colored dark blue. As shown, System A is used by most of the Eastern Hemisphere, excluding Japan, the Republic of Korea, and the Philippines. There are few differences between System A and System B.

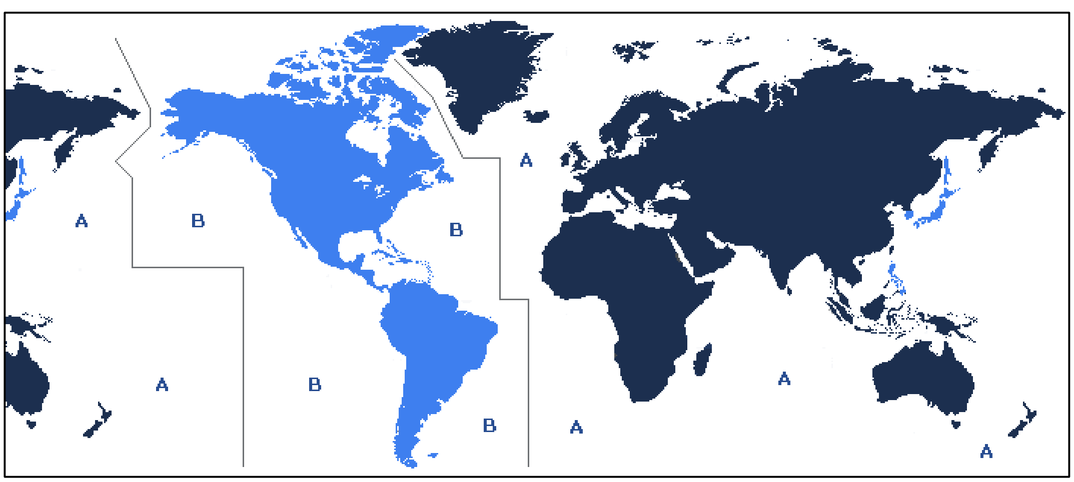

Figure 17: IALA Regions A and B (Piotrowski, 2006)

The main difference between the two systems is the color of buoy associated with the starboard (right) and port (left) side of a channel. All other aspects of the IALA Maritime Buoyage system are the same. For example, both utilize the same markers for the rest of the different buoyage systems (Maloney, 1996). While the colors may differ, the marks on the buoys guide the mariner by showing the route of safest travel.

2.3.4.2 Types of Marks

Buoys are marked to indicate their significance during the day and at night. During the day, buoys are marked by their color, shape, and top-mark. However, during the night, buoys are marked by their light color and phase characteristics. There are five types of buoy marks:

LATERAL MARKS: Lateral buoy marks indicate the side on which the buoy may be safely passed. Lateral marks are the only buoy color marks dictated by their IALA region. In System B, lateral hand and bifurcation buoys are red and on the starboard side of the channel, while the lateral hand and bifurcation buoys are green and on the port side of the channel (IALA, 1983). System A is the opposite and uses the red buoys on the port side and the green buoys on the starboard side. For consistency purposes, the lateral marks mentioned in the rest of this paper will refer to IALA-B.

When traveling upstream or into a channel from open water, the green colors, lights, and odd numbers on buoys indicate the left side of the channel. The red colors, lights, and even numbers indicate the right side of the channel. Therefore, when traveling the same channel downstream and towards the open water, the buoy colors will be switched. Figure 18 is an example of a boat passing lateral buoys traveling upstream from open waters (left) and then returning downstream to open waters (right).

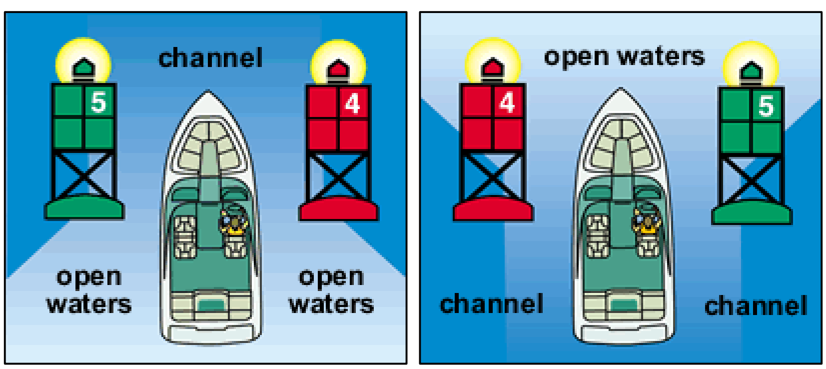

Figure 18: Passing Lateral Buoys (Texas Parks and Wildlife Department, 2015)

Some buoys may have both red and green colors. These indicate the preferred route of travel. When green is on the top, the mariner should take the channel to the right, and if red is on the top, the mariner should take the channel to the left.

CARDINAL MARKS: Cardinal buoys indicate hazard or obstruction and the direction of safe water marks, depending on the four cardinal points of a compass: North, South, East and West. These marks indicate the deepest water pertaining to the buoys' cardinal location. They should be passed on the direction which they indicate. Cardinal buoys do not have a distinctive shape, but are usually pillar or spar. They are always painted yellow and black with double cone black top-marks. See Figure 19 below for an example of cardinal buoys.

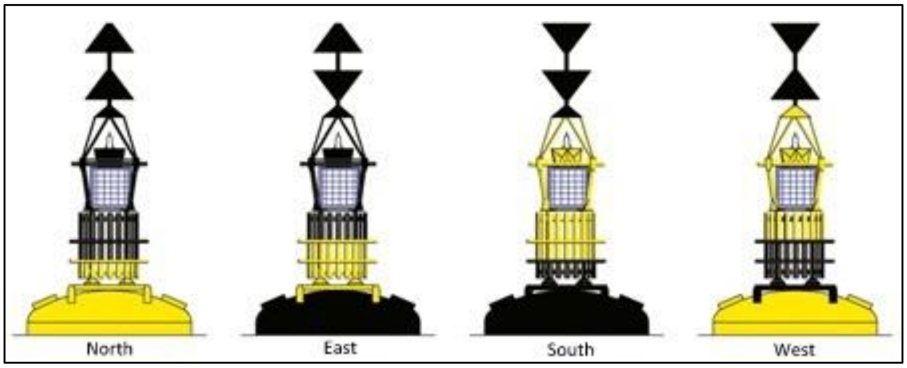

Figure 19: Cardinal Buoys (Corporation of Trinity House, 2015)

Cardinal buoys have a special system of flashing white lights for each of the four points. These lights flash very quick (VQ) or quick (Q) but are broken into varying rhythms (IALA, 1983). Each of the four cardinal points has its own distinct light rhythm characteristics. North exhibits a continuous or uninterrupted flashing white light, East exhibits three VQ or Q flashes in a group, South exhibits six VQ or Q flashes in a group with a long flash, and West exhibits nine VQ or Q flashes in a group. The concept behind these three, six, and nine phase characteristics are easily remembered by association with a clock.

ISOLATED DANGER MARKS: Isolated danger marks on buoys indicate small areas with navigable water around the danger. They are black with one or more red horizontal bands with a group of two flashing white lights, and have double black spherical topmarks which are characteristic objects placed on top of a buoy or beacon to aid in identification. These buoys often mark the center of shoals or islets. Isolated danger buoys are placed in the center of the danger and should be approached with caution because they may be slightly displaced from the exact geographic location of the danger.

SAFE WATER MARKS: Safe water marks on buoys indicate an area of navigable water without a danger and that there is navigable water all around the buoy. These buoys are typically spherical, colored with red and white vertical stripes, and may have a red spherical topmark. When lighted, safe water buoys have a flashing white light of over two seconds. Safe water buoys may be used to mark a centerline, mid-channel, a landfall, or fairways.

SPECIAL MARKS: Special marks on buoys are intended to mark an area for a specific use or feature that may not be apparent with reference to a map, chart, or other nautical document. They are yellow in color with a yellow light (without rhythm) and may have a yellow "X" topmark. Special marks can indicate recreation zones, traffic separation, spoil areas, cables, or pipelines. Special marks are not only found on buoys but can also be found on buoyant beacons in the water.

2.3.5 Beacons and Dayboards

A beacon is a single, fixed, navigational aid used to mark a feature of a channel that may be in or out of the water. Beacons vary greatly around the world, but are placed mainly for marking channels. They are either lighted or unlighted. Large lighted beacons are often lighthouses, while small lighted beacons are often buoyant. Small daybeacons can be dayboards which have lateral significance.

Dayboards are a type of daybeacon that are permanently placed signs attached to structures such as posts in or out of the water that mark a channel. Common shapes of dayboards are rectangles and squares that may be lighted or lettered. They are often installed vertically on an angle of about 30° to the channel line but are also placed to mark centerlines of channels during the day. In the case of marking centerlines, dayboards are often placed on ranges. Dayboards require little to no maintenance because they are just signs and therefore are more reliable and cost-efficient than their counterpart daytime lights, which is why they are often affixed on ranges.

Engineers design dayboards by the nominal range of the mariner and the type of signal they are used for. The USCG has established criterion for dayboard selection that can be found in the Range Design Manual (U.S. Coast Guard, 1997). Dayboards are affixed on structures that must meet or exceed a lifespan of five years. Based on the nominal range, dayboards may have different dimensions. On ranges, the dayboards on both front and rear towers will be the same colors but may be different sizes.

Dayboards best mark channels shorter than two nautical miles while daytime lights best mark channels longer than four nautical miles. Between two and four nautical miles, the USCG suggests to mark the channel with the most economic aid (U.S. Coast Guard, 1997). In areas of poor visibility, due to weather conditions such as fog or haze, daytime lights may be necessary. In this case, they may be paired with dayboards, but must reach a signal range that will exceed the dayboard in low visibility conditions.

2.3.6 Ranges

Another visual ATON is a range, which is a pair of lights, dayboards, or both, used to mark the centerline of a channel. Ranges are also called “leading lights” because they lead a vessel through a channel. Ranges have two towers, one situated at a higher elevation in the rear and one at a lower elevation in the front. A mariner will know if he is on the centerline of a straight channel if there is vertical alignment between the front and rear facing towers. Figure 20 is a profile view of the range towers (top), and the range lights as seen straight ahead from a mariner in the water (bottom). If he is not on the centerline, the towers will not be aligned as shown in the bottom left and bottom right of the figure.

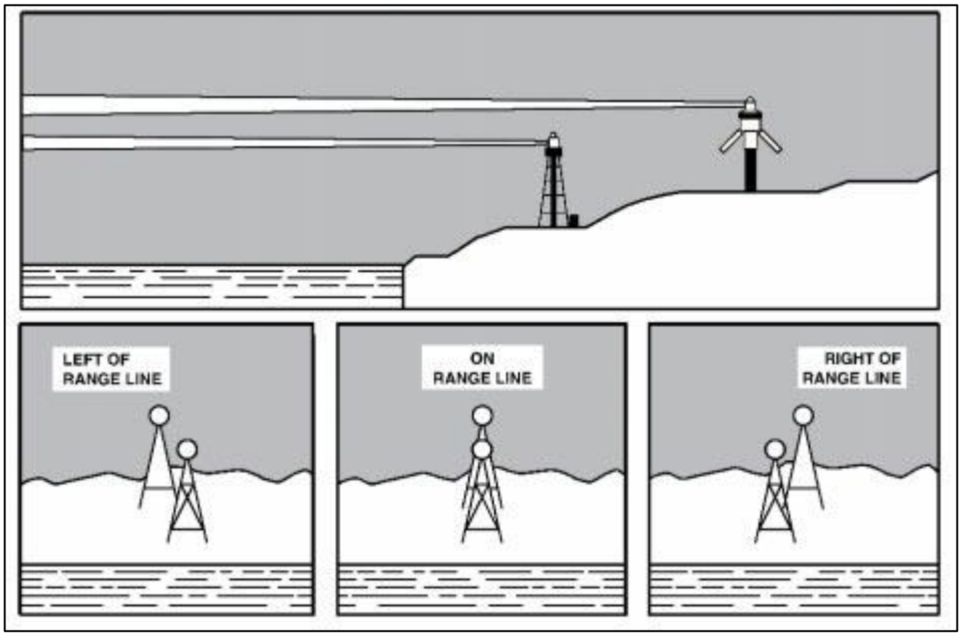

Figure 20: Ranges (Bowditch, 2002)

2.3.6.1 Design

Engineers must consider location, structure, and optics to design a range. Designing ranges is an iterative process. The tower heights, distances, and light intensities are changed to optimize the lateral distance of the range specific to each location (U.S. Coast Guard, 2002). The theory of visual signaling helps designers anticipate the visual and calculated range perception of the signal, for the most convenient placement of ranges for a channel.

When designing a range, an engineer initially considers the length of the channel that the range will be observed because it must be visible day and night through all weather conditions. Dayboards and lights must be visible from the end of the channel length 24 hours a day. To ensure this, the rear tower, which is farther away, may be designed larger, sturdier, or with lights of higher intensity than the front tower (U.S. Coast Guard, 1997). Construction and maintenance costs can be expensive on these larger towers, so engineers may adjust the design for any economic constraints.

Engineers design tall and sturdy ranges to emit a successful signal evaluated in all conditions. Ranges must be clearly visible and able to withstand all possible loads on their structural elements. Range towers may be located on a hill with high wind, in areas of high erosion, on a fault line, in icy conditions, or even in the water. Therefore they must be designed for wind, dead, live, seismic, snow, and wave loads. Range designers should choose the most appropriate design for the location of the towers based on its location's load constraints.

When designing ranges, engineers must also consider the cross-track factor, or the lateral sensitivity of the range (U.S. Coast Guard, 1997). The cross-track factor is a percentage of the lateral distance that a mariner can detect his vessel is not on the centerline of a channel divided by half the width. Therefore, a factor of 25% means that a mariner is at least 25% of the distance towards the edge of the channel before realizing he is off of the centerline. This means that the higher the cross-track factor, the lower lateral sensitivity to the centerline. Designers should aim for a cross-track factor of 10-20% to reduce risks of collision between passing vessels and in narrow channels (U.S. Coast Guard, 1997).

In addition to the lateral sensitivity, engineers must consider the minimum acceptable vertical angle and the brightness balance between the two lights. These properties depend on the height of the towers, their distance apart, and the light intensity of optics. To select appropriate optics for a pair of range towers, a higher threshold illuminance is required to ensure the lights can be seen at the end of the chosen channel.

The structural elements required for range towers depend on the topography, vegetation, and weather the tower must withstand during its lifespan. Foundations are normally built with piles or micro piles driven in the ground to support the weight of the tower through different load conditions. The piles transfer the structural loads into the soil where they are imbedded. These piles are either made from wood, steel, or precast concrete. Composites and plastics may be used on occasion, but their use depends on the availability of resources, cost, and expected lifespan of the structure. The wood, steel, and/or concrete piles are often coated to prevent corrosion (U.S. Coast Guard, 2005).

2.3.7 Directional or Sector Lights

A sector light is a directional light divided into two or more colored beams. A fixed, single light is called a directional light used to light lanes of traffic in waterways. A sector light usually consists of three colors: red, white, and green (see Figure 21). A mariner will know he is on the centerline of a channel if the sector light is white. If he sees red or green light, he is too close to the edge of the channel and must return to the white light. The small colored circles at the bottom of Figure 21 indicate the color a mariner sees when he is entering a channel from a certain angle.

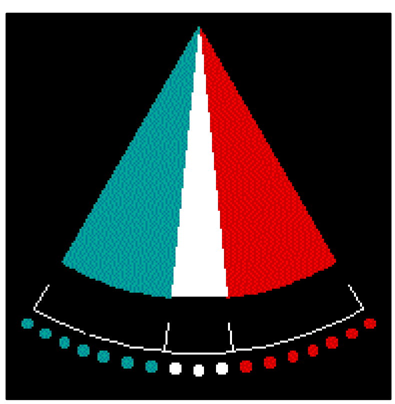

Figure 21: Sector Light Colors (Vega Industries, Ltd., 2011)

Some sector lights have an oscillating feature which gives enough information to the mariner to determine his position in relation to the centerline. An oscillating light has the same three colors, but the light rotates, creating two colors to overlap in some cases. A mariner will see this as a blinking light of green and white or red and white (Vega Industries, Ltd., 2011). For example, a longer blinking green light with a short white light will mean that the mariner is close to the right and must return to the left for the centerline.

It is uncommon for a sector light to be used in a range because it is designed to be a single light signal. For example, in the Panama Canal, sector lights are used as a secondary alignment system, and are affixed to the rear tower on some ranges in the Canal. They are located only in sailing line ranges, which are the ranges used to position a ship for bidirectional traffic. This means that sector lights are positioned in the narrowest areas of the Canal.

2.3.8 Lighthouses

Lighthouses are major lights that are placed at a significant height to increase its geographic range. They are typically located on headlands, harbors, port entrances, isolated dangers, or where mariners can best use them to identify their position (Bowditch, 2002). These major lights can also be placed inland where they function as a range (leading) light, directional light, sector light, or reference light.

Lighthouses have been used in ranges for over a century. The Bremerhaven Lighthouse along the North Sea in Germany, is the rear tower to a pair of range lights marking the northern side of the harbor's lock. The front tower is a small red and white lighthouse on the southern pier of the lock. This range pair helps ships leaving the Weser River navigate a turn into the adjacent estuary (Rowlett, 2014a). The El-Boughaz el Kebir and Al Maks Upper are the two lighthouses of the Great Pass Range located in Alexandria, Egypt. The El-Boughaz el-Kebir is the front tower and has guided ships into the Alexandria Harbor since 1908. It replaced the Al Maks Lower tower in 1908 after a change in the line of approach to the harbor. The Al Maks Upper rear tower has been in service since 1894 (Rowlett, 2015a). Figure 22 shows the two lighthouses of the Great Pass Range.

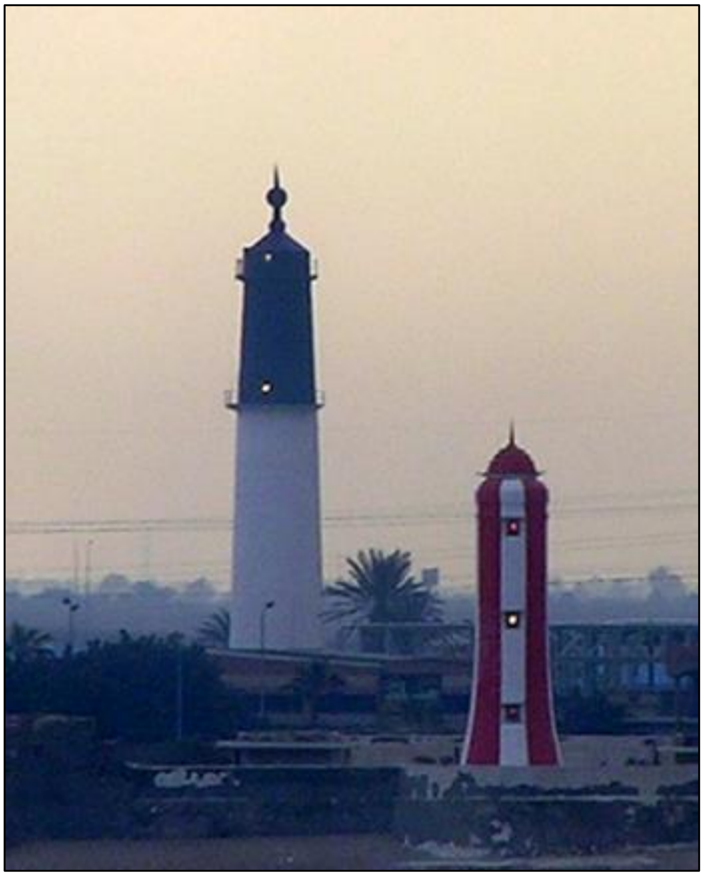

Figure 22: Great Pass Range Lighthouses in Alexandria, Egypt (Rowlett, 2015a)

2.3.9 ATON in the Panama Canal

Range towers are the preferred navigational aid for pilots in the Panama Canal, even though other aids, like buoys, exist. Although failure of a range will not stop traffic, there may be delays and complaints from the pilot force. These types of structures have been used in the Panama Canal since its construction, and although navigational technology has progressed significantly, visual ATON, specifically ranges, are the preferred method by the pilots. This report investigates alternative range tower structures that retain the same benefits as the existing structures, while addressing design limitations.

2.4 Research Plan

This project focused on researching different structures used for navigation, and explored their application in the Panama Canal through the following objectives:

- Determine the benefits and limitations of existing ranges;
- Select an alternative tower for ranges; and,
- Evaluate the feasibility of the selected alternative tower.

The project followed a detailed research plan to evaluate the potential use of an alternative structure used for range navigation in the Panama Canal. To determine the benefits and limitations of ranges in the Panama Canal, the project researched the existing range design and structures, material durability, and maintenance, as well as topography and location restraints of the existing ranges. Next, the project researched alternative structures for range towers. This included details and specifications, material used for construction, and global applications of these structures. Finally, the project compared the existing range towers to the proposed alternative tower design to evaluate its feasibility in the Panama Canal.

2.5 Benefits and Limitations of Ranges at the Panama Canal

To understand the benefits and limitations of Panama Canal ranges, this project looked at the existing structures and discussed them with the lead structural engineer who currently designs ranges for the ACP. He addressed design, structural, and maintenance benefits and limitations. Benefits of the existing ranges include the lifespan, durability, and sustainability of the towers. These benefits were important elements to consider in selecting an alternative design for range tower structures. Limitations of range structures center on the topography and location of the range as well as lack of protection. These limitations were important to consider when selecting an alternative structure.

2.5.1 Design and Structure

For new ranges in the Canal, a request must be presented to the Civil Engineering Division (IAIC[9]) by the Canal Port Captain, the Navigational Aids Unit, or the office leading an excavation project that will change the alignment of any range along the Canal. The IAIC then proceeds with the design. This design process includes the evaluation of new positions to comply with the required sensitivity, topographic work in the field to mark and evaluate any construction constraints and to prepare drawings, and specifications for construction. The IAIC presents the proposed design and drawings to the owner and the Navigational Aids Unit for comments. The final construction package is sent to the contracting division to start the bidding process. After the construction is finished, the new ranges are tested by the pilots in several partial transits along the Canal using various types of vessels to confirm that the sensitivity of the new range is adequate.

The IAIC follows range design specifications based on the U.S. Coast Guard Range Design Manual and the subsequent computer program described in the manual (U.S. Coast Guard, 1997; U.S. Coast Guard, 2002). The manual and program were adopted by the ACP after transitioning ownership from the United States in 1999. The Range Design Manual (U.S. Coast Guard, 1997) includes general information about range design as well as instructions to use the computer program. The Visual Signal Design Manual (U.S. Coast Guard, 2002) includes general information about selecting and evaluating signaling optics and uses another computer program to do so. This program, Allard's Law Computer Program, is modeled after Allard's Law, mentioned above in Section 2.3.3 Theory of Visual Signaling.

In the Panama Canal, range towers are structurally classified as Category I, meaning it is a structure whose failure implies low risk for human life (Sociedad Panameña de Ingenieros y Arquitectos, 2004). They are designed to meet the TIA-222-G standard, according to the contractor's construction plans (ACP, 2013). For the range towers, the contractor typically

[9] IAIC for Sección de Ingenería Civil, in Spanish

performs the structural analysis based on ACP specifications. These are basic requirements regarding gravity, wind, and seismic loads as well as deflection limits.

The range towers at the Panama Canal consist of a steel tower, a dayboard composed of painted aluminum panels, fiberglass servicing platforms, LED lamps, lightning rod, and ground cables. The range towers have sustainable light fixtures equipped with LED lights and solar panels. Additionally, some towers have perimeter fencing for protection. To avoid using protective coatings, all steel materials are galvanized or stainless steel (A-53-B-42 and A36[10]).

Figure 23 is a sketch of a range tower from the contractor's construction plans (ACP, 2013). The tower has a latticed design with two panels for the dayboard. The light is placed on the top of the tower and must be accessible for servicing, so a ladder and serving platforms are necessary for maintenance and safety. All of the recently erected range towers in the Canal are similar to this design, but have varying dimensions and are designed with varying maximum loads.

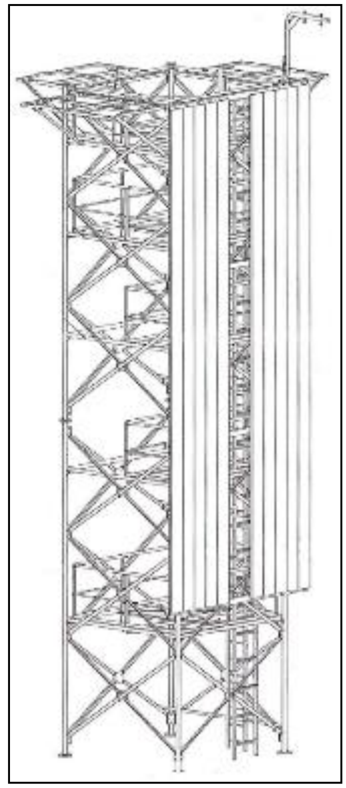

Figure 23: Range Tower Sketch

2.5.1.1 Material Durability

The current latticed range towers are open and exposed to weathering. The Panamanian climate has a dry season, a light rain season, and a heavy rain season. Therefore, range tower structures are unprotected from rain, heat, and humidity. The towers are constructed of galvanized and stainless steel to increase their durability in these harsh conditions.

Galvanized steel has a bond strength of about 3,600 psi (24.8 MPa) and the chemical reaction between the elements during creation results in a unique zinc coating that enhances durability (AGA, 2015). The inner layers of galvanized steel are hard for higher resistance to abrasions and uniformity of the steel protects from corrosion. However, there are limitations to galvanized steel. If manufactured improperly, the zinc coating may chip or peel off, exposing the inner layer of steel. The zinc coating on steel develops a natural carbonate on its surface with exposure to the atmosphere and rainwater. This carbonate eventually becomes brittle and splits which exposes fresh zinc for corrosion which can corrode up to the inner layer of steel (GSA, 2014).

Stainless steel is a low carbon steel with corrosion resistant properties containing chromium of 10% or more by weight (Berkeley Point, 2015). The durability of stainless steel depends on the steel grade, the environment it is located in, and the surface finish. The grade

[10] Standards that were established by ASTM International

of steel is essential to meet the need of the stainless steel of a structure. It has a higher initial cost, although, over the lifespan of a structure, stainless steel is cost efficient. Stainless steel is lightweight and has an optimal strength to weight advantage.

2.5.1.2 Maintenance

The materials used for ranges require little maintenance; therefore ranges have a long lifespan in the Panama Canal. The existing ranges in Gaillard Cut have been in operation for about 13 years. However, they need to be replaced, solely because the range alignment changed after the straightening and widening of the Gaillard Cut from the expansion project.

Although vehicular impacts have not occurred, it is a potential risk. Automobiles travel within close proximity to range towers because some are located in urban areas near roads. In addition, marine impacts are possible since some range towers are located in the water. If a substantial impact occurs, it may take a couple of days or weeks to replace essential parts or the tower itself. Therefore, the ACP assumes the risk of damage to both land and marine based range towers. While these impacts have not occurred, the ACP should protect the towers to sustain the efficiency of the Canal.

The structure and electric systems are very reliable and if damage occurs, it is often minor. However, some of the old ranges in Lake Gatun are being defaced and looted for parts. As shown in Figure 23, the design of towers is open, making them easily accessible to climb. Although some range towers have perimeter fencing, a significant number do not because they are located in remote areas in Lake Gatun. These remote towers are being targeted by looters. Besides the locations with perimeter fencing, there are minimal precautionary measures taken to safeguard ranges. With locations in remote areas, in the water, and around urban areas, ranges are at risk from impact and looters.

2.5.2 Topography

Range design constraints include the topography and soil along the Canal. The topography is very uneven with numerous hills of hard and soft geological formations. The geology varies throughout the canal, comprising of fine and coarse grainy matter, soft, half-hard, and hard rock. The hard rock has resistance above 7,250 psi (50 MPa) and is most commonly found on the Pacific side of the Canal. The Atlantic side, however, is composed of sediment, clay, mud, and sand. More specifically, geological and geotechnical explorations in the Gaillard Cut and near the Gatun Locks indicate that strong basalt with variable fractures and weak sedimentary rocks are common. Residual soils from basalt and agglomerates are typically clay, which erode in the rainy season.

2.5.3 Location

Selecting range location is an iterative process, especially with the challenging terrain of the Canal. To aid in the selection process, the Panama Canal is broken into a set of Reaches that span from the Gatun Locks to the Pedro Miguel Locks. Two pairs of ranges are associated with each Reach for Northbound and Southbound transit, marking the opposite end of the channel when entering the Reach. This totals 60 range towers used for transit in the Canal that must accurately mark the centerline of the channel. They range from 40 to 140 ft in height (about 12.2 to 42.7 m), depending on the distance the range must travel for a mariner to detect the signal and the location of the range towers. Towers may need to be taller or spread farther apart depending on the geographic range or the lateral distance in which the signal can be detected.

One example of range spacing is the Gatun Reach which is 3.22 nautical miles in length. The Northbound towers are 90 and 140 ft (27.4 and 42.7 m) while the Southbound towers are 50 and 60 ft (15.2 and 18.3 m). Although they seem similarly spaced (see Figure 24), both towers of the Northbound range are significantly higher than the Southbound range. Another difficult location to design for is near or inside the locks. With the required heights for towers to reach their intended geographic range, placement of a tower on the locks may obstruct visibility for mariners.

Figure 24: Map of Gatun Reach Range Towers (Canal de Panamá, 2014)

Another example of range spacing is the San Pablo Reach which is 2.22 nautical miles in length. The Northbound and Southbound towers are 40 and 60 ft (12.2 and 18.3 m) in height. The rectangle in Figure 25 outlines the Northbound and Southbound ranges in red and the towers in yellow stars. The stars for the Northbound range on the left are closer together and almost three times nearer than the Southbound range seen on the right.

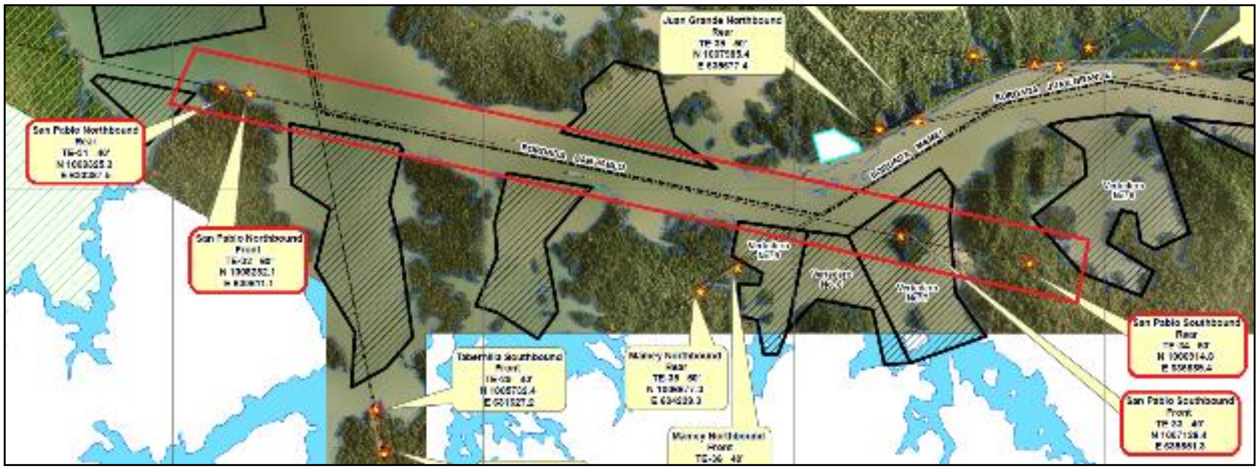

Figure 25: San Pablo Reach and Ranges (Canal de Panamá, 2014)

The range tower structure dimensions are designed by the ACP to each specific location in the Canal. They have similar structures and are constructed of the same materials. While the ACP has designed these structures to meet the topographic and location constraints, some towers are not protected, all are exposed to harsh weather, and equipment and structures are at risk of damage and property loss. An alternative structure may be necessary to avoid these limitations of the existing structures.

2.6 Selecting an Alternative Tower

To select an alternative tower for the Canal, this project investigated concrete lighthouses and glass reinforced plastic towers as alternative structures to the existing latticed range towers in the Panama Canal. The following sections include the results from researching these alternatives. They explore what the structures are, the material they are made of, the benefits and limitations of their designs, and some of their applications around the globe. The alternative tower was selected based on the materials of the structure and its design.

2.6.1 Lighthouses

Lighthouses may be used as an alternative to the latticed steel structures. They have the strength to hold daymarks to mark the centerline, as well as lighting equipment, and are enclosed and protected. The Panama Canal has used small lighthouses for inland navigation as ranges. With the widening of the Canal and addition of new towers, some of these permanent structures have become inactive with changing navigation lines. Many of these old lighthouses are now used for sailing lines, marking the widest possible line for vessels to use while transiting the Canal.

Pairs of lighthouses still exist in the Canal, and can be seen by vessels as they are transiting. The ACP has retrofitted some of these double lighthouse ranges with latticed steel structures as one or both of the towers. In Figure 26, the Balboa Southbound Rear range tower was originally a lighthouse (left), but has recently been replaced by a latticed steel structure (right). Figure 27 is an example of a range front tower with the lighthouse still existing near the newly erected latticed steel structure.

Figure 26: Balboa Southbound Rear Range Tower (Rowlett, 2014b)

Figure 27: Lighthouse Used for Range (ICONSA, 2015)

A lighthouse can be constructed from many materials depending on its geographic location or environment. The inland lighthouses at the Panama Canal used for navigation are mostly white-painted concrete towers. Black-painted concrete lighthouses in the Canal are inactive, like the Pacific Entrance Rear range tower near the Pacific Entrance of the Canal or the Gamboa Southbound Front range tower in Gamboa. The ACP will also paint portions of lighthouses black if they are used for single directional traffic. Figure 28 is an example of the Miraflores Northbound Front range tower that is painted white on the south-facing side for navigation, and black on the other half.

Figure 28: Miraflores Northbound Front Range Tower (Rowlett, 2014b)

The lighthouses in the Panama Canal have been constructed with cast-in-place reinforced concrete as their main structural material. Like many other lighthouses erected along the coast and near fault lines, reinforced concrete was chosen because of its ability to withstand high winds, harsh climate, and seismic activity (Browning, 2014; NPS, 1997). Not only was it stronger than the previous iron and steel lighthouses, but also cheaper and required less maintenance.

Concrete is the fourth most common material of all existing lighthouses for construction after masonry, iron, and wood (NPS, 1997). Concrete deterioration is caused by environmental factors, materials and poor workmanship, and improper maintenance. Environmental factors include harsh marine environments, weathering, and erosion. Early concrete buildings were constructed with aggregates that produced weak and porous concrete which cause alkali-aggregate reactions within the concrete and resulted in cracking and staining. Early concrete was rodded for consolidation when poured, leaving voids in areas around reinforcing bars and other structural locations. Improper maintenance like prolonged exposure to water causes leaks in the structure. Some major signs of concrete deterioration include cracking, spalling, erosion, and corrosion (NPS, 1997).

Port authorities stopped constructing reinforced concrete lighthouses by the mid-20th century because of high maintenance costs and the introduction of electronic ATON. Concrete lighthouses became unnecessary and outdated. Throughout the lifespan of reinforced concrete lighthouses, steel lighthouses were being erected globally and still are to this day. It was not until 1982, when the first fiberglass tower in the United States was introduced as a lighthouse off the coast of the Boston Harbor. Today, the two materials used for lighthouse construction are steel and fiberglass (NPS, 1997).

After researching the construction materials of lighthouses, it was determined that the concrete lighthouses are not a viable option for alternative range towers. The existing concrete lighthouses cannot be moved without damaging their structural integrity. Since steel lighthouses are still being constructed and the existing towers are steel structures, fiberglass towers were investigated as an alternative structure for the range towers.

2.6.2 Glass Reinforced Plastic Towers

Glass reinforced plastic (GRP) towers are fiberglass beacon towers used for navigation (Figure 29). Fiberglass was invented in 1938 by Russel Games, and is referred to as glass reinforced plastic in industry (Ryan, 2010). The concept was developed to reduce the maintenance costs of metal structures. GRP towers are designed to accommodate a variety of light fixtures including sector lights, range lights, solar modules, and lightning protectors. They have a base and tower, but the middle consists of cylindrical modules that are each 3.3 ft (1 m) in height, that can be layered to reach the total required height. GRP towers are designed and manufactured by many companies willing to suit customer's requirements.

Figure 29: GRP Tower (Tideland Signal Corporation, 2010)

2.6.2.1 Specifications

The biggest advantage of GRP towers is their easy constructability and light weight making them ideal structures to be erected in secluded locations. Modularly designed, they are made ready for on-site construction and have different sections for ease of installation on a concrete foundation (Pharos Marine Automatic Power, 2003; ANST, 2012). GRP towers can be erected in remote areas with little equipment because the 3.3 ft (1 m) modules are lightweight and easy to transport. They are often supplied with a lifting davit to enable construction on-site without use of a crane, scaffolding, or ladders (ANST, 2012).

Glass reinforced plastic is a compound material, well known for its use in plane construction and in piping of jet planes to reduce weight. The lightweight material is durable, weather resistant and anticorrosive, making it an ideal material for marine conditions. Little to no metal is used in GRP towers, so saltwater corrosion is not an issue. However, some GRP towers have bolts and nuts for connections made from galvanized steel (Floatex, 2015). Tideland Signal Corporation, a GRP tower manufacturing company, states "glass reinforced plastic is manufactured from high quality non-crimped glass fiber." The pigments are often added to the plastic so painting is unnecessary (Tideland Signal Corporation, 2010). GRP towers are colored per the customer's request, and therefore many GRP towers are unique to their location.

GRP towers are manufactured for heights ranging from 16.4 to 65.6 ft (5 to 20 m) with a minimum wall thickness of about 0.3 in (8 mm) (ANST, 2012; Tideland Signal Corporation, 2010). Towers can withstand gale wind forces of up to 125 mph (56 m/s) and some are wave resistant for up to 6.56 ft (2 m) (Floatex, 2015). The added modules, as seen in Figure 29 with the red and white stripes in the middle, are typically 3.3 ft (1 m) in height. These structures and their safety equipment are enclosed with a hatched door. GRP towers vary depending on the manufacturer and can be specially manufactured based on unique design factors like location, height, and weather.

2.6.2.2 GRP Towers around the Globe

Glass reinforced plastic beacon towers are used globally to mark waterways. Deer Island Light, for example, is a GRP tower that marks the entrance of the Boston Harbor. After replacing the original lighthouse in 1982, this GRP tower was the first GRP lighthouse constructed in the United States. It was chosen because it occupies minimal space, withstands high winds, and was inexpensive (Browning, 2014). Deer Island does not have a daymark on the brown structure (Figure 30, left). The Cape Cod Canal Breakwater Light located along the Cape Cod Canal in Massachusetts is also a GRP tower, but it marks the entrance of the Cape Cod Canal (Figure 30, right). It has a red triangular daymark.

Figure 30: Deer Island Light and Cape Cod Canal Breakwater Light (Rowlett, 2015d)

GRP towers are used in urban areas like the city of Istanbul, Turkey, to light the Bosphorus Strait. The Bosphorus Strait connects the Black Sea to the Sea of Marmara next to the Mediterranean Sea. The GRP towers are used in ranges, some of which are colored with daymarks to indicate lateral passage. GRP towers light the Bosphorus strait with associated daymarks and colors that match IALA requirements (Rowlett, 2015c).

GRP towers are also used to light the Red Sea near the Gulf of Suez in Egypt. Two GRP lighthouses mark the entrance to the Gulf of Suez at the Strait of Gubal, and Siyul Island. The lighthouse at the Strait of Gubal, located on an island east of Gamasa, is a cylindrical white tower that guides ships through a narrow passage on the south end of the Gulf of Suez. The lighthouse on Siyul Island has an hourglass shape and is colored with black and white horizontal bands (Rowlett, 2015b).

2.6.2.3 GRP Towers for the Panama Canal

After researching GRP towers and their prevalence around the globe, GRP towers were selected as the alternative tower for the Panama Canal. GRP towers are highly durable, easy to maintain, and simple to construct. They can be used in ranges and can support the weight of lighting and solar energy equipment. GRP towers are simple to transport and construct which is ideal for the remote areas in the Canal. The towers are designed for the client’s needs to meet height requirements and to have specific colors for daymarks.

2.7 Evaluating GRP Tower Feasibility

To evaluate the feasibility of GRP towers' presence in the Panama Canal, they were compared to several existing towers on varying topographies in the Canal. The purpose of comparing them was to ensure that the GRP tower has the right structural capabilities to support the range lighting and signal equipment for the design loads. The durability of the material was important to determine if the structure could withstand the harsh weather of the Canal's climate. The construction time and costs were compared for efficiency. If the tower structures were similar, affordable, and efficient, then the alternative structure was a feasible alternative to the existing range structures in the Canal.

2.7.1 Existing Range Selection

Two pairs of ranges were chosen based on the varying topographies and locations of ranges throughout the Canal as mentioned in the previous sections. Information was gathered from navigational maps and construction documents to determine which ranges were unique in their surrounding topography and location of placement. The two pairs of ranges are located in Lake Gatun and are shown in Figure 31. The labeled numbers correspond to the selected ranges.

(1) Gatun Northbound range
(2) Buena Vista Southbound range

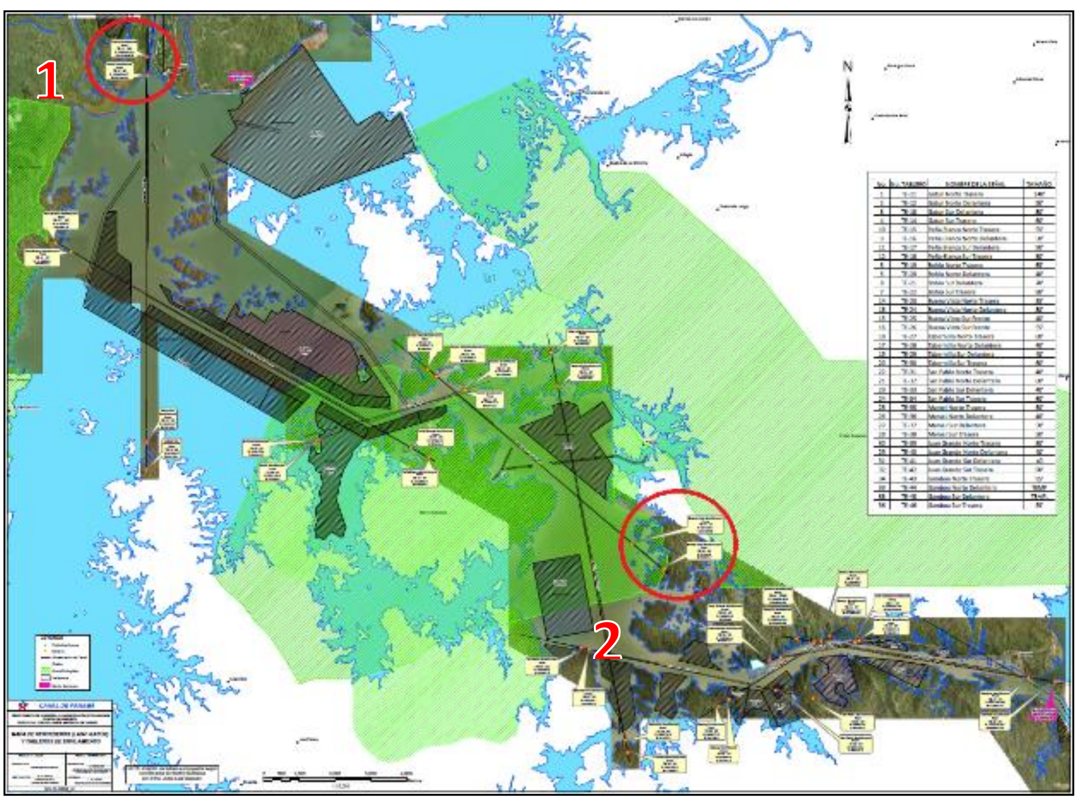

Figure 31: Map of Chosen Ranges in Lake Gatun (Canal de Panamá, 2014)

The first set of range towers chosen was the Gatun Northbound range, located on and near the existing Gatun Locks. Seen in Figure 32 below, the front tower is located between the lanes of traffic at the Gatun Locks as ships either enter the locks (going Northbound) or Lake Gatun (going Southbound). The rear tower is located beside the locks. Both the front and rear towers are some of the tallest in Lake Gatun at 90 and 140 ft (27.4 and 42.7 m) because they must be visible to vessels traveling Northbound when other vessels are passing through the locks ahead of them. The towers must be tall enough so that these vessels will not obstruct the range of the signal. These towers are unique because they are the only towers located on and near any locks in the Canal. With considerable structural and design elements, the Gatun Northbound range was selected for its complexity.

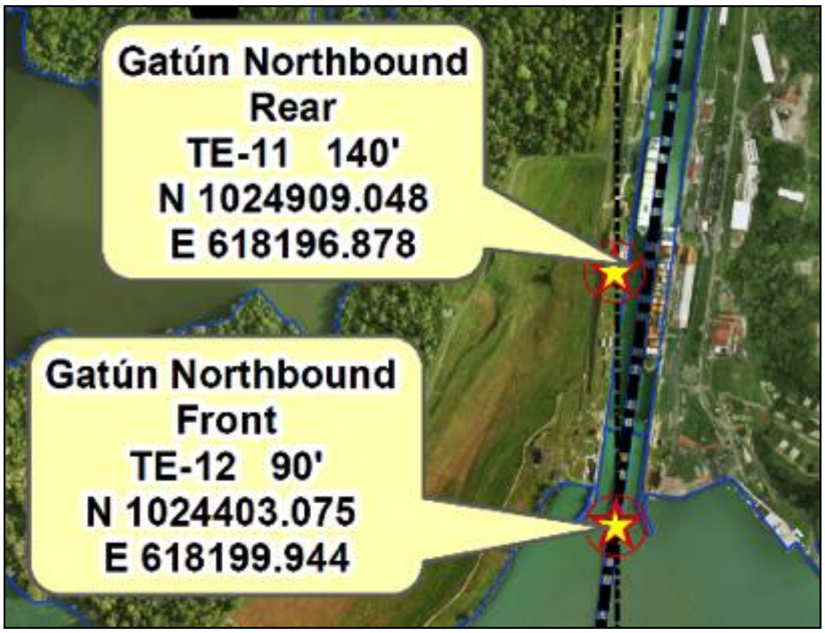

Figure 32: Gatun Northbound range (Canal de Panamá, 2014)

The second set of range towers chosen was the Buena Vista Southbound range, located in Lake Gatun. Seen in Figure 33 below, the front tower is located in the water while the rear tower is located on land. Unlike the Gatun Northbound range, the Buena Vista Southbound range has towers at 40 and 55 ft (12.2 and 16.8 m). The front tower is located in the water so the signal can reach the acceptable nominal and geographic range for the mariner to know he is on the centerline. This range was chosen because constructing a range tower in the water has challenging structural constraints.

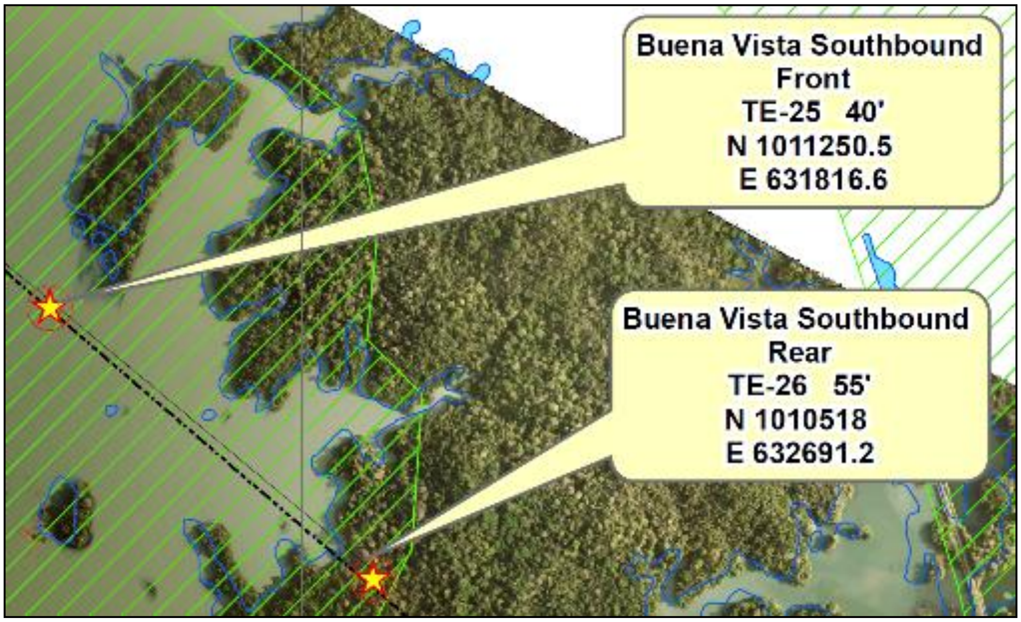

Figure 33: Buena Vista Southbound range (Canal de Panamá, 2014)

2.7.2 GRP vs. Existing Towers

This project collected and compiled the structural analyses, schedules, and cost estimates of the Gatun Northbound and Buena Vista Southbound range towers in the Panama Canal. Information was gathered from the approved contractor's construction documents and plans and two GRP manufacturing companies: Tideland Signal Corporation and Advance Navigation and Solar Technologies (ANST). The following sections compare the tower conditions and locations of the existing latticed steel towers to the proposed GRP towers.

2.7.2.1 Gatun Northbound Rear and Front Towers

The goal of this section was to determine if the range towers can be manufactured to meet the height requirements of the tallest range tower. The Gatun Northbound Rear tower is the tallest range tower within the Panama Canal. It is the successor of the Gatun Northbound Rear tower lighthouse, which still exists nearly 50 ft (15.2 m) from the new steel structure.

GRP manufacturing companies have range towers that vary from 16.4 to 65.6 ft (5 to 20 m), however, they also state that they can meet client's requests for towers (ANST, 2012; Tideland Signal Corporation, 2010). After researching other fiberglass towers used around the world, there is no published information regarding fiberglass towers exceeding 65.6 ft (20 m). It can be concluded that manufacturers do not construct towers taller than this limit and therefore, cannot replace towers exceeding this limit. The Gatun Northbound Rear tower is 140 ft (42.7 m) and greatly exceeds the maximum requirement from the manufacturers.

The Gatun Northbound Front tower was initially studied to determine if the towers cause any visual constraints to vessels passing through the Canal. This information was deemed unnecessary because the tower height is 90 ft (27.4 m), which exceeds the maximum height of range towers established by the manufacturers. Therefore, neither the front nor the rear towers on the Gatun Northbound Range can be replaced due to their heights. Unless companies begin designing and manufacturing taller towers, replacing the Gatun Northbound range towers with GRP towers is not feasible.

2.7.2.2 Buena Vista Southbound Rear Tower

The goal of this section was to compare the schedules of construction between the existing range towers to the proposed GRP towers. The Buena Vista Southbound Rear tower schedule states that tower installation for the Buena Vista Southbound rear range tower took 25 days. Installation included the dayboards, lights, and lightning rod. The installation of the tower structure alone lasted six days. While no information was available by the GRP manufacturers on the exact number of days that tower construction takes, it is presumed that construction takes less time since the towers are modular, fit together easily, and require very few parts. In addition, the GRP towers do not need dayboards mounted to them because the daymarks are painted on the structures, so time for installation will decrease.

2.7.2.3 Buena Vista Southbound Front Tower

The goal of this section was to determine whether the structural specifications of the GRP towers matched the existing steel structures. The Buena Vista Southbound Front tower was compared to the GRP tower specifications from Tideland Signal Corporation (2010) and ANST (2012) product descriptions. This sole tower is compared to the GRP towers because the height dimensions match those provided by the two GRP manufacturing companies' product descriptions.

The base areas of the two types of towers vary drastically for the 40 ft (12.2 m) tower. The quadrangular base area of the latticed steel tower is 84.5 ft^2 (7.85 m^2) while the circular base area of the GRP tower is 33.8 ft^2 (3.14 m^2). The latticed steel tower's area is almost three times the area of the GRP tower. This shows that the surface area of the foundation for the GRP tower is much smaller than the steel tower. If a replacement tower for the latticed steel structure is needed in a different location due to changing centerlines, the construction costs for one GRP tower foundation would be much less than constructing another latticed steel tower foundation.

The foundations for latticed steel structures vary from the GRP tower requirements. The latticed steel structures require reinforced cement concrete (R.C.C.) foundations with footings and micro piles to transfer the load of the structure to the soil for the rectangular structure. The GRP towers from ANST require a R.C.C. foundation with long, high tensile steel anchor bolts embedded in the concrete with equidistant spacing for the cylindrical structure (ANST, 2012).

Design loads for both structures depend on the maximum wind load. The latticed steel tower has a design load of 88 mph (39.3 m/s) while the GRP tower is designed to withstand 125 mph (55.9 m/s). It is important to note, however, that latticed steel towers are open and exposed to the environment and have less horizontal forces acting on them than the GRP towers that are solid and enclosed. The GRP towers are designed to withstand wind loads greater than the existing latticed steel towers at the Panama Canal.

2.7.3 Summary

Information gathered from background research and product details are summarized below in Table 3, comparing the latticed steel towers with the proposed GRP tower. The information suggests that while different in their structures, the towers have similar capabilities in their performance. The results are divided by specifications, durability, and other categories. As seen in Table 3 below, there are few differences between the two towers and their capabilities. It is important to note, however, that this table compares the two towers based on product descriptions and basic information of the existing Panama Canal ranges, and therefore should only be used as a brief comparison. Further research of companies and costs with exact specifications would provide a more informative comparison between the two towers. This initial research suggests that GRP towers should be further investigated for use as range towers in the Panama Canal.

Table 3: Summary of Tower Comparison

Summary of Tower Comparison		
	Latticed Steel Tower	**GRP Tower**
Specifications		
Material	Galvanized and Stainless Steel	Glass Reinforced Plastic
Tower Type	Latticed, skeletal tower	Enclosed tower
Elements of structure	Steel members	Modular
Height	All	< 65.6 ft.
Tower Base Area	84.5 $ft.^2$	33.8 $ft.^2$
Foundation Type	R.C.C.	R.C.C.
Dayboard	2 aluminum boards affixed to structure	Colored during manufacturing
Durability		
Lifespan	>10 years	>10 years
Protection	Metal fencing for land-based towers, none for water-based towers	Additional fencing to protect from vandalism and collision
Safety	Inspected	Inspected
Maintenance	Low	Low
Other		
Social Implications	N/A	N/A
Sustainability	Lighting elements	Lighting elements
Constructability	Moderate	Simple

2.8 Conclusion and Recommendations

ATON at the Panama Canal are constantly being updated and improved for the most safe and efficient passage through Canal waters. To ensure this, it is important that the ACP considers historical and progressive ATON methods and products. While many electronic ATON are increasingly being implemented into navigation systems, they are not the only aid that is developing. Visual ATON are evolving, whether it is by incorporating environmentally friendly moorings to buoys and buoyant beacons (Bolzenius, 2013), or implementing GRP towers for inland coastal navigation. The ACP must be cognizant of these trends, and consider incorporating GRP structures to their ATON system.

While the proposed GRP structure is a more feasible tower option due to its constructability and maintenance, it should not be immediately implemented. The ACP is about to finish replacing and updating all range towers in Lake Gatun with latticed steel structures because of the changing centerlines due to the expansion project. Upon the completion of the expansion project, these new range structures will accommodate the Post-Panamax vessels transiting the Canal by marking the new centerlines. The following conclusions and recommendations were drawn based on the information gathered from research and evaluations of adding GRP towers as structures for the Panama Canal ATON ranges. The findings and recommendations are divided by economics, safety, sustainability, social, and manufacturability.

Economics

The existing latticed steel towers have a long lifespan, so the first finding is that immediate replacement of these new towers is financially unnecessary. However, purchasing and erecting GRP towers will reduce labor, installation, and maintenance fees. Since GRP towers are modular, they are easy to construct. With fewer elements involved, less equipment is needed for construction, including less labor. Tower daymarks are integrated into the plastic, so they are manufactured with the rest of the tower. Therefore, panel installation is not necessary on the new GRP towers. In the event of replacing an existing tower, the lighting elements can be transferred to the new GRP tower. The new GRP tower has the structural integrity to support the existing lights. It is assumed that the total cost of GRP towers is less than the latticed steel towers. However, this project recommends that the ACP should request cost estimates from GRP manufacturing companies to complete a full cost analysis comparison with the existing latticed steel structures.

Safety

With safety as a priority of the ACP, it is important that the towers are safe structures for workers to inspect and maintain. The existing latticed steel structures have safety features installed on them, like resting platforms and climbing equipment. The tower must be approved by an ACP inspector for safety and quality assurance before it is in full operation. Therefore, these open latticed steel structures are safe.

To protect ACP property, range towers should be protected. The land-based existing steel structures have metal fencing around their perimeters which protects the tower and equipment from looters while the water-based range towers are unprotected. Loss of property can lead to extra costs taken for precautionary measures and replacing the equipment. In the event of replacing one of these towers from damage or stolen equipment, it is recommended to construct a GRP tower for its protection capabilities. Due to their hourglass structure and hatch door, the structures would be difficult to break in to or scale the walls. GRP towers are enclosed structures and therefore are easier to ascend in harsh weather, protecting workers who need to inspect and maintain the tower. Since the GRP tower is enclosed, any additional protection like fences around its perimeter would only be necessary for protection against vandalism and vehicular collisions.

Sustainability

This project found that sustainability is incorporated in the design of range towers with sustainable light fixtures equipped with LED lights and solar panels. When the structure needs to be replaced, the lighting elements can be transferred to the next structure. The current structures are equipped with these elements, as will any alternative tower structure. This means that sustainability would remain equivalent between the structures. This project recognizes the sustainability of the lighting elements, and does not suggest any improvements to the system.

Social

This project found that some range towers are located in or near communities and on the locks where vessels transit the Canal. The existing steel structures are metal, open, and exposed to the environment, so they are not distracting to communities or mariners transiting the Canal. However, GRP towers around the world do not exceed 65.6 ft (20 m) so they are not tall enough to replace any of the tall range towers near communities or the locks at the Panama Canal. While some towers can be specially ordered, it is not recommended that the existing latticed steel structures be replaced with specially ordered GRP towers without investigating community opinions and visual implications of mariners transiting the Canal.

Manufacturability

GRP towers are simpler to manufacture and construct than the existing latticed steel towers. The GRP towers have cylindrical modules for manufacturing while the existing latticed steel towers require many galvanized and stainless steel members to be manufactured. In addition, the GRP towers require little equipment and are easily constructed while the latticed steel structures take longer to build. It is recommended to compare duration of the manufacturing and construction of GRP towers with that of the latticed steel towers for a concise evaluation of efficiency between the two structures.

Chapter 3: Assurance of Drinking Water Quality on Tugboats

3.1 Design Statement

This project fulfills the design capstone and Major Qualifying Project requirements at Worcester Polytechnic Institute. The goal of this project was to evaluate the quality of drinking water stored in the potable water tanks on tugboats in the Panama Canal. Water was collected at all tugboat landings along the Canal and also directly from the potable water storage tanks on the tugboats. The samples were tested for residual chlorine levels, turbidity, total coliforms, and *E. coli*. Results from water quality testing aided in the design of a drinking water management plan to improve the quality of water stored in potable water tanks on tugboats of the Panama Canal. This project met capstone design requirements by considering the following design constraints during the design process: economic, sustainability, health, and safety.

Economic constraints were crucial to consider while designing a method to maintain residual chlorine levels in the water stored on the tugboats. Currently, there are 46 tugboats that make up the tugboat fleet at the Panama Canal. A method to regulate water quality must be economically feasible in order to be implemented on all tugboats.

Sustainability of the proposed drinking water management plan was also an important component during the design process. Water quality will always need to be managed; therefore, it was necessary to consider the long-term applicability of the drinking water management plan.

Health was another aspect that played a major role during the design process. Turbidity was monitored to improve the disinfection process. The purpose of regulating residual chlorine levels was to ensure successful water treatment. Total coliforms and *E. coli* may be indicative of pathogenic contamination, which can cause the most adverse health effects. The proposed management plan considers these parameters to improve water quality in the potable water tanks on tugboats.

This project was also concerned with the safety of ACP employees. Tugboats of the Panama Canal guide ships through narrow channels to ensure safe transit. Without guaranteeing the health of tugboat workers, the safety of transporting ships through the Canal could be hindered.

3.2 Introduction

On September 26, 1913, the tugboat Gatún was the first ship to make a trial run through the Gatun Locks (Figure 34) (Smith, 2014). Tugboats assist vessels in their travel between the Atlantic and Pacific Oceans by maneuvering and guiding the large ships into the locks and through narrow channels of the Canal. Due to the increased size of vessels transiting through the Panama Canal, over time, the tugboats required more power and eventually converted from steam to diesel engines. Unlike conventional propulsion motors that are mounted horizontally and thrust in only the forward and backward directions, tugboats are equipped with Voith Schneider propellers that allow tugboats to push and pull in any direction (A&E Television Networks, 2014). This propulsion system gave tugboats more capabilities and increased their role in the traffic control of vessels through the Panama Canal.

Figure 34: Gatún Tugboat making the first pass through the Gatun Locks (Smith, 2014)

The current Panama Canal lock system utilizes locomotives that run parallel to the locks to steer ships into the lock chambers (Llacer, 2005). The expansion of the Canal will accommodate the passage of larger vessels; however, it would require 12 to 16 locomotives to guide each Post-Panamax ship through the chambers. Therefore, with the Canal expansion, tugboats will be utilized to align ships into the chambers with one tug each at the bow and stern (Reagan, 2009).

Currently, the tugboat fleet of the Panama Canal is comprised of 46 tugs. The tugboats have been constructed from six different shipyards between 1970 and 2014. In 2010, the ACP purchased 13 new tugboats and decommissioned any ship serving over 35 years. The new fleet of tugboats has an award winning design, comprised of stronger engines, better clutches, an advanced propulsion system, and an output capacity of 5,840 hp (4,360 kW) and bollard pull of more than 71.7 tons (65 tonnes) (ACP, 2010). As previously mentioned, the expansion of the Panama Canal adds another responsibility for tugboats and the fleet of 46 tugs is readily equipped.

Although the Panama Canal tugboat fleet has the mechanical capability to accommodate the Panama Canal expansion, in early 2015, tugboat engineers and crews expressed concerns regarding the water quality of the potable water supply aboard the tugs. On February 25, 2015, the Water Quality Division of the Energy, Environment, and Water Unit (EAA-CA)[11] of the ACP established a new plan for the assessment of potable water quality on tugboats of the Panama Canal. The new plan improves water quality on the tugboats and presents feasible alternative solutions. This project addresses the following three objectives to improve the quality of the water stored in the potable water storage tanks aboard the tugboats:

- Establish the quality of water at intakes where tugs receive fresh water along the Panama Canal;
- Launch a diagnosis of potable water in each tug; and,
- Prepare a safe drinking water management plan to improve the current water quality.

[11] EAA-CA for Energía, Ambiente y Agua- Calidad de Agua, in Spanish

3.3 Framework for Safe Drinking Water

On April 7, 1948, the World Health Organization (WHO) was established as a "public health arm" for the United Nations. The WHO is responsible for "directing and coordinating authority on international health within the United Nations system" (WHO, 2015). The mission of the United Nations, as stated in in the Preamble of the Charter, is "to promote social progress and better standards of life in larger freedom" (United Nations, 2015b). On November 13, 1995, Panama became a Member State of the United Nations, thereby adopting the regulations of the WHO (United Nations, 2015a).

In 1983, the WHO published the first edition of the *Guidelines for Drinking-Water Quality*. These international standards are primarily for the "protection of public health" (WHO, 2008). Since the original first volume of the *Guidelines for Drinking-Water Quality,* there have been multiple revisions and three different volumes. These standards provide information regarding assessment, surveillance, and monitoring of drinking water quality. Within these international standards, the WHO has established a framework for safe drinking water (WHO, 2008).

The framework for safe drinking water is composed of five main parts; health targets, system assessment, monitoring, management, and surveillance (Figure 35). This project adapted the WHO framework for safe drinking water to assess the water quality in the potable water storage tanks on the tugboats of the Panama Canal and recommends viable options for improvement. The following sections describe the components of the framework in relation to this project.

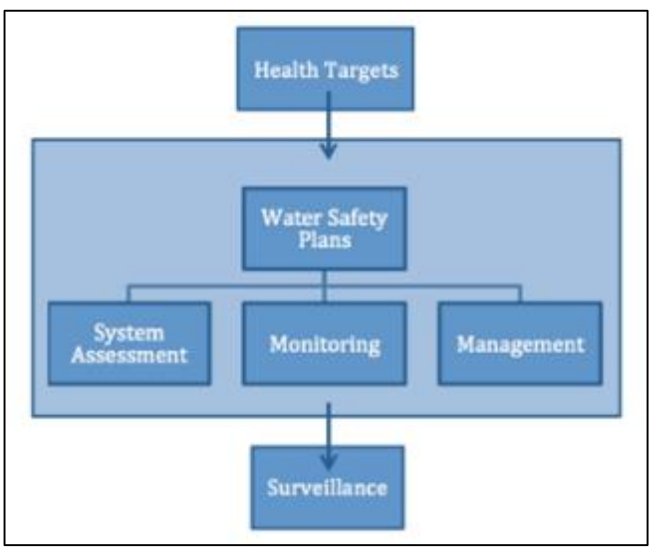

Figure 35: Framework for Safe Drinking Water Quality (WHO, 2008)

3.3.1 Health Targets

Health based targets are the established water characteristics and guideline values that represent the desired water quality. Usually, these qualities are set and measured by a well-trained authoritative figure. Health targets for a water system consider public health and emphasize the importance of ensuring access of potable water to consumers (WHO, 2008). This project, as determined by the EAA-CA, considers microbial and disinfection aspects for health targets.

3.3.1.1 Microbial Contamination

Microbial contamination pertains to bacteriological, viral, protozoan, or other biological impurities that pollute water (WHO, 2008). According to the WHO, "[t]he potential health consequences of microbial contamination are such that its control must always be of paramount importance and must never be compromised" (2008). Water exposed to human and other animal feces pose the highest risk for microbial contamination if consumed. Feces are likely to be a source of pathogenic bacteria, viruses, and protozoa. Microbial contamination attributes to many health risks associated with drinking water including outbreaks of intestinal and other infectious diseases (WHO, 2008).

Testing drinking water for microbial contamination involves analysis and identification of total coliforms. Total coliforms are a thermotolerant group, meaning the bacteria is capable of fermenting lactose at temperatures between 95-98.6° F (35-37°C). Total coliforms are not fecal indicators; however, their presence in water suggests failure in water treatment and lack of integrity and cleanliness of the water distribution system. According to the WHO,

> [t]otal coliforms should be absent immediately after disinfection, and the presence of these organisms indicates inadequate treatment. The presence of total coliforms in distribution systems and stored water supplies can reveal regrowth and possible biofilm formation or contamination through ingress of foreign material, including soil or plants (2008).

Total coliforms are measured in 100 mL drinking water samples through membrane filtration followed by incubation on a selected media that enhances bacterial growth for 24 hours at 95-98.6° F (35–37 °C) (WHO, 2008).

Water contaminated with total coliforms should be analyzed for fecal indicator bacteria such as *Escherichia coli* (*E. coli*). *E. coli* is a subset genus of total coliforms that ferments lactose at 111-113° F (44–45°C) (WHO, 2008). *E. coli* is highly present in human and animal feces and rarely found in the absence of feces. The WHO states that *E. coli* is the optimal fecal indicator bacterium for drinking water and that "[w]ater intended for human consumption should contain no indicator organisms" (2008). *E.coli* is also measured in 100 mL drinking water samples through membrane filtration; however, incubation is increased to 111-113° F (44–45 °C) for 24 hours (WHO, 2008).

Water containing total coliforms and *E.coli* represent potential microbial contamination. Both total coliforms and *E. coli* are identified in the laboratory by the presence of colonies, or a cluster of bacteria. For the health and safety of the tugboat workers of the Panama Canal, this project established a health target for total coliforms and *E. coli* that is less than one colony per 100 mL sample of drinking water obtained from the potable water tanks aboard the tugboats and at the water intakes at tugboat landings.

3.3.1.2 Disinfection

The WHO defines disinfection as "an effective barrier to many pathogens (especially bacteria) during drinking water treatment" (2008). Drinking water is disinfected to destroy potentially present microbial pathogens. Chemical agents, specifically chlorine, are used as reactive agents for disinfection (WHO, 2008).

Chlorine disinfectants are added to drinking water during the treatment process to kill microorganisms that can cause typhoid, cholera, hepatitis A, and other diarrheal diseases (Reed, 2011). Upon initial application to water during treatment, chlorine reacts with organic material and other compounds present in the water. Once the chlorine demand of the water has been reached, the remaining chlorine concentration is considered the total chlorine. The total chlorine consists of combined chlorine and free chlorine. Combined chlorine is the chlorine that joined with nitrogen in the water and is unavailable for disinfection purposes. Free chlorine is the concentration of chlorine that is still available for disinfection and is also known as residual chlorine (WHO, 2008). Figure 36 outlines the chlorine batching, or disinfection, process.

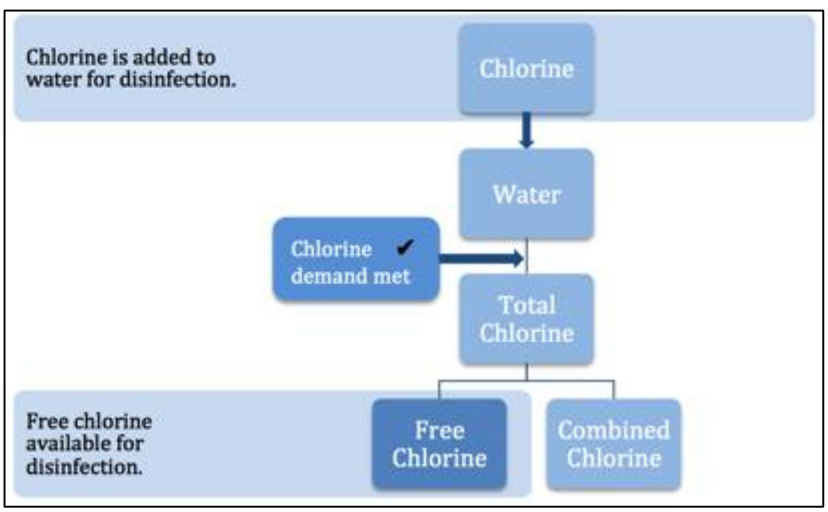

Figure 36: Process of Chlorine Batching

Residual chlorine is a safeguard against low-level microbial contamination following treatment (WHO, 2008; Wiant, 2013). The presence of residual chlorine indicates that the water was initially treated with enough chlorine to deactivate bacteria and protect the water against potential recontamination during storage and distribution. Residual chlorine in drinking water is a measure of potable water and is tested using a color comparator or spectrophotometer (WHO, 2008). To achieve effective disinfection, the WHO suggests a residual chlorine measure of >0.50 mg/L. This value should be maintained throughout the system and the chlorine residual should not degrade to <0.20 mg/L at the point of delivery. The guideline value of residual chlorine is 5 mg/L; however, this value is conservative, as no adverse health effects are observed at this level. Conversely, consumers rely predominately on their senses when assessing water quality and are likely to reject the taste of drinking water with chlorine residual levels at concentrations between 0.60 and 1.00 mg/L.

Chlorine disinfection is crucial during and after the treatment process of drinking water; batching of chlorine during water treatment eliminates harmful microbial bacteria while the residual chlorine after disinfection is a safeguard against regrowth and recontamination. Disinfectants are important to monitor and control in order to warrant the protection of drinking water. This project has a health target value for residual chlorine between 0.80 and 1.50 mg/L to ensure safe drinking water quality in the potable water storage tanks on the tugboats of the Panama Canal.

When disinfecting water it is important to evaluate the turbidity. Turbidity measures the clarity of a liquid and is an indication that there is presence of suspended matter and impurities. Turbidity does not indicate water contamination; however, turbid water can provide shelter and protect bacteria from disinfectants (WHO, 2008). Controlling the turbidity of drinking water is a protective measure against pathogens, and increases the efficiency of disinfection. The WHO states, "[n]o health-based guideline value for turbidity has been proposed; ideally, however, median turbidity should be below 0.10 NTU for effective disinfection, and changes in turbidity are an important process control parameter" (2008). Turbidity is measured using a turbidity tube, which reads the clarity in Nephelometric Turbidity Units (NTUs) (WHO, 2008). To guarantee the efficiency of disinfection of the drinking water aboard the Panama Canal tugboats, a health target for turbidity has been set at <1.00 NTU.

3.3.2 Water Safety Plans

A water safety plan outlines the fundamental actions necessary to ensure safe drinking water and is unique to the specific drinking water system. There are three principal objectives of water safety plans: minimize contamination of water sources, reduce or remove contamination, and prevent contamination through the drinking system (WHO, 2008). The WHO states that, at a minimum, the three essential actions of a water safety plan to guarantee safe drinking water are: a system assessment, effective operational monitoring, and management (2008).

The first action of a water safety plan is an assessment of the existing drinking water system. A system assessment determines whether the drinking water supply system from the source to the point of consumption can deliver water of a quality that meets the established health targets. First, a multidisciplinary team of qualified individuals is assembled to execute the system assessment. Ideally, the project team should have an expert associated with each stage of the water supply for a complete understanding of the drinking water system. After a team is organized, the system is documented and described with the use of a flow diagram. With an understanding of the current drinking water system, water needs to be collected and tested against the regulated health targets at multiple points throughout the system. Based on the health targets and the results from water testing, potential hazards, hazardous events, and risks are recognized. Hazards, defined by the WHO, are, "biological, chemical, physical or radiological agent[s] that have the potential to cause harm" (2008). Hazardous events are incidents that can cause hazards to arise and risks are the probability of recognized hazards to inflict harm to the population consuming this source water. Risk evaluation includes the degree of harm and the consequences. The final system assessment also analyzes historical water quality data to completely understand the performance of the existing drinking water system. Systems should be evaluated routinely to verify the capability of the drinking water system to consistently meet health target values for water quality (WHO, 2008).

After a thorough system assessment, the project must identify control measures that, when effectively monitored, regulate and minimize deviation from the established health targets. The WHO defines control measures as "steps in drinking-water supply that directly affect drinking-water quality and that collectively ensure that drinking-water consistently meets health-based targets. They are activities and processes applied to prevent hazard occurrence" (2008). Ideally, each identified potential hazard from the system assessment should have a control measure associated with it for mitigation purposes. The control measure should be proportional to the associated risk of the potential hazard. Operational monitoring of control measures assesses the performance of the measures to mollify hazards within the drinking water system (WHO, 2008).

With the outcomes of the drinking water system assessment, identification of potential hazards and establishment of control measures, the subsequent action is to develop management procedures that will result in the capability of the drinking water system to effectively and routinely meet health based targets. The WHO states

> [e]ffective management implies definition of actions to be taken in response to variations that occur during normal operational conditions; of actions to be taken in specific "incident" situations where a loss of control of the system may occur; and of procedures to be followed in unforeseen and emergency situations. Management procedures should be documented alongside system assessment, monitoring plans, supporting program[s] and communication required to ensure safe operation of the system (2008).

It is critical that management procedures be developed in response to predictable and unpredictable incidents. Management plans should be periodically reviewed and practiced to increase readiness and efficiency of procedures in the case of emergency incidents. The WHO recommends that management procedures include a fully documented monitoring plan incorporating the following information (2008):

1. Parameters to be monitored;
2. Sampling or assessment location and frequency;
3. Sampling or assessment methods and equipment;
4. Schedules for sampling or assessment;
5. Methods for quality assurance and validation of results;
6. Requirements for checking and interpreting results;
7. Responsibilities and necessary qualifications of staff;
8. Requirements for documentation and management of records, including how monitoring results will be recorded and stored; and,
9. Requirements for reporting and communication of results.

Management plans should also accommodate training of staff to ensure proper response to incidents and emergencies (WHO, 2008).

The primary objectives of water safety plans are to minimize contamination of water sources, reduce or remove contamination through treatment processes, and to prevent contamination during storage, distribution, and handling of drinking water (WHO, 2008). The following subsections will propose a water safety plan for this project concluding with the design of a drinking water management plan. This project researched a detailed system assessment, development of control measures for operational monitoring, and the establishment of management procedures for the assessment and improvement of the drinking water quality from the potable water tanks aboard the tugboats of the Panama Canal.

3.3.2.1 System Assessment

Conducting a system assessment was the next step taken after the establishment of the health targets. The system assessment involved organizing a project team, documenting the water system, and determining water testing locations and methods. After testing the water using these methods, the subsequent action of the system assessment was analyzing the water quality results, inspecting the potable water storage tanks on tugboats, and lastly, identifying potential hazards in the drinking water system. The following sections outline and present the findings from the drinking water system assessment conducted through this project.

Establishing a Project Team

On February 25, 2015, the EAA-CA established a new plan to assess the potable water on tugboats of the Panama Canal. The EAA-CA project team consists of individuals from four different divisions of the ACP. Members of the team include the Executive Manager of the Water Division, Manager of Tugboats, Manager of Preventative and Support Maintenance, Supervisor of Environmental Protection, Chief of the Maintenance of Flotation Equipment, Electromechanical Engineer, Supervisor of Civil Engineering and Secretary of the Energy, Water, and Environment department. This team represents a diverse group of individuals that are involved with the supply of drinking water to tugboats at various stages along the water system. Victor Bazan, chemist for the EAA-CA Division, has been assigned to this project to assess the potable water quality on the tugboats. This system assessment presents data retrieved from and alongside Mr. Bazan.

Documenting the Water System

The Panama Canal Authority has three water treatment plants that yield 100 million gallons (379 million liters) of water daily; the Miraflores Water Treatment Plant produces nearly half of this treated water (Vásquez, 2010). Constructed in 1913, the Plant opened for operation in 1915 (Figure 37) (Canal de Panamá, 2015). At the Miraflores Water Treatment Plant, the ACP is responsible for treating raw water from Lake Gatun and producing drinking water. This Plant has a maximum capacity of 50 million gallons (189 million liters) per day, 90% of which is sold to the Institute of Aqueducts and Sewer Systems by the ACP for distribution to the city (Vásquez, 2010). There are two pumping stations at the Miraflores Water Treatment Plant: one for the East and one for the West parts of the city (Figure 49) (Vásquez, 2010). The ACP stores 10% of treated water to service the Canal zone (Vásquez, 2010).

Figure 37: Miraflores Water Treatment Plant (Canal de Panamá, 2015)

Figure 38 outlines the water treatment process at the Miraflores Water Treatment Plant. The treatment process begins with the extraction of raw water at the Gamboa and Paraiso intakes in Lake Gatun (Figure 39 and Figure 40, respectively). Then, the water is transported to the Miraflores Water Treatment Plant through a series of underground pipelines. Upon arrival at the Miraflores Plant, the water undergoes several stages of treatment. First, the raw water travels through an aeration process (Figure 41) (Vásquez, 2010).

Aeration removes odor-causing gases and replenishes oxygen in the water. Next, the aerated water travels through three channels (Figure 42), at which time batching of chlorine, aluminum sulfate, polymers, activated carbon, and fluoride are added to the water. Chlorine is added to kill bacteria and algae, aluminum sulfate aids the flocculation process, polymers remove solids, activated carbon eliminates bad odor, and fluoride improves dental health. After chemical batching, the water continues to travel through the three channels to chambers that rapidly mix the water and the added chemical reagents through a hydraulic system (Figure 43) (Vásquez, 2010). At the end of the hydraulic chambers, the water moves to three series of seven basins (Figure 44). The first basin is for flocculation (Figure 45). Large propellers slowly stir the water and the ionic charge of the water brings the chemicals together to create flocs (Figure 46). The flocs move through the other basins and as they increase in size and weight, the particles sink to the bottom of the basins where workers remove it as sludge (Figure 47). This process is called sedimentation. Sedimentation separates suspended solids and reduces turbidity. When the water reaches the end of the seven basins it merges and travels into one of 20 water filtration basins (Figure 48). The filtration process moves the water through media consisting of anthracite coal, sand, and gravel into a recollection chamber (Vásquez, 2010). At this point in the treatment process, the water is now potable. Another batch of chlorine is added to the water as it moves to the pumping stations to disinfect and create a safeguard against further contamination.

Figure 38: Water Treatment Process at the Miraflores Water Treatment Plant (Miraflores Water Treatment Plant, 2015)

Figure 39: Water Intake at Gamboa

Figure 40: Water Intake at Paraiso

Figure 41: Water Aeration Process

Figure 42: Chemical Batching in Channels

Figure 43: Hydraulic Mixing Chamber

Figure 44: Water Treatment Basins


Figure 45: Flocculation Basin


Figure 46: Flocculation Propellers


Figure 47: Sedimentation Sludge at Bottom of Basin

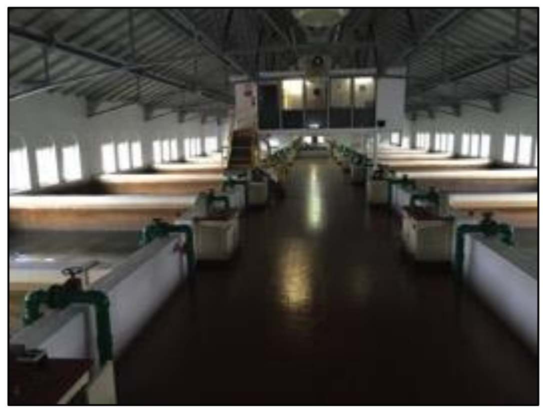
Figure 48: Water Filtration Chambers


Figure 49: Water Pumping Station

One use of the ACP stored water is to supply water to the tugboats at several landings along the Canal for drinking purposes. This project analyzed water quality from two different ACP tugs; Veraguas II and Guía. Houma Fabricators constructed the tugboat Guía in 1987. It has two potable water tanks with a combined capacity of 7,020 gallons (26,600 liters). Due to the age of this vessel, there are no diagrams regarding the potable water system aboard. Cheoy Lee & Hin Lee Ltd. constructed the tugboat Veraguas II in 2007. Veraguas II has two potable water storage tanks with a combined capacity of 3,240 gallons (12,300 liters).

Although there are no diagrams for the potable water system on Guía, it is assumed that the systems between the two tugboats are similar (Figure 50 and Figure 51). Referring to the figure below of the potable water drinking system aboard Veraguas II, drinking water enters the system at two filling connections on the main deck (A and B) and is stored between two potable water storage tanks (C and D). The blue path traces the potable water distribution system aboard the tugboat and the pink boxes mark intakes and retrieval points for drinking water consumption.

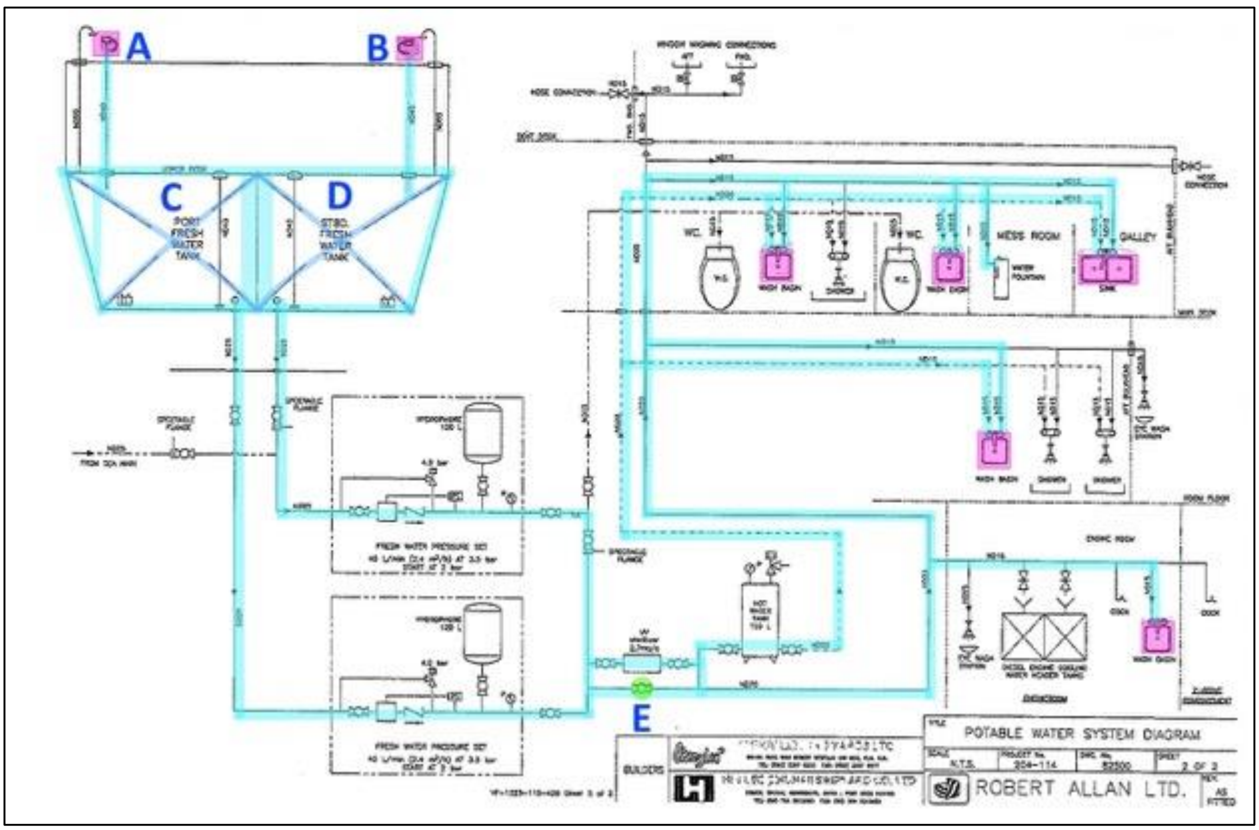

Figure 50: Tugboat Potable Water System Diagram (Zhang, 2013)

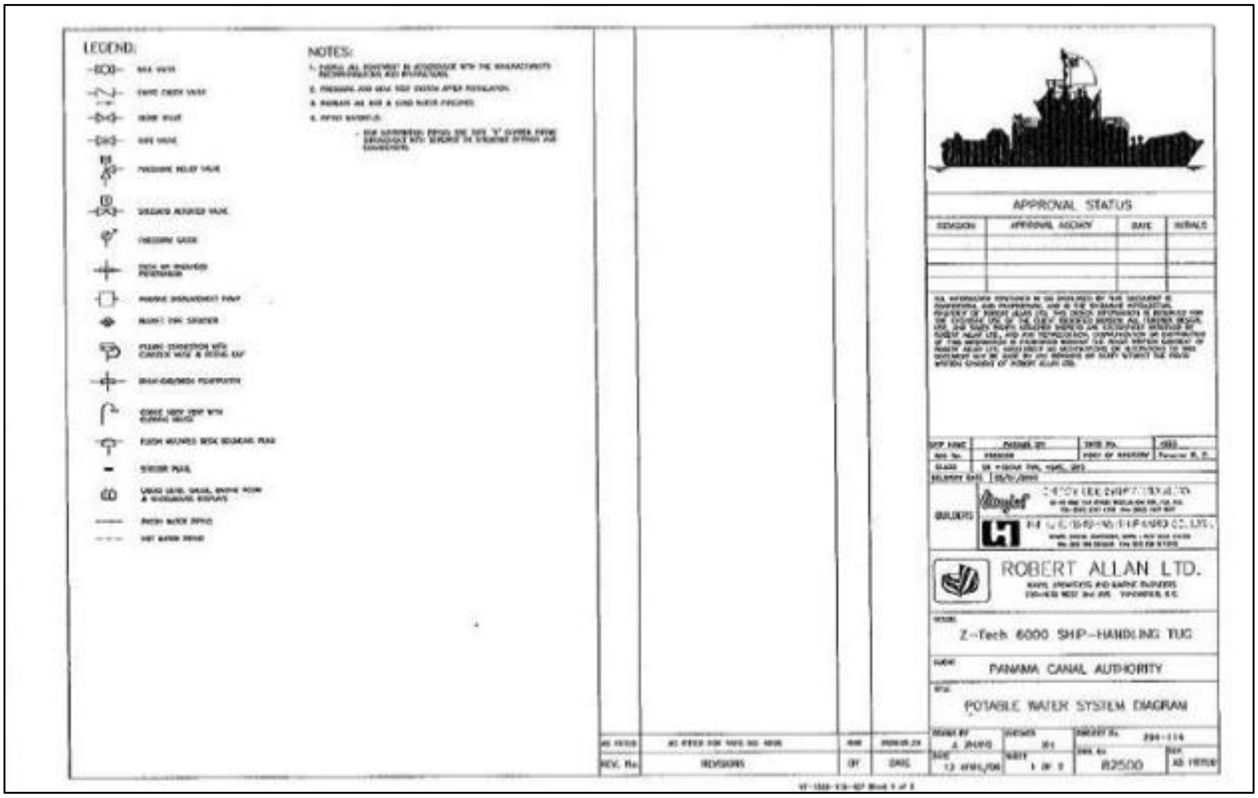

Figure 51: Legend for Distribution System Diagram (Zhang, 2013)

Establishing Water Testing Locations

In order to fully assess the drinking water system aboard the tugboats of the Panama Canal, this project recognized the value of testing the water quality before entering the tugboat as well as at a point within the water system. Along the Panama Canal there are five different tugboat landings that supply potable water to the tugboats at multiple retrieval points, called takes; Miraflores, Paraíso, Gamboa, Gatún and Davis (Figure 52).

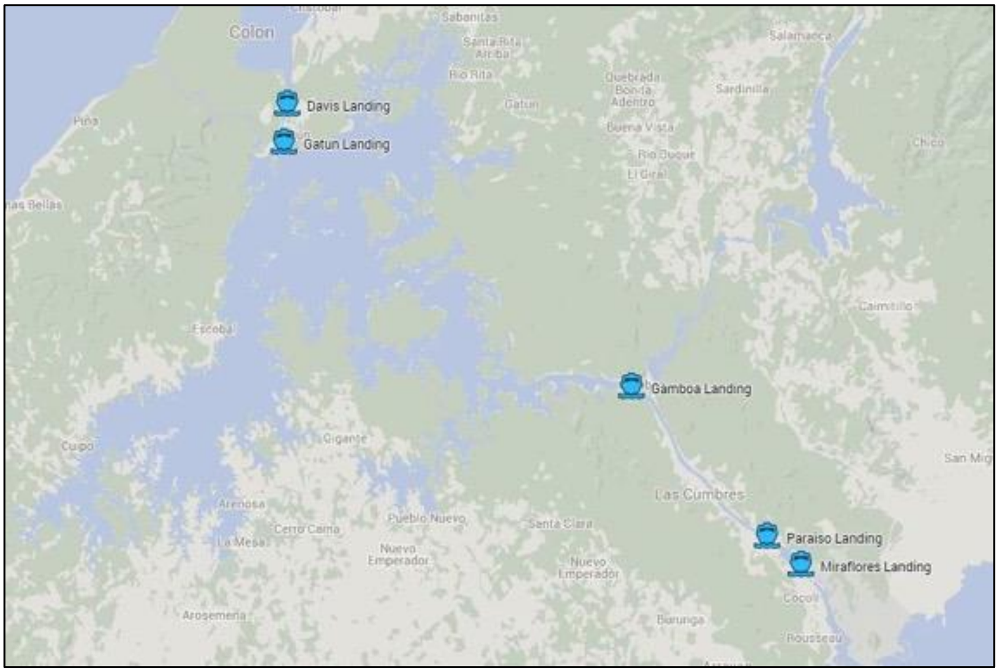

Figure 52: Tugboat landings throughout the Panama Canal (Google Maps, 2015)

Table 4 provides the landing and their respective identification code for labeling water samples and documentation. Water samples were also collected at a point within the water system on the tugboats Veraguas II and Guía (Figure 50, location labeled E). The water samples collected from the tugboats Veraguas II and Guía were labeled as R-VER and R-GUÍA, respectively. These sample locations were chosen in order to confirm that the water quality provided at tugboat landings met the health targets. The data obtained was used to determine whether the water maintained quality after traveling through the potable water system aboard the tugboats.

Table 4: Identification Codes for Tugboat Landing Sample Locations

TUGBOAT LANDING	TAKE	IDENTIFICATION CODE
Miraflores	1	LMT1
	2	LMT2
Paraíso	1	LPT1
	2	LPT2
Gamboa	1	LGA1
	3	LGA3
	4	LGA4
	5	LGA5
Gatún	1	LGT1
	2	LGT2
Davis	1	LDT1
	2	LDT2

Water Sampling

Throughout the duration of this project, the team collected water samples from both the water intakes at the tugboat landings in Miraflores, Paraíso, Gamboa, Gatún, and Davis, as well as the tugboats R-VER and R-GUÍA. The team collected two 100 mL water samples at each intake at landings and on tugs; one sample to test chlorine residual and turbidity and the other for microbiological contamination. A member of the team turned on the water system to maximum flow and the water ran for five minutes before collecting a sample. After five minutes, a team member rinsed the collection bottle for testing residual chlorine and turbidity three times by the faucet water before collecting a 100 mL sample. The team immediately filled the collection bottle for microbiological tests, without rinsing, after removing the sterilized seal. Both samples were transported to the lab in coolers as to minimize factors that may alter the results of water testing. Water sampling techniques follow guidelines of ISO Standard 5667-1: 2006*, Water quality -- Sampling -- Part 1: Guidance on the design of sampling programmes and sampling techniques* (Appendix C) (International Organization for Standardization, 2006). Figure 53 displays the residual chlorine and turbidity (right) and microbiological (left) collection containers along with the cooler used to transport samples. After collecting water samples from landings and tugboats, team members conducted water quality evaluations in the laboratory at the Miraflores Water Treatment Plant. Water was tested, in no particular order, in relation to the health target values for turbidity, residual chlorine, total coliforms, and *E.coli*.

Figure 53: Water Collection Materials

Water Testing: Turbidity

The team tested water samples against turbidity health targets using a HACH 2100N Turbidimeter (Figure 54). This device utilizes a stable halogen-filled tungsten filament lamp that is capable of analyzing samples up to 4,000 NTU. The HACH 2100N Turbidimeter meets the reporting requirements of the United States Environmental Protection Agency (EPA) Method 180.1 (Appendix C) (Hatch, 2015). To determine the turbidity of a water sample, a team member filled the sample cell provided with the Turbidimeter to the line etched on the outside of the cell and replaced the cap. After, the conductor of the test wiped the outside of the sample cell to remove any water residue or fingerprints. Then, the conductor placed the sample cell into the instrument cell compartment of the Turbidimeter and closed the cover. The Turbidimeter displayed a reading of the turbidity of the sample.

Figure 54: HACH 2100N Turbidimeter

Water Testing: Residual Chlorine

Water testing to determine residual chlorine in the samples involved the use of a GENESYS 20 (Figure 55). The GENESYS 20 is a visible spectrophotometer that uses a tungsten-halogen light source and a single beam optical design (Thermo Scientific, 2012). To determine the residual chlorine, a team member rinsed a syringe three times with water from the 100 mL sample, then collected 10 mL and emptied the contents of the syringe into a 50 mL plastic beaker. The conductor of the test added 0.50 mL of phosphate buffer and 0.50 mL N,N-diethyl-p-phenylenediamine to the 10 mL sample of water. The water, depending on the amount of residual chlorine, began to change to a red color. A deeper red corresponded to a higher residual chlorine concentration. The team member swirled the sample for 10-15 seconds and then poured the solution into a 1 cm sample cuvette. After, the conductor of the test wiped the outside of the cuvette to remove any water residue or fingerprints and inserted the cuvette into the vacuum sealed compartment of the spectrophotometer. The GENESYS 20 printed a reading of the residual chlorine of the water sample. Testing for residual chlorine followed guidelines of ISO Standard 7393-2: 1985*, Water quality -- Determination of free chlorine and total chlorine -- Part 2: Colorimetric method using N,N-diethyl-1,4-phenylenediamine, for routine control purposes* (Appendix C) (International Organization of Standardization, 1985).

Figure 55: GENESYS 20

Water Testing: Total Coliforms and E.coli

Team members conducted membrane filtration tests to analyze the collected water samples for presence of total coliforms and *E. coli*. This method involved filtering 100 mL of water through a sterile membrane, cautiously placing the membrane into an agar plate, and incubating the sample for 24 hours at 95-98.6° F (35–37 °C). If no colonies developed after 24 hours of incubation at this temperature, then the water was considered not contaminated with total coliforms or *E. coli*. However, if the presence of total coliforms was indicated, then the sample was incubated for another 24 hours at 111.2-113° F (44–45 °C). If the water sample was harboring *E. coli*, then the sample developed coliforms on the media at this temperature. This process of membrane filtration followed guidelines of ISO Standard 9308-1: 2014*, Water quality -- Enumeration of Escherichia coli and coliform bacteria -- Part 1: Membrane filtration method for waters with low bacterial background flora* (Appendix C) (International Organization of Standardization, 2014).

It was crucial for the team to run a water system analysis based on the health targets established for this project in order to produce a water safety plan that effectively addressed and resolved all potential health hazards. Therefore, this water system analysis required that the collected water samples be tested for turbidity, residual chlorine, total coliforms, and *E. coli*. The team documented all results from the water quality testing in a laboratory notebook and later transferred the data onto the computer in Microsoft Excel. This project statistically analyzed the results from the water quality testing to identify the potential hazards of the water system aboard the tugboats of the Panama Canal.

Water Quality Results at Tugboat Landings

Team members collected and tested water samples at each of the five tugboat landings along the Panama Canal. All collected data from water quality testing at tugboat landings can be found in Appendix D. Victor Bazan collected and tested all water samples from May 2015 to July 22, 2015; after which the water samples were collectively sampled and tested as a project team. The team was only able to sample water from the Gamboa tugboat landing once and therefore the results were not considered.

This project set health targets regarding the turbidity, residual chlorine, and microbial aspects of the water provided to and aboard the tugboats of the Panama Canal. Turbidity was not to exceed 1.00 NTU, the residual chlorine was to be between 0.80 ppm-1.50 ppm, and there should have been less than one colony of total coliforms and *E. coli* per 100 mL sample of water. Table 5 and Table 6 display a summary of the turbidity and residual chlorine values, respectively, from the landings. None of the water samples from tugboat landings had presence of total coliforms or *E. coli*. Based on the results obtained from water quality testing at the tugboat landings, the team confirms that water provided to tugboats, on average, meets the health target values for this project.

Table 5: Summary of Turbidity from Tugboat Landings

Location	Low	Mean	High
LMT1	0.15	0.46	0.78
LMT2	0.24	0.51	0.98
LPT1	0.36	0.67	1.09
LPT2	0.39	0.79	1.69
LGT1	0.23	0.45	0.63
LGT2	0.21	0.43	0.61
LDT1	0.25	0.50	0.74
LDT2	0.30	0.53	0.93

Table 6: Summary of Residual Chlorine from Tugboat Landings

Location	Low	Mean	High
LMT1	0.35	0.80	1.14
LMT2	0.54	0.91	1.03
LPT1	0.43	0.85	1.42
LPT2	0.43	0.83	1.16
LGT1	0.62	0.93	1.47
LGT2	0.65	0.93	1.23
LDT1	0.08	0.76	1.27
LDT2	0.30	0.82	1.60

To interpret the results from the water quality data obtained from water testing and sampling, the results were statistically analyzed. Appendix E presents all data results along with descriptive statistical analysis of the data sets. Descriptive statistical analysis includes the mean and the standard deviation of the results from the sample. The mean is the average of the results, which represents 50% of the data. The standard deviation is a measure on the diversity of the results, or how spread out the data is from the mean. According to the data, all landings, on average, meet or fall between the health targets for turbidity, residual chlorine, total coliforms, and *E. coli*. However, the data has a high standard deviation meaning the results are very spread out and do not follow a normal trend. This observation could be a result of a small sample size causing the standard deviation from the mean to be relatively high. Therefore, although the average results of the water quality data meet health targets, the data should be considered theoretically true but not confirmed.

Water Quality Results from Tugboats

Water was collected and tested from two Panama Canal tugboats; Veraguas II and Guía. All of the collected data from the water quality testing on the tugboats can be found in Appendix F. The results prior to July 27, 2015, correspond to the collecting and sampling work of Victor Bazan. After that date, water was sampled and tested collectively as a project team. Victor Bazan only consecutively tested water samples from R-VER for residual chlorine. after However, after July 24, 2015, water samples collected from R-VER were tested for turbidity, residual chlorine, total coliforms, and *E. coli*.

The water tested from the two Panama Canal tugboats were assessed based on the health targets established in 3.3.1 Health Targets. Table 7, Table 8, and Table 9 display a summary of the turbidity, residual chlorine, and total coliform values, respectively, from the tugboats Veraguas II and Guía. None of the water samples collected from the tugboats showed the presence of *E. coli.* The water samples from the tugboats had high turbidity and low residual chlorine levels, which suggested a potential hazard related to consuming this water.

Table 7: Summary of Turbidity from Tugboats

Location	Low	Mean	High
R-VER	0.48	0.66	0.83
R-GUÍA	0.80	3.92	13.00

Table 8: Summary of Residual Chlorine from Tugboats

Location	Low	Mean	High
R-VER	0.00	0.60	1.58
R-GUÍA	0.00	1.21	5.13

Table 9: Summary of Total Coliforms from Tugboats

Location	Low	Mean	High
R-VER	0	0.00	0
R-GUÍA	0	0.55	6

On average, the water samples from R-VER meet the health target for turbidity. However, since only four samples of water from R-VER were tested for turbidity levels, the data should not be relied on as being representative of the water quality because there is a large deviation between results. Likewise, although no samples tested positive for total coliforms from R-VER, the sample population should not be considered representative. For residual chlorine, however, a larger sample population of water from R-VER was tested and on average, these water samples do not meet the health target established for residual chlorine. This suggests a potential health hazard in the potable water quality from the tanks aboard R-VER.

Water from R-GUÍA only met health targets for *E. coli* and residual chlorine. On average, the samples did not meet any of the established health targets for turbidity or total coliforms. However, the water quality results from R-GUÍA have many outliers and the mean should not be considered representative of the data. Therefore, the median of the data samples was used as a measure of central tendency. Table 11 shows the median turbidity, residual chlorine, and total coliform values from R-GUÍA. According to these results, at least 50% of the water from R-GUÍA does not meet the established health targets for turbidity or residual chlorine.

Alternatively, at least 50% of water tested from R-GUÍA met health targets for total coliforms and *E. coli.* However, it should be noted that one water sample tested positive for harvesting total coliform colonies which could suggest either a testing error or a risk in the drinking water system. Appendix G presents the descriptive statistical analyses of the water from the tugboats.

Table 10: Median Values for Water Testing on R-GUÍA

Parameter	Median
Turbidity	2.57
Residual Chlorine	0.55
Total Coliforms	0.00

Findings from water testing at tugboat landings along the Panama Canal imply that water supplied to tugboats, on average, meets the established health targets for turbidity, residual chlorine, total coliforms, and *E. coli*. Since the results from water testing aboard the tugboats R-VER and R-GUÍA do not meet the health targets, the team focused its investigation on the water system aboard the tugboats. The absence of *E. coli* and total coliforms in the drinking water from the Panama Canal tugboats suggest that the decay of residual chlorine is not due to fecal contamination. However, the deficiency of residual chlorine causes the water to be susceptible to future contamination. Therefore, it was important to investigate the potential factors that contribute to the rapid decay of residual chlorine.

Residual Chlorine Decay

Chlorine, due to its low cost, is the most commonly used disinfectant for water treatment (Deborde & Gunten, 2007). Batching of chlorine gas (Cl_2) into water (H_2O) results in the formation of hypochlorous acid (HOCl), and hydrogen (H^+) and hypochlorite ions (OCl^-). Reaction 1 describes this process as:

$$Cl_2 + H_2O \rightarrow HOCl + H^+ + OCl^-$$

Reaction 1

Together, hypochlorous acid and hypochlorite are referred to as free or residual chlorine and are available for disinfection. Hypochlorous acid and water enters and breaks down enzymes in the cell wall of bacteria. This increases the permeability of this protective barrier for the bacteria, making it vulnerable, and killing the microorganism (Calomiris, 1998). However, in the presence of organic or inorganic compounds, hypochlorous acid will react and form a by-product. This reaction is generically described in Reaction 2:

$$HOCl + B \rightarrow product$$

Reaction 2

Where B is an organic or inorganic compound (Deborde & Gunten, 2007). In this situation, hypochlorous acid is no longer available for disinfection and therefore the residual chlorine levels decrease.

Iron is an inorganic compound that commonly reacts with hypochlorous acid. Dissolved iron (II) (Fe^{2+}) will transform from a soluble state to a precipitate when combined with hypochlorous acid and water. The resulting solid is iron (III) oxide-hydroxide ($Fe(OH)_3$), which is commonly known as rust. With this reaction, hypochlorous acid is no longer present, therefore decreasing the residual chlorine levels of the water (Shan et al., 2014). According to the EPA, rust is a typical source of turbidity (1999). Reaction 3 describes this process as:

$$2Fe^{2+} + HOCl + 5H_2O \rightarrow 2Fe(OH)_3(s) + Cl^- + 5H^+$$

Reaction 3

The tugboats of the Panama Canal have two steel-walled potable water storage tanks. Steel is a ferrous alloy and, therefore, is prone to rusting under the proper circumstances. The team decided to inspect the potable water storage tanks on R-GUÍA for indications of corrosion. If corrosion was observed, not only could the low residual chlorine levels be accounted for, but also the high turbidity of the water.

Inspection of Potable Water Storage Tanks

Prior to the inspection of the potable water storage tanks, tugboat crewmen and engineers drained the tanks and opened the access doors. Figure 56 to Figure 62 are photographs of the inside of the potable water storage tanks aboard R-GUÍA. Inspection of the tanks confirmed the presence of rust in the potable water storage tanks.

Figure 56: R-GUÍA tank inspection 1-7

Figure 57: R-GUÍA tank inspection 2-7

Figure 58: R-GUÍA tank inspection 3-7

Figure 59: R-GUÍA tank inspection 4-7

Figure 60: R-GUÍA tank inspection 5-7

Figure 61: R-GUÍA tank inspection 6-7

Figure 62: R-GUÍA tank inspection 7-7

Identifying Potential Hazards, Hazardous Events, and Associated Risks

Three potential hazards were identified based on the results of the potable water system assessment on the tugboats of the Panama Canal:

HAZARD 1: R-GUÍA does not meet the established turbidity health targets.

HAZARD 2: One sample from R-GUÍA tested positive for harvesting total coliforms.

HAZARD 3: Neither tugboat meets residual chlorine health targets.

Hazardous events could arise from the consumption of drinking water from the tugboats of the Panama Canal. If there is a deficiency in the residual chlorine, the water does not have a safeguard against recontamination. Since one sample from R-GUÍA tested positive for total coliforms, consumers of this water could be at risk. Additionally, turbidity levels are high which can minimize the effects of disinfection.

The project team ran a risk assessment for each identified potential hazard in order to determine the degree of attention necessary for mitigation. Based on the WHO, *Guidelines for Safe Drinking-Water Quality,* the risk associated with each hazard was determined using a semi-quantitative matrix that scored the likelihood of occurrence for the event and the severity of the hazard (2008). Likelihood is described as rare, unlikely, moderately likely, likely, or almost certain. Severity is described as insignificant, minor, moderate, major, or catastrophic.

For this project, likelihood of the hazardous events was determined based on the results from the water quality testing. If none of the results confirmed the occurrence of the hazard, then the likelihood was rare. Conversely, if all of the results confirmed the occurrence of the hazard, then the likelihood was almost certain. Based on the likelihood of the hazard, it was given a scaled score that was proportional to increased risk. Table 11 relates the likelihood description with the percentage of occurrence from the results and the associated scaled scoring.

Table 11: Determining Likelihood of Hazards

Likelihood	Occurrence	Score
Rare	0-25%	1
Unlikely	26-49%	2
Moderately Likely	50-74%	3
Likely	74-99%	4
Almost Certain	100%	5

Severity was determined based on the risk of the established health targets. The health targets for this project represent the desired water quality for ensuring access of potable water to consumers. Since it was important for all health targets to be met, no potential hazards were considered insignificant. However, water results that exceeded turbidity levels and confirmed *E. coli* were considered minor and catastrophic, respectively. Since turbid water has no directly related health effects, and can only suggest the presence of bacteria, the project identified turbid water as having minor risk. Conversely, *E. coli* is the most harmful pathogenic contaminant and can have negative health affects for the consumer; therefore, the project identified *E. coli* as a catastrophic risk. Similar to the likelihood descriptions, the severity of the hazard was given a scaled score that increased with risk. Table 12 relates the severity description with the health target and the associated scaled scoring.

Table 12: Determining Severity of Hazards

Severity	Health Target	Score
Insignificant	-	1
Minor	Turbidity	2
Moderate	Residual Chlorine	3
Major	Total Coliforms	4
Catastrophic	*E.coli*	5

A simple scoring matrix was used to prioritize the hazards based on the associated risk. Table 13 is the simple scoring matrix used for this project and is based on Table 4.2 of the WHO, *Guidelines for Safe Drinking-Water Quality.* The associated risk assessment is the product of the scores for the likelihood and severity of the hazard.

Table 13: Simple Scoring Matrix

Likelihood	Severity of Hazards				
	Insignificant **(1)**	Minor **(2)**	Moderate **(3)**	Major **(4)**	Catastrophic **(5)**
Almost Certain **(5)**	5	10	15	20	25
Likely **(4)**	4	8	12	16	20
Moderately Likely **(3)**	-	6	9	12	15
Unlikely **(2)**	-	4	6	8	10
Rare **(1)**	-	-	-	4	5

The first identified hazard stated that the turbidity results from R-GUÍA exceed the established health targets. Based on the data in Appendix F, 72% of the water samples from R-GUÍA confirm the occurrence of this hazard. Thus, Hazard 1 was considered a moderately likely hazard. Also, since the identified hazard is associated with the turbidity health target, it is considered a minor severity. Therefore, Hazard 1 has an associated risk of six.

The second identified hazard stated that one sample from R-GUÍA tested positive for harvesting total coliforms. Based on the data in Appendix F, 9% of the water samples from R-GUÍA confirm the occurrence of this hazard. Hazard 2 was considered a rare hazard. However, since the identified hazard is associated with the health target for total coliforms, it is considered a major severity. As a result, Hazard 2 has an associated risk of four.

The third identified hazard stated that both tugboats do not meet the established health targets for residual chlorine. Based on the data in Appendix F, 75% of the water samples from R-GUÍA confirm the occurrence of this hazard. Therefore, the hazard had a likely occurrence, and since it was related to the residual chlorine health target, it was moderately severe. Consequently, Hazard 3 has an associated risk of 12.

The associated risk assessment of the identified hazards concluded that priority should be given to mitigating Hazard 3. After which, Hazard 1 and Hazard 2 should be addressed. Due to time constraints, this project took actions to control Hazard 3 and made recommendations to control Hazards 1 and 2.

3.3.2.2 Operational Monitoring

Operational monitoring included identifying control measures, that when monitored, reduce deviation from the established health targets. To address the low residual chlorine levels of the water on R-GUÍA, the team focused on the identification of rust within the potable water storage tanks. Therefore, the team recommended cleaning and epoxy painting the inside walls of the potable water storage tanks on the tugboat.

To clean the potable water tanks, maintenance crew drained and opened the tank hatches. The remaining water at the bottom of the tank was dried. Then, the interior walls of the tank were cleaned, paying close attention to soiled and oxidized locations. Lastly, the tank was rinsed down and the walls were dried.

After the preparatory cleaning of the tank walls, they were painted using an epoxy. Epoxy was used to increase the steel's resistance to water. Figure 63 and Figure 64 show the inside of the potable water tanks of R-GUÍA after cleaning and painting the walls. As the pictures exhibit, no rust remained in the tanks.

Figure 63: R-GUÍA Potable Water Tank Post Cleaning and Epoxy Painting 1-2

Figure 64: R-GUÍA Potable Water Tank Post Cleaning and Epoxy Painting 2-2

The paint was given time to dry then the tanks were cleaned again. Cleaning of the potable water tanks followed the Panama Canal Maritime Safety Standards 2600SEG-307 titled, *Maritime Safety Standard Cleaning Procedure for Drinking Water Storage Tanks Aboard Floating Equipment*[12] (Maritime Safety Standards, 2012). A paraphrased and translated cleaning process and procedure from this document can be found in Appendix H.

Since this project had time limitations, there was no continued water testing after the cleaning of the potable water storage tanks to confirm whether or not this control measure was effective. However, by eliminating and maintaining the presence of rust in the drinking water system, the potable water aboard the Panama Canal tugboats should be capable of meeting the established residual chlorine health target. Also, by removing rust from the storage tanks, the turbidity of the water should decrease, which will cause the residual chlorine to have more

[12] This title and procedure is a paraphrased translation from the original document, 2600SEG-307 *Norma de Seguridad Marítima del Procedimiento de Limpieza de Tanques de Almacenamiento de Agua Potable a Bordo de Equipos Flotantes.*

efficient and effective disinfection. With effective disinfection, residual chlorine has the capability to kill total coliforms and *E. coli* if there is a presence in the water. Therefore, operational monitoring of this suggested control measure not only has the potential to mitigate Hazard 3, but also the other two identified hazards.

3.3.2.3 Management

This project designed a drinking water management plan to ensure that the control measures properly maintain the potable water quality on the tugboats of the Panama Canal. The management plan was designed based on the established health targets, the results of the drinking water system assessment, and the operational monitoring of the proposed control measures. The designed drinking water management plan recommended improved methods from those carried out by this project. The complete Drinking Water Management Plan for the Panama Canal tugboats is located in Appendix I.

This Drinking Water Management Plan established the water quality health target parameters, sampling locations, and frequency for the continuation of the EAA-CA project. Testing methods and scheduling were included in the proposed Drinking Water Management Plan. Additionally, the plan designed a form for the documentation, interpretation, and management of water system assessment results.

3.4 Conclusion and Recommendations

According to the WHO, the concluding component of a safe drinking water framework is surveillance of the drinking water system (2008). Surveillance is defined as, “the continuous and vigilant public health assessment and review of the safety and acceptability of drinking-water supplies” (WHO, 2008). This process ensures the health of consumers by promoting improvement of the drinking water system. Therefore, this project recommends that the EAA-CA Division of the ACP continue to monitor and assess the potable water quality on the tugboats and at the landings along the Panama Canal.

Under continued surveillance of the drinking water system, this project recommends continued research pertaining to the water quality on tugboats. Although this project assessed the drinking water system from treatment at the Miraflores Water Treatment Plant to the distribution system on the tugboats, further investigation should be conducted. More water samples need to be collected from the five tugboat landings to confirm that the water provided to the tugboats at the landings meet the established health targets. Furthermore, water should be collected directly from the faucets and from the end of the hoses that are used to fill the tanks. By testing the water from the hoses, the ACP can verify whether residual chlorine levels are decreasing because of contamination present in the hoses or in the potable water tanks. Additionally, water samples should be collected from points of consumption in the tugboat distribution system rather than a valve in the engine room, because contaminants could be affecting the water quality after the collection point, which could affect consumers. With these small modifications in the method of collection of the water samples, the ACP can gain a better understanding of the water quality provided and aboard Panama Canal tugboats.

For a more thorough system assessment of the water quality on the tugboats, this project recommends that water be sampled and collected from the tugboats weekly, for several months. Each week, three samples should be collected at the beginning of the week and one sample at the end. Collecting water samples throughout the week would allow the ACP to determine if the water quality diminishes with increased time in the potable water tanks. Moreover, collecting the samples under the same circumstances for several months will give the ACP more regulated data and a larger sample size to analyze the tugboat water quality.

This project also recommends that the ACP keep a log of all filling and cleaning of the potable water tanks and conduct water tests after each. Tracking these dates and testing the water will allow the ACP to better monitor the system. If the water does not meet drinking standards after filling the potable water tanks, then this could suggest that the tank needs to be cleaned, and help determine the frequency of cleaning. Likewise, if the water after cleaning still does not meet drinking standards, then the ACP could test the water provided to the tugboats at the landings. Documenting the cleaning and filling of the potable water tanks aboard the Panama Canal tugboats could allow the ACP to notice trends in the water quality and better understand the water system.

Throughout the duration of this project, the team established health targets and conducted a system assessment of the potable water on two tugboats of the Panama Canal. Based on the results of water quality testing and inspection of the potable water tanks, the team concluded that water provided to the tugboats at landings meets the established health targets; however, more samples should be collected to improve the sample size and minimize deviation in the results. Additionally, water tests from the tugboats confirmed that the water meets the health targets for total coliforms and *E. coli*, but improvements need to be made to meet the turbidity and residual chlorine health targets. After inspecting the potable water tanks of R-GUÍA, the team found presence of rust, which could be the source of deteriorating residual chlorine levels and increased turbidity. To mitigate potential hazardous events from occurring due to low residual chlorine levels, tugboat maintenance crews thoroughly cleaned the rust from the walls of the potable water storage tanks and epoxy painted the interior walls. The project team recommends continued testing of the water to determine whether this control measure affectively improves the residual chlorine levels and turbidity of the water from the tugboats.

This project designed a water management plan taking into consideration the results from the system assessment and the assumption that cleaning and epoxy painting the interior walls of the storage tanks improves the drinking water quality. If followed, this plan could mitigate diminishing residual chlorine levels and high turbidity of the water on the Panama Canal tugboats. In the future, the ACP should continue surveillance on the drinking water system to improve the proposed management plan. In conclusion, the implementation of the Drinking Water Management Plan intended to improve the drinking water quality aboard the Panama Canal tugboats, leading to better health of the tugboat crew consuming the water, and overall, ensuring the continued successful navigation of ships through the Panama Canal.

Chapter 4: New BEC Spillway Design

4.1 Design Statement

The Gatun Spillway, built in 1913, is the existing spillway for the Panama Canal and controls the water level of Lake Gatun, the feeding water and power source for the Panama Canal locks. Since the establishment of this spillway, the lake level has risen and the spillway no longer has the hydraulic capacity to regulate the water level. In 2005, the ACP hired an outside company to study the Gatun Dam and Spillway and conduct a feasibility study for a new spillway. Design began in 2012, but ended abruptly when the ACP discovered a fault line under the proposed location. Three years later, a new location and design are in progress. This project works in collaboration with the Project Management Division of the ACP (IAP)[13] to investigate the best techniques and design for the new spillway.

Designing a new structure, such as this new spillway, requires extensive planning. In this project, design was an iterative process including considerations of economic, environmental, social, constructability, health and safety, and ethics. Economic considerations required cost estimations for running pipe to off shore disposal sites. Geological processes and construction of large dam standards exhibit considerations of environmental impacts. The largest environmental impact the new spillway will have is erosion of the surrounding area. If the erosion is not properly controlled the high velocity of water the spillway releaseses could affect the integrity of the land around the spillway. Additionally, loss of species due to effects on flora and fauna in the region must be considered in this project. Social impacts are present in this project through the relocation of ACP employees who work in the area where the new spillway will be constructed. The project must abide by design standards from ACI, ASTM, and other international organizations to regulate the health and safety of the spillway project. The project must assess feasible designs of the new spillway to ensure constructability. Since the spillway site is an island, the materials used to construct the spillway must be able to arrive to the site via water. Lastly, all members of the BEC Spillway Design project team must maintain ethical communication to guarantee that designs and ideas are recognized properly. This project meets the Worcester Polytechnic Institute capstone design requirements through the consideration of the aforementioned constraints.

[13] División de Administración de Proyectos (IAP), in Spanish

4.2 Introduction

In 2007, the ACP began to expand the Panama Canal. Eight years later, this multi-billion dollar project is near completion. The expansion of the Panama Canal created new projects either to replace existing structures, or construct new ones to complement the expansion. One of these new structures is a spillway. When a dammed body of water contains excess water, this excess is released and transported to another location through a passageway called a spillway. The new spillway is currently in the initial design phases and its planned location is in the Lake Gatun region. Located toward the Atlantic side of the Canal, Lake Gatun is an artificial lake used to not only provide a passageway for vessels to transit the Canal, but it is also the source that feeds and powers the locks and provides fresh water for many Panamanian residents. As part of the expansion project, Lake Gatun's operating level was raised to 89 ft (27.1 m). The existing Gatun Spillway, part of the Gatun Dam, is an older structure, completed in 1913. The Gatun Dam and Spillway are no longer able to support the Probable Maximum Flood (PMF) of the lake. For this reason, a new spillway is needed to meet the demands of the discharge capacity reached by the lake in the case of a flood. This project outlines the preliminary phases for the new spillway through three factors: location, geological data, and design, following these objectives:

- Research different types of spillways and flow velocities on erosion;
- Revise technical drawings and check for conflicts; and
- Assess possible excavation techniques/routes for disposing of material.

4.3 Background

Dams and spillways have been constructed and utilized for centuries and their designs have progressed with technology. There are several types of dams and spillways and the choice of which depends on factors such as location, velocities of the released water, materials in the construction area, purpose of the dam, travel path of the spilled water, and operating conditions. Erosion is a hazard to dams and spillways regardless of the type utilized to impound a body of water. To control the effects of erosion, energy from spillways is neutralized through means of dissipation techniques in the channel. However, even when energy dissipaters are used, the forces of erosion are still active. Throughout its use over the past 100 years, the Gatun Dam and Spillway has experienced many floods and has had erosion problems. Due to the increased water level in Lake Gatun, the dam is retaining more water. If a flood occurred and the spillway released more water than necessary, a possible dam failure could occur and the effects of erosion would be detrimental to both the dam and surrounding spillway area. A new spillway to complement Gatun Spillway in Lake Gatun has been a work in progress for over a decade. Currently, the ACP is carrying out construction plans for this addition.

4.3.1 Dams

Dam building is an engineering concept that has been used for centuries. Since the earliest civilizations, people built and utilized dams to manipulate and control river water for crops or as a source of energy. Dams are often used to impound water for recreational or navigational purposes (Baxter, 1977). In most cases, dams are accompanied by a spillway for the occurrence of overflows and floods.

4.3.1.1 Types of Dams

The four main types of dams are arch, gravity, buttress, and embankment dams (Figure 65). Arch dams are usually made of concrete and are able to resist the forces of the water exerted on them for long periods of time. This type of dam is commonly found in narrow or steep valleys. Gravity dams must be built on strong, solid rock, usually found in wide or narrow valleys. Concrete and masonry are typical materials used to build this type of dam, which relies on gravity alone to hold it down. Like gravity dams, buttress dams are seen in wide or narrow valleys and have to be built on strong bedrock. These dams also use concrete or masonry and the buttresses, or triangular shaped piers, are spaced in intervals along the dam wall span. An embankment dam is trapezoidal in shape and can be composed of earth fill such as clay and other types of soils, or rocks that have been excavated. These materials make up the “core” of the dam between the concrete walls (British Dam Society, 2011).

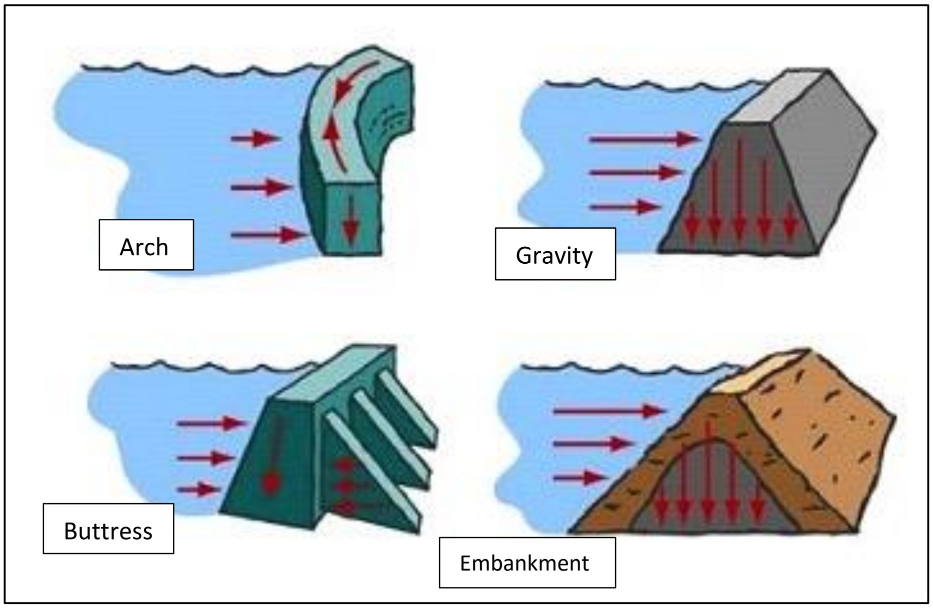

Figure 65: Different types of dams (ASCE, 2011)

4.3.1.2 World Commission on Dams (WCD)

In 1997, an international organization, the World Commission on Dams (WCD), formed with the support of the World Bank and World Conservation Union (IUCN). Each person on the WCD was an individual participant from different sectors of industry, but did not represent a country or institution. With the increase in large dam building and their impact on the environment, the commission assessed the environmental impacts and developed standards for all stages of dam building, operation, and decommissioning (WCD, 2015). The WCD's guidelines are meant to protect both the environment and the residents of surrounding areas of a dam. Additionally, the WCD looked into the effectiveness of dams. Considerations included water and energy needs, social issues from dams, public acceptance, and river quality modifications after dam construction (WCD, 2015). In the four year period that the WCD existed,

> The organization wrote over 130 technical papers, studied seven dams and three dam-building countries in great depth, reviewed another 125 dams in less detail, carried out consultations in different parts of the world with 1,400 participants, and accepted 950 submissions from experts and the interested public. Altogether, the WCD reviewed experiences from 1,000 dams in 79 countries (WCD, 2015).

The WCD wrote its final report in 2001, detailing the organization's research and establishing guidelines in their entirety. Although the organization disbanded in 2001, the standards and papers they produced are still widely used by other dam organizations today.

4.3.1.3 Environmental Impacts of Dams

Dams have many environmental and social impacts. The construction of dams is not always accepted in proposed locations since thousands of people may be displaced from their homes and land (WCD, 2000). The WCD tried to consider these misgivings and find solutions by enforcing rules and recommendations in the reports they published. After the existence of the WCD, people began to speak out against the construction of dams. Many protested that although corporations often support the erection of large dams due to their clean energy appeal, they do not take into consideration the people that will be affected, which may jeopardize a person's fundamental rights (Finley-Brook & Thomas, 2010). In 2000, 40-80 million people were displaced due to large dam projects (WCD, 2000).

Dams significantly affect the environment as well as people; they create an obstruction to rivers and their ecosystems. Freshwater occupies a small percentage of the Earth's water but within this small area, an exceptional amount of species are found. It is estimated that approximately 60% of Earth's rivers have discontinuities caused by dams (Revenga, Brunner, Henninger, Kassem, & Payne, R, 2000). By creating a blockage, dams disturb the flow of nutrients, sediment, species, and chemical balances in a river.

Nutrients and sediments come from the headwaters, or beginning of the river, and travel downstream, feeding plants and other species and depositing sediment along its path. When the river drains into the reservoir created by the dam, the nutrients and sediment end their routes. Both build up in the reservoir, depriving the remainder of the river downstream from their benefits. Rivers downstream from dams often experience increased amounts of erosion in the banks and beds because the sediment material is not being replaced.

When the excess materials deposited into the reservoir begin to decompose, they release toxins, which are ingested by fish, and consequently, humans and other animals. Many studies have been conducted about the water temperature of reservoirs in relation to organic material and the release of carbon dioxide and methane. In warmer, shallow reservoirs, levels of carbon dioxide and methane are higher because decomposition thrives in a warmer environment (McCartney, 2009). These findings indicate a major risk for fish and their predators.

Migratory patterns and travel for fish have been affected greatly by discontinuations in rivers for years. Almost half of the world's fish population resides in freshwater (Nelson, 1994). In dammed areas, fish are not able to travel downstream and reproduce, causing reductions in the population and a threat of extinction. Likewise, birds and other animals that live downstream from dams are deprived of their food source if the movement of fish ceases. Additionally, flooding in rivers is significantly reduced by dams, causing vegetation along the banks to become scarce.

Another environmental issue concerning the construction of dams is earthquakes. Scientific research organizations are becoming increasingly aware of the risks associated with erecting large dams. Scientists believe that there is a link between dams and earthquakes. Most dams are located in valleys, which are usually active earthquake areas. Sometimes dams are built on fault lines, and scientists believe that this weakens the fault (Zielinski, 2009). When a dam is constructed, a reservoir is created. It has long been accepted that reservoirs can cause earthquakes due to the changes in weight from the water on the ground and groundwater pressure that tests the strength of bedrock. This type of earthquake is termed reservoir induced seismicity (RIS). These earthquakes heavily depend on the types of rocks under the reservoir because of permeability and shear stress. Most RIS occur within the first few years after filling but some occur immediately. Shallower depths within 0.620 to 1.86 miles (1 to 3 km) are more predictable for RIS. This phenomenon takes longer to occur in deeper reservoirs. Across the globe, many earthquakes have been determined to be RIS, including two in Australia, one in India, and two in China (Seismology Research Centre, 2015).

4.3.1.4 Environmental Protection

After the WCD decommissioned in 2001, other organizations formed and began to create standards for large dam building in order to lessen their impact on the environment. Organizations such as the International Commission on Large Dams, International Hydropower Association, and International Energy Agency all developed guidelines for dam construction in conjunction with the WCD standards (McCartney, 2009). After a dam is built, management becomes important for environmental protection. The WCD proposed that dams should be audited regularly to ensure safe working conditions (WCD, 2000). Due to the awareness surrounding the issues that may be caused by dams, construction companies are very cautious because they know they could suffer negative publicity or self-inflict economic harm. Research on environmental impacts and the best measures for protection continue to be at the forefront of the initiative to improve dam construction (McCartney, 2009).

4.3.2 Spillways

Although there are many different types of spillways, the general purpose is to release excess water in an impounded body of water. Flooding of a dammed lake or reservoir can cause damage to the structure and surrounding areas. Spillways alleviate the excess water so damage is not inflicted. Depending on the type and height of the dam, different spillways are used. All spillways must have some sort of energy dissipater to neutralize the kinetic energy and velocity of the released water. Typically, spillways are controlled by nearby operating centers and release water through gates. However, in some cases where the spillway is difficult to reach, the structure may be ungated and surplus water is released without control by an operating center.

4.3.2.1 Types and Designs of Spillways

One type of spillway is a free overfall spillway (Figure 66). In these spillways, water flows over the crest of the dam into a plunge pool. Occasionally, crests will have a lip, used to propel the falling water away from the foot of the dam. These spillways can be gated or ungated (Hydraulic Structures for Flow Diversion and Storage, 2012).

Figure 66: Free falling spillway at Gross Reservoir, CO (Baker, 2013)

A shaft spillway is generally used when a dam is located in a narrow, steep gorge. This type of spillway contains a circular structure located within the lake or reservoir that funnels surplus water through an underground passageway (Figure 67). This tunnel creates a channel under the dam and deposits the water downstream to another location, as seen in the figure below to the right. Since shaft spillways tend to produce a strong vortex, placing piers along the top of the spillway is a common method of energy dissipation to prevent strong sucking action (Hydraulic Structures for Flow Diversion and Storage, 2012).

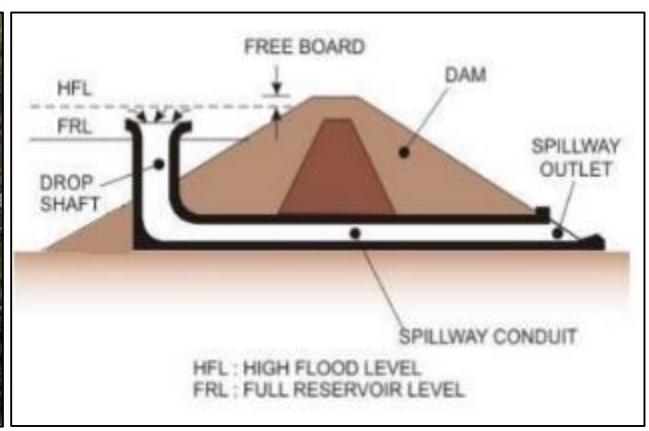

Figure 67: Shaft spillway (Black, 2015) and profile of shaft spillway (Hydraulic Structures for Flow Diversion and Storage, 2012)

A common type of spillway that accompanies embankment dams is a chute spillway. This type is an open channel utilized to discharge water downstream and can be constructed on any type of soil due to its simple design (Department of Water Resources, 2000). There are variations of this spillway where the chute is placed below or on the side of the dam, typically called a side-channel spillway. In chute spillways, energy dissipation is crucial. Baffle blocks or stepped channels are a means of energy dissipation for this spillway design (Figure 68) (Hydraulic Structures for Flow Diversion and Storage, 2012).

Figure 68: Open chute spillway with large baffle blocks (C. William Hetzer, Inc., 2012)

An ogee-type spillway is like a chute spillway, where both utilize an open downstream discharge channel. However, an ogee-type is an "S" shaped slope that conforms to the profile of land. When water is released, it adheres to the slope. The released water has a lower nappe and upper nappe. The lower nappe is the water that physically travels on the concrete surface of the ogee (Kabir, 2015). The upper nappe is the water that flows over the surface while following the profile but does not physically touch the concrete (Figure 69). If any more water is released than was designed for, it will detach from the profile of the slope and shoot forward, reducing the efficiency of the spillway (Hydraulic Structures for Flow Diversion and Storage, 2012).

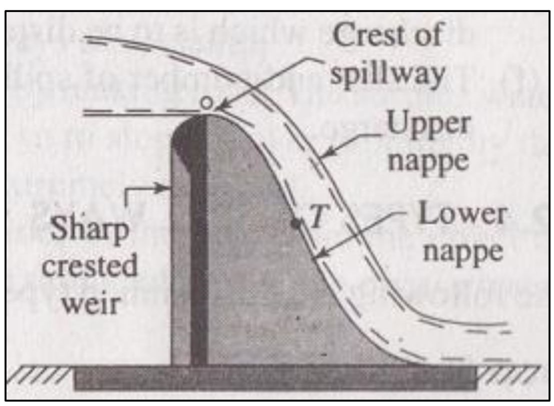

Figure 69: Ogee spillway profile (Kabir, 2015)

Most spillways tend to incorporate elements from other spillways. For example, although an ogee spillway itself is a type of spillway, an ogee, or "S" shape, is a characteristic seen on other designs such as chute spillways. There are numerous other types of spillways and factors such as location, resources, accessibility, water flow, and erosion influence their design (Hydraulic Structures for Flow Diversion and Storage, 2012).

4.3.2.2 Erosion

The largest problem resulting from spillways is erosion. Water discharge from spillways is very powerful, and appropriate precautions and measures must be taken to avoid unnecessary erosion. Erosion from a spillway puts the dam in danger of cracks in the concrete, sagging, or even complete structural failure. The most prominent threat to dams and spillways are scour holes. When water is released from an overtopping dam, spillways produce high velocity flows. This water plunges into a basin at the foot of the dam and causes scour. Scour is a type of abrasive erosion where the plunging water removes sediment from the base of dam. Depths of scour holes are evaluated constantly because they can cause severe damage to a dam's structural integrity (Annandale, Wittler, & Scott, 2000).

There are many ways to avoid scour and reduce its effects. For example, a concrete-lined spillway channel can be used because it is more resilient to the effects of scour than natural earthen material. Additionally, some sort of energy dissipater must be used on large dams with high velocity flows. Baffle blocks or rocks are commonly utilized to disperse the water in the channel of the spillway (Figure 70). Seen in Figure 70 on the left, small concrete rocks line this spillway channel, but on the right, large concrete baffle blocks are used. Other energy dissipaters revolve around the design of the channel of the spillway, which depends on the amount of space, how much water will be released, and the dam size, among others. Although these techniques assist in avoiding scour, they do not make the spillway resistant to erosion. A form of erosion is seen in any lake or reservoir that contains a spillway because the released water flows at such a high velocity.

Figure 70: Energy dissipation technique using rock lined spillway channels (Tandon, 2014)

4.3.3 Lake Gatun

Lake Gatun was formed as a result of constructing the Gatun Dam across the Chagres River and through excavation of the Gatun region over 100 years ago during Panama Canal construction. Approximately 167 square miles (433 km^2) in size, the lake contains about 1.4 billion gallons (5.3 billion liters) of water. The Chagres River, its tributaries, other runoff sources from small rivers, and rainfall supply water to the lake. In 2000, there were over 30 precipitation gauges monitoring the rainfall in the Gatun region. These gauges determined that the amount of annual rainfall was approximately 10.8 ft (3.30 m) (Pabst, 2000). Today, this average remains roughly the same. From May to October, the Canal zone receives its heaviest rainfall. Most often, the lake reaches a maximum operating lake level (MOLL), now a level of 89 ft (27.1 m), by the end of October and the gates for the spillway must be opened to allow drainage and return the lake to its MOLL (ACP, 2015f).

4.3.4 Gatun Dam and Spillway

Built between the years of 1907 and 1913, the Gatun Dam is one of the largest water containment structures of its time. As seen in Figure 71, the embankment dam is located on the upper western side of Lake Gatun, southwest of the existing and new locks. The dam is primarily made of hydraulic fill (Moffatt & Nichol Engineers, 2005). The inner fill of the Gatun Dam is composed of rock, clay, and sand obtained from the excavation of the Gaillard Cut and Pedro Miguel Locks during the construction of the Canal. The walls of the Gatun Dam are made of the Gaillard Cut rock and the fill between the two walls was placed by dredgers (Taylor, 1913). There is approximately 21 million yd^3 (16 million m^3) of the sand and clay mixture in the core of the structure (Taylor, 1913). In total, the Gatun Dam weighs 30 million tons (27 million tonnes) and “contains enough earth and rock to build a fence 18 in (0.460 m) thick and 3 ft (0.910 m) high around the earth at the equator” (Bennett, 1915). The purpose of the dam is to impound the water of the lake filled by the Chagres River and provide water and hydropower for the locks.

Figure 71: Location of Gatun Spillway (Colón, Panamá, 2015)

4.3.4.1 Hydropower

Hydropower uses the forces from moving water to create electricity. There are many sources of hydropower but most come from large dams. Within the dam structure, there is a channel that contains turbines. When the water rushes through the channel, it turns the turbine blades connected to a shaft, which then spins a generator, and generates electricity (National Hydropower Association, 2015) (Figure 72).

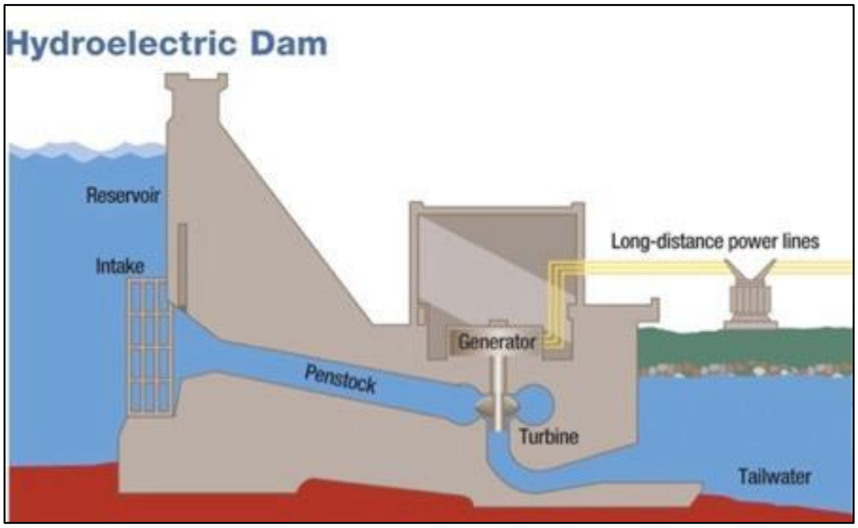

Figure 72: Diagram of how hydropower works (Tennessee Valley Authority, 2015)

The Gatun Dam is equipped to produce hydropower and powers the locks, facilities, and lighting along the Canal in the 37 mile (59.5 km) stretch of land between the Gatun and Pedro Miguel Locks (Bennett, 1915). Along this stretch, there are many power lines and underground electrical and telecommunication lines that carry this energy from the lake to the locks. The Gatun Dam has been able to power the locks and areas surrounding the Canal since its opening because of its size and the amount of water in the lake readily available for hydropower.

4.3.4.2 Measurements and Characteristics

Measuring 8,200 ft (2,500 m) along the top of Gatun Dam, the entire structure, including the spillway, is over a mile in length (Moffatt & Nichol Engineers, 2005). At the base of the dam underwater, the width reaches up to 2,100 ft (640 m) and 400 ft (122 m) wide at the exposed water level (Taylor, 1913). The radial (semi-circular) spillway itself measures 738 ft (225 m) along the top and the crest (top of the spillway) is 18.7 ft (5.70 m) below the top of the lake level (Re, 2012). The spillway is located on “Spillway Hill” in the center of the length of the dam between two hills that abut the structure. Figure 73 shows a front view of the spillway. This ogee-type spillway contains concrete piers that support the 14 Stoney gates and a footbridge, allowing maintenance access across the top of the structure (Moffatt & Nichol Engineers, 2005). The gates of the spillway measure approximately 45 ft (13.7 m) wide and 19 ft (5.79 m) tall. Each of the spillway gates weighs 42 tons (38.1 tonnes) (Bennett, 1915). The footbridge’s elevation is 116 ft (35.2 m), or 26.5 ft (8.10 m) above the top of the lake.

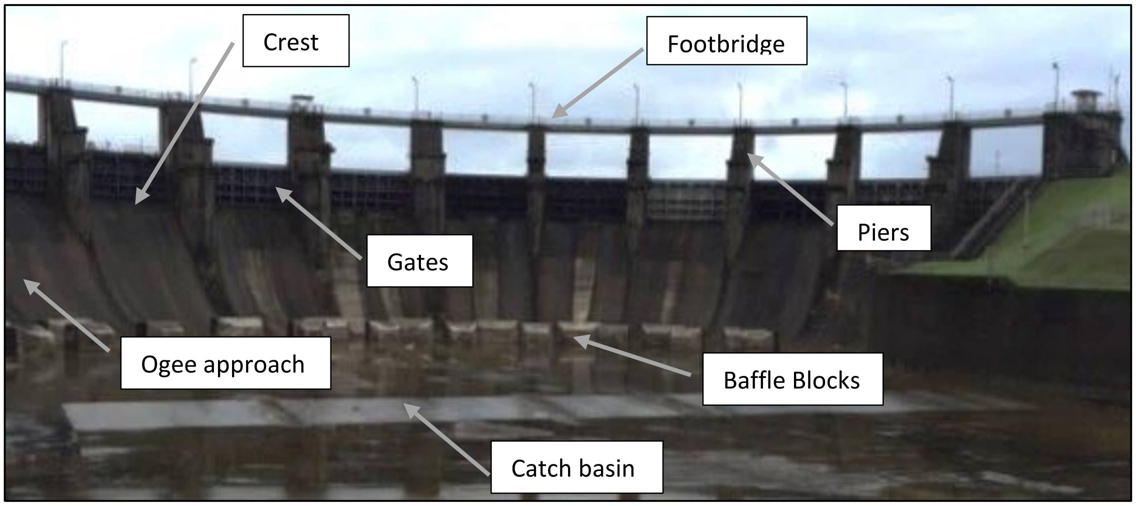

Figure 73: Gatun Spillway

The spillway is composed of about 250,000 yd^3 (191,000 m^3) of concrete (Moffatt & Nichol Engineers, 2005). The basin that catches released water and the baffle blocks that dissipate the kinetic energy of the water are also made of concrete. The large steel-faced baffle blocks and catch basin are located at the foot of the spillway (Figure 74). Beyond the catch basin, the concrete-lined channel continues slightly past the traffic bridge over the spillway and feeds into the Chagres River (Figure 75). At the end of the lined channel, a large scour hole is present demonstrating that erosion is a considerable problem for this region. Unprotected by concrete, the soft clay and soils erode very easily.

Figure 74: Baffle blocks of the Gatun Spillway and basin

Figure 75: Gatun Spillway traffic bridge

4.3.4.3 Opening the Spillway

If the spillway gates are required to open, an operator will do so from the control desk that overlooks the spillway (Figure 76). The desk is located on a mezzanine in the Gatun Hydroelectric Plant to the left of the spillway. The mezzanine has small windows that are opened to view the spillway while operation is in progress. Each gate has a number (1-14) posted on the footbridge in the center of the gate so the operator knows which gates are which. Additionally, the spillway gates must be opened in a specific sequence to minimize the powerful impact of currents and flow on the gates, spillway, and power station (Figure 77) (O. Fontalvo, personal communication, August 21, 2015). In Figure 76, the controlling knobs are switched to the off position. The spillway will be opened if approved by the hydrology staff, in the case of flooding, who will establish a time duration for the gates to be opened. When the gates are fully open, the flow rate of the water is 13,400 ft^3/s (379 m^3/s) (O. Fontalvo, personal communication, August 21, 2015). The velocity of the water being released is approximately 58.1 ft/s (17.7 m/s) (Re, 2012).

Figure 76: Control desk where the spillway gates are opened and closed

Figure 77: Order of opening Gatun Spillway gates: 10-14-7-6-8-9-11-13-12-5-4-1-2-3. The order is reversed for closing the gates.

4.3.4.4 Maintenance of Spillway

Considering the age of the dam and spillway, it is necessary to perform maintenance regularly to ensure its safety. When the dam was originally constructed, the MOLL of the lake was 85 ft (25.9 m). Since then, the MOLL had been raised to 87.5 ft (26.7 m). Now, with the need to accommodate the Post-Panamax vessels, the MOLL has been raised to 89 ft (27.1 m) and the ACP removed 162 million ft^3 (4.60 million m^3) of dredged material from Lake Gatun (ACP, 2015f). The water storage capacity of the lake has increased by 262 million yd^3 (200 million m^3), allowing about 1,100 more transits through the Canal per year (ACP, 2015f). Due to the increase, the ACP repaired and extended the height of the 14 gates of the spillway, fabricated, and added two new caissons, or floating gates (ACP, 2015f).

After water is released through the gates, the spillway is inspected for structural failures caused by vibrations, and maintenance of the Stoney gates is performed. Inspectors look for problems in the rolling bearings along the tracks that raise the gates when they need to be opened and perform service if needed (O. Fontalvo, personal communication, August 21, 2015). Through maintenance, the structure is kept in safe and working condition.

4.3.5 Feasibility Studies for a New Spillway

As early as 1945, after 32 years of operation, Panama Canal engineers proposed a new spillway for Lake Gatun. Capacity studies on the spillway determined that it was unfit to handle a probable maximum flood (PMF). At the time, nothing came of the proposal. In 2005, the ACP hired the firm Moffatt & Nichol Engineers to conduct an intensive study on the existing Gatun Dam and Spillway. The structure was examined, as well as the ground and concrete underwater. This study categorized the dam as high hazard and labeled it as unable to meet the hydraulic capacity required to release sufficient amounts of water in safe quantities for flood control. The dam no longer met the safety requirements according to the WCD standards (Moffatt & Nichol Engineers, 2005). The dam, categorized as high hazard, stirred alarm of potential structural failure, causing a concern for the operation of the locks. If the dam failed, there would be no water to feed the locks, shutting them down and inflicting damage to Panama's economy and worldwide trade.

The report concluded that the dam and spillway are inadequate to handle the hydraulic capacity of the 87.5 ft (26.7 m) lake and included a PMF plan. Activating this plan entails the release of water through the lock culverts (Moffatt & Nichol Engineers, 2005). In December of 2010 when Panama City and surrounding Canal zone areas experienced the largest storm in its history, flood water surged through the lock culverts to lower Gatun's water level (Re, 2012). However, this was not the only time the lock culverts were used. Examinations of the locks after releases of water through the culverts determined that the locks experience damage from this action (Moffatt & Nichol Engineers, 2005).

When the spillway was originally erected, it was not designed to accommodate an operating level of 87.5 ft (26.7 m). The piers of the spillway have no vertical steel reinforcement, thus lacking lateral stability (Figure 78). The ACP completed this structural analysis in 2005 and the solution was to provide support by "retrofitting vertical tendons in the piers and horizontal struts between the tops of the piers" (Moffatt & Nichol Engineers, 2005). Moffatt & Nichol Engineers estimated the cost for the tendons at about $2.50 million and replacement of gates and hoists at $27.3 million. Following this analysis, the ACP performed this work, but a new spillway was still needed (ACP, 2015j). Even though the gates and concrete were strengthened, the capacity of the dam, and safety standards were still considered insufficient for a PMF.

Figure 78: Piers of the Gatun Spillway

This feasibility study for a new spillway in 2005 proposed the location of the new structure to be west of the original. The prospective plan indicated the spillway to have seven gates, twice as tall as the Gatun Spillway gates and of a radial design, to reduce pressure against them. Like the existing spillway, the design proposed a short ogee approach channel with a concrete-lined basin to catch the water. The estimated cost of this new spillway was $95 million and would take about 4.5 years to complete, including site investigations, design, and construction (Moffatt & Nichol Engineers, 2005).

4.3.6 Geological and Seismic Factors

As part of the 2005 feasibility study for a new spillway, the hired firms conducted research and tests on Gatun's geological and seismic features. In the northern Lake Gatun region, the Gatun Formation is prominent. The Gatun Formation is an ancient geological formation consisting of many layers of rock, the oldest containing numerous fossils from the early formation of Panama. The rock layers are composed of sandstone, siltstone, and conglomerates of clay and soft rock. Also found in the area is Atlantic Muck, consisting of clayey sand, sandy clay, sand, and clay. In certain areas of the northern Lake Gatun region, Atlantic Muck reaches a depth of 197 to 295 ft (60 to 90 m). These materials are not ideal for construction in the area because they do not provide a solid base, only providing a compressive strength of 145 to 290 psi (1 to 2 MPa) (Golder Associates, Ltd., 2005).

In addition to weak compressive strength, these materials are also not suitable for seismicity. In the northern Gatun region, the Rio Gatun and an unnamed fault line are present.

The Rio Gatun fault is located 42,700 ft (13 km) away from the Gatun Spillway. A moderate level earthquake hazard is defined in the Lake Gatun area because the faults located in the area are not extremely active (Moffatt & Nichol Engineers, 2005).

4.3.7 New BEC Spillway

After 2012 when the ACP discovered a fault line in the proposed area for the new spillway, the project was terminated. This past year, the ACP began to search for a different location and contractors for a new spillway. The project is titled “BEC Spillway Design,” where BEC stands for the three engineers that proposed the idea: Bal, Espinosa, and Calvo. In early 2015, the ACP released a call for proposals. On June 29, 2015, planning for the new spillway began.

The ACP hired a Colombian company, INGETEC[14], to do the subsurface investigations, laboratory work, and design work for the new spillway (ACP, 2015e). This work involves geological explorations and testing of samples, as well as a design for the new spillway. The design will include a physical model on a scale of 1:40 or greater, numerous dimensional drawings, fluid dynamics models, and dredging and earthwork design. As far as accommodations, the spillway must have utility tunnels, vehicular crossing ability, erosion control works both upstream and downstream, a discharge channel, energy dissipation basins, and an approach channel (ACP, 2015j). As a summary, INGETEC must provide the ACP with a total cost estimate for all work, design calculations, and several different design options. The ACP is involved in this type of preliminary work, and is responsible for supplying existing drawings that identify where buildings, utilities, electrical, and water lines are on-site for planning purposes. Key components currently being evaluated for the new spillway are location, geological testing, and conceptual design. The ACP’s Peer Review Board is the entity contracted to support the ACP in the review and decisions on the new spillway, therefore, it is important to have many options to present.

Once a design for the spillway is complete, including specifications and construction drawings, the bidding process for the construction contract can begin. The ACP will hire another company to perform the construction services. This project is scheduled to commence in 2017 and finish in 2019 (ACP, 2015j). With a project of this caliber, representatives of many fields of engineering are involved; specifically, civil, mechanical, electrical, seismic, geotechnical, structural, hydraulic, hydrology, geology, environmental science, and cost engineers. This project also requires economics, construction, project management, and social work. People from all different areas of study are involved to ensure maximum quality for the spillway.

[14] INGETEC for INGETEC Ingenieros Consultores, in Spanish

4.3.7.1 Location of Spillway

Currently, the proposed site to build the new spillway is between the existing and Third Set of Locks (Figure 79). As shown in Figure 79, the existing Gatun Locks are to the left of the spillway and the new locks to the right. The spillway will have a downstream flow and empty into Limon Bay, or the start of the Canal on the Atlantic side. In this area, no residential communities are present. The only buildings affected by the new spillway are owned by the ACP and the people who work in these buildings would be relocated. Since the ACP used this location for equipment storage and as excavation grounds for the Third Set of Locks, there are already facilities available to house equipment and other construction related needs. Some concerns about the area involve the hazards of hitting electrical, water, and power lines. All the lines that supply the locks with power will have to be moved eventually during construction.

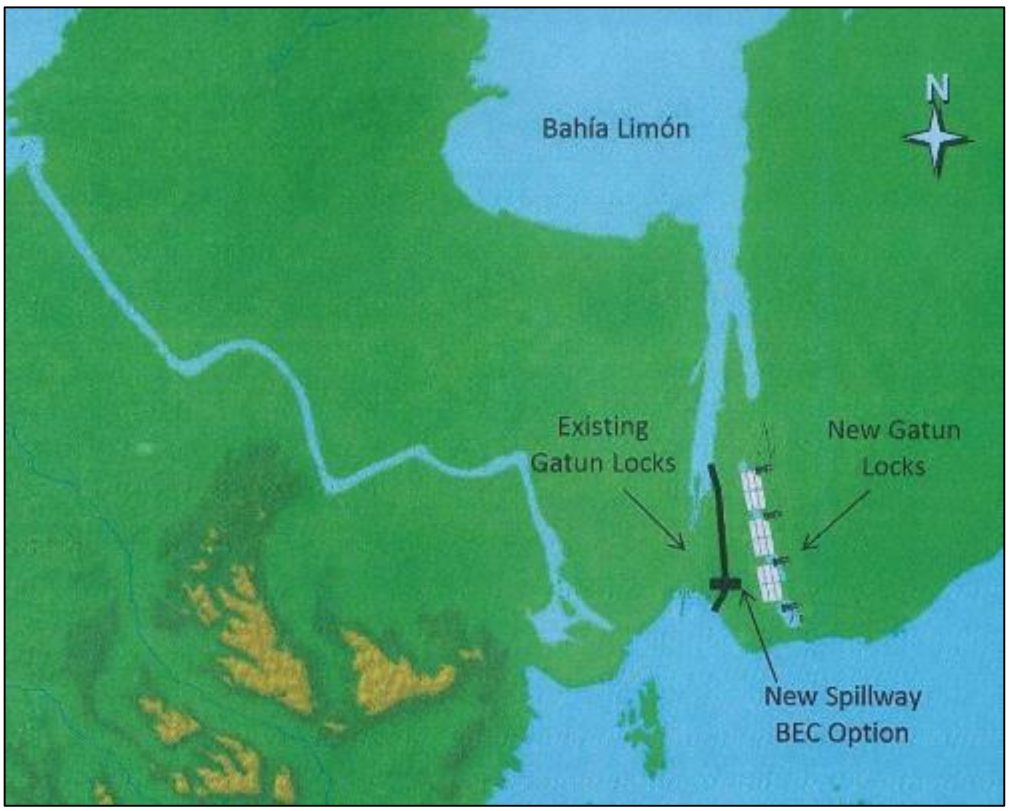

Figure 79: Proposed location for new BEC Spillway (ACP, 2015e)

4.3.7.2 Geological Testing

The ACP and INGETEC are currently conducting geological assessments, including site visits and sampling within the proposed location of the new spillway. This sampling is done through extracting boreholes. Boreholes are a type of exploration tactic geologists use to determine what type of soils and rock are found in an area. Although boreholes are drilled in many locations on a site, samples are not taken from every hole. In order to extract the cores from the ground, a large machine with a powerful hydraulic drill attached to the rear is needed, called a drilling rig (Figure 80). Samples, called drilling cores, are taken and placed into a “core box” for testing (Figure 81). Core samples vary in size depending on the specifications indicated by the contracting company. In this project, the ACP specifies HQ3 cores, a 2.41 in (61.1 mm) diameter core (Major Drilling, 2015). From these samples, geologists analyze aspects such as what type of soil or sediment is contained within the sample and the age of the rock. After soil testing is complete, geologists conclude what types of materials should be used in an area in order to ensure safety in the designs for a structure (Learning Development Institute, 2015). While new boreholes and testing are being performed on the project site, the ACP geologists have geological data for the existing and new set of locks for comparison.

Figure 80: Machinery used for borehole drilling (Raimonde Drilling Corporation, 2015)

Figure 81: Example of core box (EVCO, 2015)

4.3.7.3 New Spillway Design

Since the site of the new spillway is located between the existing and new set of locks, the ACP and hired contractors are familiar with the geological and structural restrictions that exist for this area. However, to obtain the best results and ensure maximum quality of the spillway, the ACP and hired contractors are carrying out research on studies of spillways from around the world, assessing different types of spillways, construction processes, successes and failures, and statistics. The area must also have an environmental impact study conducted according to standards such as *Equator Principles*, *World Bank Group Environmental Health and Safety Guidelines*, and the *Environmental and Social Performance Standards and Guidelines 2012*. All design elements must meet American Concrete Institute and American Association of State Highway and Transportation Officials standards (ACP, 2015j).

As defined by the ACP, the conceptual design of the new spillway is very similar to the Gatun Spillway design but includes radial gates instead of the existing vertical gates. Like Gatun Spillway, an ogee-type and stepped chute spillway is thought to be the best option. The new spillway will not have power generation abilities like the Gatun Dam (ACP, 2015j).

While constructing the spillway, natural north and south plugs consisting of excavated material will be made to keep water out of the area. The preliminary design included two catch basins, in a stepped chute form (Figure 82). The dimensions of the dam will be 3,940 ft (1,200 m) long and 410 ft (125 m) wide, with the piers measuring 8.20 ft (2.50 m) wide. The base of the dam will be located 24.6 ft (7.50 m) below lake level. The crest for the new spillway will be elevated at 69 ft (21 m), which is 20 ft (6.10 m) below the lake level. There will be 8-14 radial gates to allow a discharge capacity of 90,000 ft^3/s (2,550 m^3/s). The structure will open its gates if the water elevation of Lake Gatun exceeds 91.5 ft (27.9 m) (INGETEC, 2015a). If further flood control is needed, the lock culverts will be utilized. Gatun and Pedro Miguel's lock culverts will be opened first, followed by the new Third Set of Locks on the Atlantic side (ACP, 2015j).

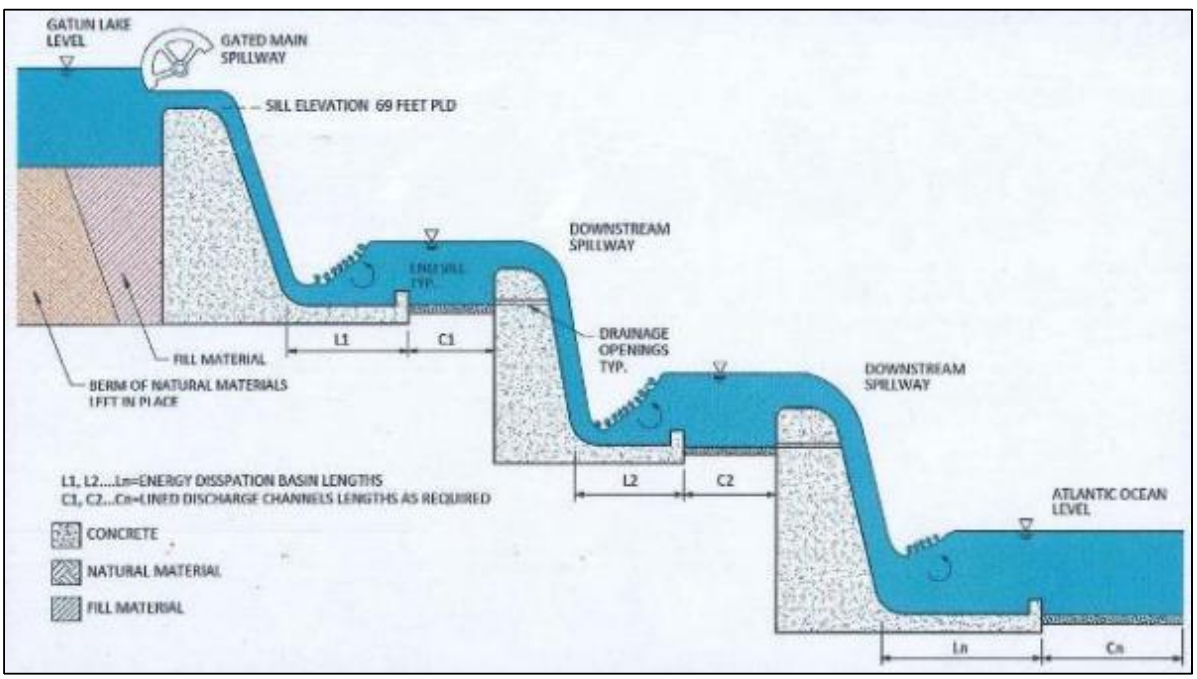

Figure 82: Original potential design for new BEC Spillway (ACP, 2015e)

4.4 Methodology

The BEC Spillway Design project is in the designing phase. Due to this, there is still much research to be done regarding the best possible design for the project based on geological information, flow velocities of the spilled water, and technical drawings. These drawings must also be examined and checked for accuracy. In order to best assist the ACP, three main objectives for this project were outlined:

- Research different types of spillways and flow velocities on erosion;
- Revise technical drawings and check for conflicts; and,
- Assess possible excavation techniques/routes for disposing of material.

This project aims to provide the ACP with preliminary information regarding research and design for the construction of the new spillway.

4.4.1 Guidance

Before beginning this project, the contract titled "Engineering Services for BEC Spillway Design" was consulted. After gaining access to the project folder on the computer, all drawings, documents, and pictures were reviewed to become familiar with the subject matter. The civil engineer assigned to this project held a meeting to explain all project objectives and its current state. After this meeting occurred, site visits and meetings were conducted with the contractor, INGETEC.

During site visits, the proposed location for the spillway was examined. The ACP and INGETEC geologists took small geological samples of the area and gained a general knowledge of the layout of the land. INGETEC also assessed exposed existing utilities, electrical, and water lines to make note of for designing purposes. Photographs were taken to document the course of the project.

By having meetings with INGETEC in person or via Skype, updates were given to the ACP and thoughts were discussed between both parties. Through these discussions, concerns about geological data, the overall design, and other inquiries were addressed. As previously mentioned, a major conflict for dams and spillways is fault lines. Therefore, the ACP and INGETEC spent a large amount of time discussing the issues around fault lines in the Gatun area. Geological data and the types of soil available in the Gatun area were also key discussion points. INGETEC thought it might be worthwhile to research ski jump spillways for the project because it would be more cost effective compared to a stepped chute spillway. From these meetings, research needed to be conducted on the topics discussed.

While researching, many questions arose about factors that were not discussed in meetings or explained in the contract. Therefore, inquiries were directed towards Mario Granados, the civil engineer assigned to this project, and Oscar Fontalvo, an operator for the Gatun Spillway. Through emails and verbal communication, a better understanding of plans for the new spillway and operation of Gatun Spillway was gained.

4.4.2 Research

Based on background research on spillways, this project narrowed its focus on types of spillways and flow velocities on erosion. As previously outlined in Section 4.3.2.1 Types and Designs of Spillways, there are many types of spillways. The best design for the spillway depends on factors such as its location, geological data, available materials, cost, among others. Potential types of spillways considered for this project were a stepped chute ogee-type spillway and a ski jump spillway. After INGETEC submitted a few possible designs to the ACP for review, it became necessary to start weighing the best options for construction materials. Since erosion is an immediate threat to the integrity of this new spillway, the ACP decided to use a 4,000 psi (27.6 MPa) concrete-lined channel for water flow. Although lined spillways reduce erosion better than unlined channels, concrete is not completely immune to the effects of erosion, or more specifically, scouring. In order to gain a general knowledge of when concrete starts to scour and how the process happens, research was completed.

4.4.3 Drawings

Following a site visit and meeting with INGETEC and the ACP's geologists, the contracting company proposed locations to perform geological sampling. Through the use of Autodesk AutoCAD 2013, technical drawings of the Gatun area, plans for the new spillway, and geological plans were studied. INGETEC documented the proposed locations for drilling on AutoCAD drawings of the layout for the new spillway and submitted them to the ACP for review (Figure 83). Charts showing the borehole ID, the location (northing and easting), depth, and type of borehole were shown on the drawings (Figure 84). From these charts, all borehole locations were drawn and labeled in the "Existing Utilities, Electrical and Telecommunication" and "Existing Utilites, Water, Sanitary & Storm Sewers" AutoCAD drawings supplied by the ACP. In these ACP drawings, INGETEC's proposed locations for drilling were checked to see if the boreholes conflicted with any buildings, electrical or water lines, and roads. If there was a conflict, comments were made on an official review sheet and then sent to the civil engineer to review and send to the contractor. The newly inputted borehole locations into the ACP drawings were printed and showed to other ACP divisions involved in the BEC Spillway Design project to discuss. This process was repeated for revisions.

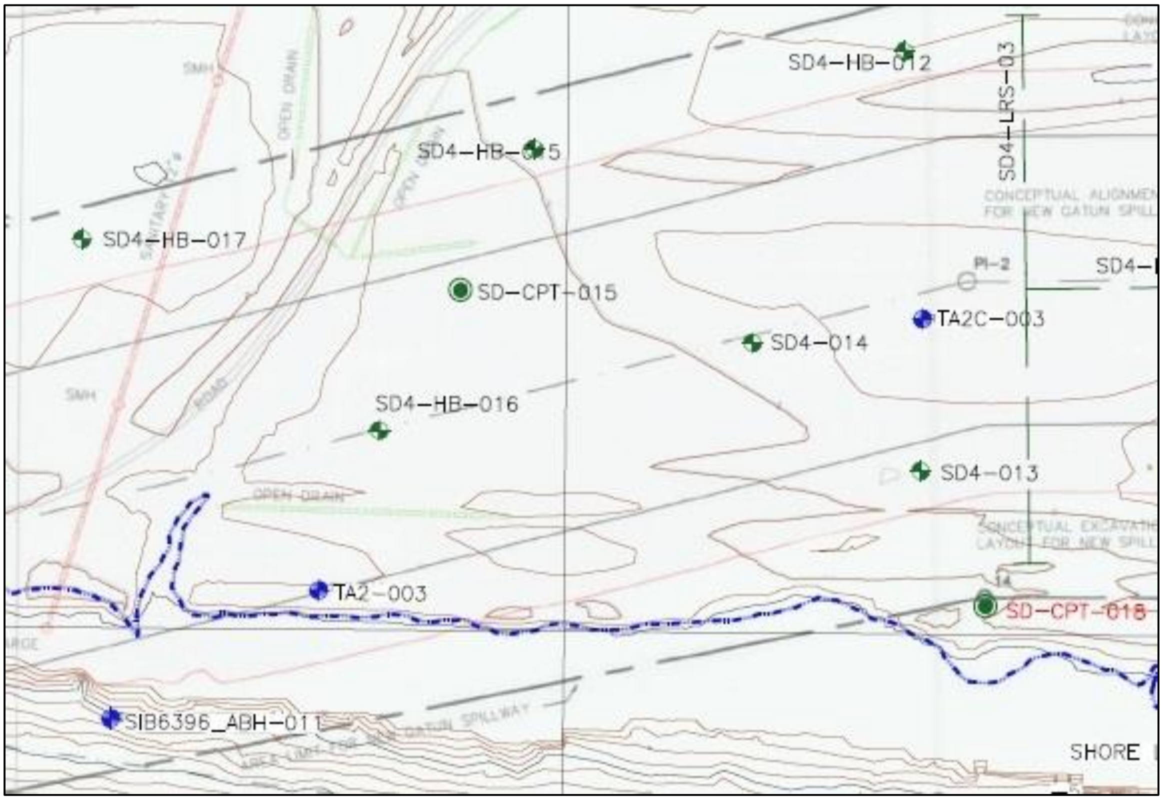

Figure 83: Sample of INGETEC's borehole locations, (INGETEC, 2015b)

PROPOSED GEOTECHNICAL EXPLORATIONS				
HOLE ID	NORTHING	EASTING	DEPTH (m)	TYPE
SD4–HB–010	1 025 930,31	618 630,29	30	NQ3
SD4–HB–011	1 026 032,42	618 728,27	20	NQ3
SD4–HB–012	1 026 177,39	618 812,55	30	HQ3
SD4–HB–013	1 026 170,30	618 659,56	30	HQ3
SD4–HB–014	1 026 231,99	618 705,76	20	NQ3
SD4–HB–015	1 026 312,20	618 776,03	20	NQ3
SD4–HB–016	1 026 367,89	618 672,82	30	NQ3
SD4–HB–017	1 026 476,94	618 741,72	30	NQ3
SD4–HB–018	1 026 530,91	618 651,84	30	NQ3
SD4–HB–019	1 026 685,73	618 689,52	30	NQ3

Figure 84: Sample of INGETEC's borehole locations, (INGETEC, 2015b)

4.4.4 Excavation Techniques

The site for the new spillway is an island located between the new Third Set of Locks and existing Gatun Locks. The only way to access the island is to drive over one of the new locks. However, construction equipment will not be allowed to drive on the new locks and must arrive to the site via water. When excavation begins, system is needed for transporting the excavated material off-site to the designated disposal locations approved by the ACP. In Figure 85 below, the suggested disposal locations are shown. These disposal locations include Monte Lirio, located east of the site, Peña Blanca, located southeast of the site in Lake Gatun, Black

Tank South, located west of the site past the Gatun locks, Isla Telfers, located slightly northeast of the site, and Northwest Breakwaters, located far past the entrance to the Canal in the Atlantic Ocean. The most practical options are Monte Lirio, Black Tank South, and Isla Telfers because they are fairly close to the spillway but transporting the material to these sites is an issue.

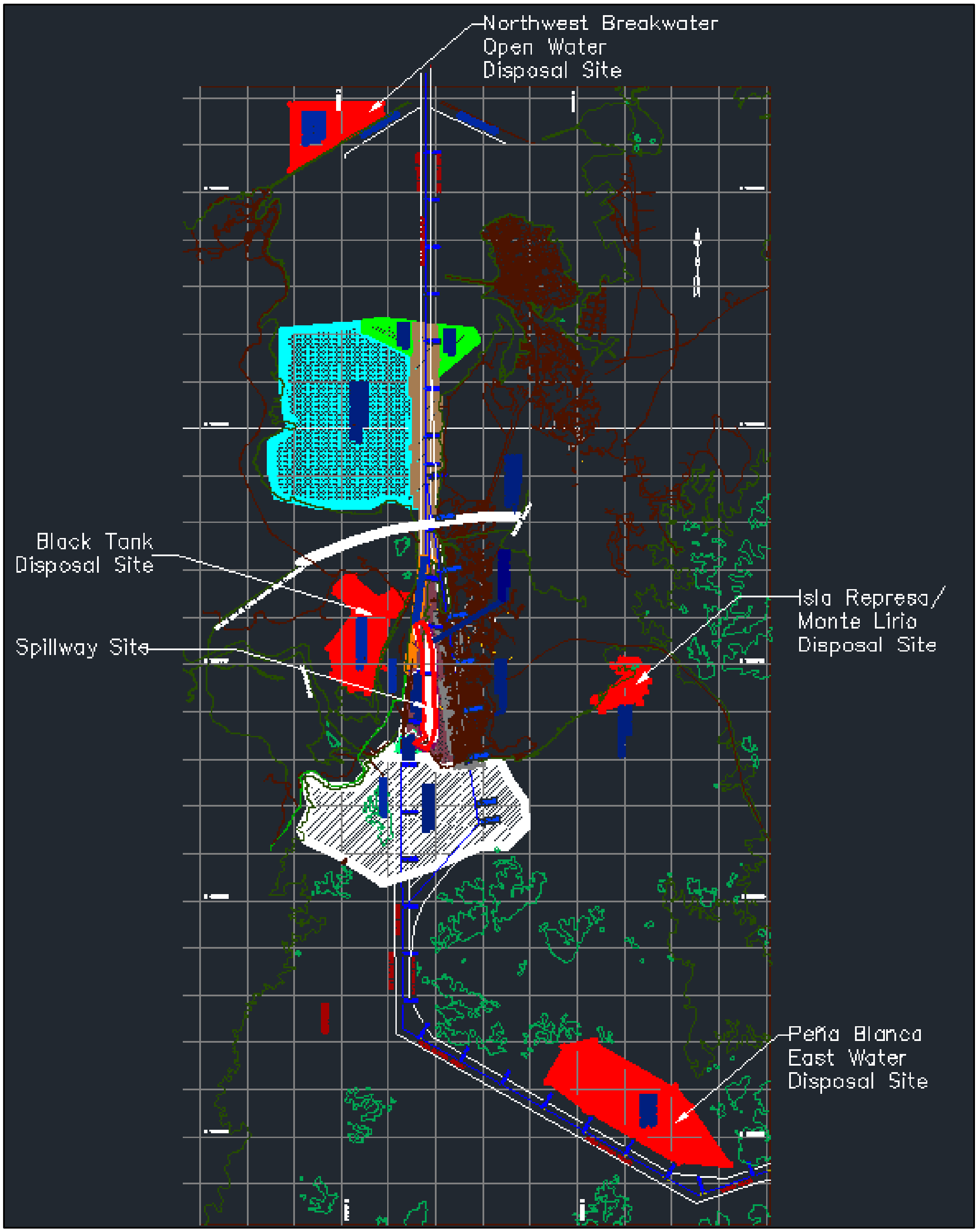

Figure 85: Disposal Sites for excavation (ACP, 2015d)

Because trucks cannot be utilized for excavation, the ACP is investigating transporting excavated material through steel dredging pipes, as shown in Figure 86. Approximately 2.95 ft (0.90 m) in diameter, the pipes would have to be run under the new locks or sunk in either Lake Gatun or Limon Bay (Figure 86). In order to move the excavated material through the pipes, slurry, a combination of soil and water, is made and then pumped through the length of the pipe. Typically, there is one large pump at the beginning of the connected pipe length, then a few smaller pumps along the remaining pipe route. These pumps provide the necessary pressure to move the slurry to its destination. Pumps vary depending on the total distance and how many angles are present in the pipelines throughout the route.

The ACP is particularly interested in running the steel pipes through one of the new crossunders of the new locks. These crossunders are tunnels around and under the locks that house telecommunication and electrical lines, as well as other equipment to operate the locks. They are equipped with stairs and an elevator to allow for maintenance. Running pipe through a crossunder offers a shortcut to the Monte Lirio site without having to sink the pipes in Lake Gatun. The feasibility study of this method involved looking at the crossunder plans for each lock and noting the features to determine if any obstacles were present. Additionally, routes for excavation were examined.

Figure 86: Excavation pipe size (ACP, 2015c)

4.5 Results and Analysis

In order to identify the best design components for the new spillway, research was conducted on types of spillways, flow velocities, and excavation techniques. AutoCAD drawings were also modified to produce accurate plans for borehole locations. From these results, the ACP gained more insight into potential designs that could be utilized.

4.5.1 Research

The following subsections describe the types of spillways and flow velocities on erosion which were the topics researched to gain a better understanding of spillways. This information aided in the design process for the new BEC Spillway.

4.5.1.1 Types of Spillways

The ACP and INGETEC considered a stepped chute and ski jump spillway for this project. Since the ACP already had conceptual designs of the stepped chute spillway and the current Gatun Spillway incorporates an ogee-type approach channel, further research was unnecessary for this type. However, when INGETEC mentioned using a ski jump spillway, the ACP did not have much information on this design. Due to the possibility of reducing costs, the ACP requested research on ski jumps.

Ski jumps are very effective and economical when trying to decide what type of energy dissipater to use in the case of a spillway (Najafzadeh, Barani, & Hessami-Kermani, 2014). When the velocity of the released water exceeds 65.6 ft/s (20 m/s), this type of spillway is typically used. A ski jump spillway consists of a large chute with a flip bucket at the end, causing the water to shoot up into the air, adding air entrainment into the water and thus slowing down its velocity (Figure 87). This decline in velocity reduces the risk of a scour hole forming upon impact into the plunge pool (Heller, 2013). Aside from decreasing erosion, the goal of a ski jump spillway is to discharge the water as far away from the foot of the spillway as possible. By releasing the water away from the base of the dam, the probability of scour affecting the structural stability of the dam is significantly reduced.

Figure 87: Karakaya Spillway, Turkey (Karakaya Dam, 2015)

In order to improve these spillways, dentate splitters are generally added to further aid in energy dissipation, as seen in Figure 87 above. Dentate splitters, or teeth, are part of the spillway structure and divide the one jet flow of water into many flows, reducing the kinetic energy and overall impact the water will have on the plunge pool. The jet becomes weak when this method is utilized, allowing the water to hit the plunge pool with decreased speed. A longer trajectory is better for this ski jump method (Rahatabad, 2004). Physical modeling is important to use to test different situations and determine the number of dentate teeth to effectively reduce scour. Studies done on this type of energy dissipater have concluded that the plunge pool erodes nearly half as much when dentate splitters are used (Rahatabad, 2004).

Another variation of ski jump spillways is the shape of the flip bucket. The bucket can be either circular or triangular (Figure 88, Figure 89). Triangular ski jumps are appealing because they are easier to construct and yield larger throwing distances of the water, as seen in Figure 89, which is better for reducing the possibility of scour holes. More choking, or holding back of water, is present in triangular ski jumps because the water shoots from the spillway at an inclined angle. This also moderates the velocity (Hager, Heller, Minor, & Steiner, 2008). Circular flip buckets do not incorporate a large take off angle.

Figure 88: Circular shaped buckets (Roberson, 2015)

Figure 89: Triangular shaped buckets (Altaf, 2015)

In terms of mathematics, ski jump spillway geometrics are solved through a variety of computational programs or through conventional equations. Computer programs like MATLAB output relevant data. A method called Group Method Data Handling uses many algorithms combined from a number of sources, such as back propagation (locates errors in a network), particle swarm optimization (iterative methods for accuracy), and genetic programming (creates a computer function that can solve high level problems) to accurately predict the amount of scour formed from spilled water (Najafzadeh et al., 2014).

After conducting this research, a detailed outline was given to the ACP for review. The research was discussed, but the contractor decided after performing their own research and looking at geological data that the soil in the Gatun area would be likely to erode. Since the Gatun area is composed of mostly clays and soft rock, having a plunge pool for the ski jump would cause too much erosion and structural problems. Therefore, the ACP decided to use the stepped chute spillway with a concrete-lined channel to significantly diminish the effects of erosion.

4.5.1.2 Flow Velocities on Erosion

Although concrete is more immune to scour than unlined, natural earthen spillways, it is not totally resistant to erosion. Some concretes are better at reducing scour than others. Concrete with larger aggregates have a higher porosity, which lowers compressive strength. Porosity, or permeability, allows water to seep through holes and expand the concrete, causing cracks and uplift of the particles. Higher compressive strength concrete generally consists of finer aggregates, reducing spacing between aggregates for better compaction.

Another concern for the integrity of concrete is weather and the environment it is in. Acidic or alkali environments decompose the surface of concrete. An additional threat to concrete is a bacterium called *Thiobacillus*. Found in warm water environments, this type of bacterium reduces the sulfur in concrete. Originally when concrete is poured, it has a pH level of 12, but neutralizes over time. When the pH reduces to nine, this bacteria starts to degrade the surface of the concrete and make it more susceptible to failure (ACI Committee 210, 1998).

Lastly, two types of erosion that act upon concrete-lined spillway channels and cause problems are cavitation and abrasion. Cavitation is the formation of bubbles in water caused by high velocity travel (Figure 90). When pressure drops and water vapor becomes present, cavities are formed. Cavitation causes severe damage in spillways because of the high velocities. This kind of erosion strips the concrete down to the steel reinforcement and makes the concrete crumble over time, as seen in Figure 90 (ACI Committee 210, 1998).

Figure 90: Cavitation in concrete (ACI Committee 210, 1998)

Abrasion is another concern in concrete-lined spillways. This type of erosion occurs when debris mixes with the spilling water. The effects of abrasion depend on size, shape, quantity, and hardness of the fragments (ACI Committee 210, 1998). After extended periods of time, the concrete becomes pitted, especially in fine-grained types. In order to help reduce abrasion, it is important to clean the concrete after it is constructed and regularly after spilling events.

When water travels down a spillway to its destination, its velocity is naturally reduced by a process called aeration. As water travels downward, air travels upward and forces the velocity of the water to slow. This process helps with scour, but is not powerful enough to sufficiently slow the water. Higher strength concrete also aids in decreasing the amount of erosion. For limiting the effects of cavitation, a lower water to cement ratio, water-reducing admixtures, chilled concrete, and an aggregate size of less than 1.50 in (38 mm) are suggested (Momber & Kovacevic, 1994). The surface should also be as smooth as possible.

4.5.2 Drawings

Once research was complete, AutoCAD drawings were examined. After all borehole locations were inputted into the two AutoCAD drawings supplied by the ACP, the locations were checked against existing infrastructure and utility lines. In total, there were 26 conflicts. The majority of conflicts related to the proposed locations that obstructed a road or building (Figure 91). Only five proposed locations interfered with utility lines. Once each drawing was checked, comments were made in Microsoft Word 2013 about each instance of interference on the ACP Submittal Review Sheet, supplied by the civil engineer. The comment sheet detailed the borehole location, section of the spillway, which INGETEC AutoCAD sheet the problem occurred on, and the reason for the conflict (Figure 92). This review sheet was then e-mailed to the civil engineer and contracting officer for review. Upon their approval and additional comments, the sheet was sent to INGETEC, along with the drawings for changes.

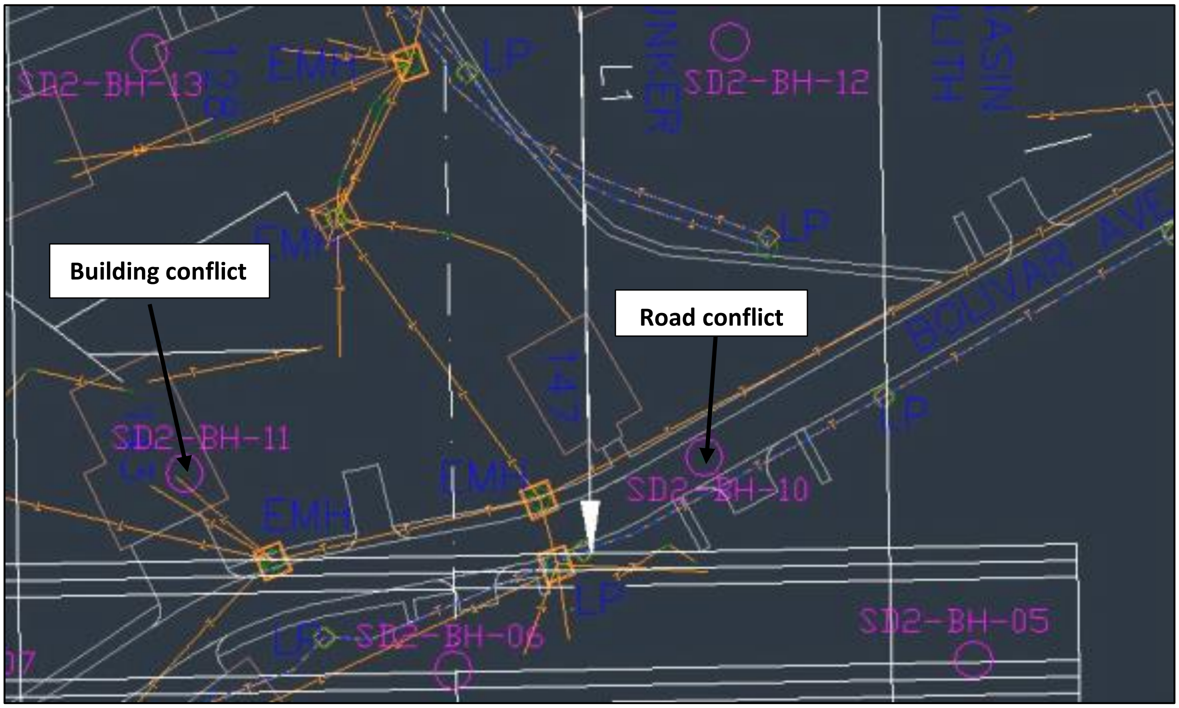

Figure 91: Example of borehole conflicts

CANAL DE PANAMÁ

SUBMITTAL REVIEW SHEET

Project/Contract #	Contract No. SAA-334354	Contractor Document No.	Letter ACP-SD-014	P - Proceed
Date Received	Aug 11, 2015	Submittal Log No.	00290	PN - Proceed as noted
Submittal Title	Geotechnical Exploration Program	Primary (BIC) Reviewer	Mario H. Granados	PR - Proceed as noted, Resubmit
Submittal Reference No.	02 30 00-001	Review Cycle Disposition		DR - Dissaproved and Resubmit

Contracting Officer Approval Req'd: ◉ Yes ○ No — Contracting Officer: Roderick Lee: ____________

Comment Number	Comment Status Code	Submittal Sect. No.	Submittal Page/Fig.	Contract Section Reference	Review Comment	Reviewer's Initials
1		SD1-BH-02	Anexo 3- Figura 2 hoja 3	Geological Boring- South Section	Building Interference (Main Workshop)	CMG
2		SD1-BH-03	Anexo 3- Figura 2 hoja 3	Geological Boring- South Section	Road Interference, move to one side	CMG
3		SD1-BH-05	Anexo 3- Figura 2 hoja 3	Geological Boring- South Section	Building Interference (Washing & Maintenance)	CMG
4		SD1-BH-06	Anexo 3- Figura 2 hoja 3	Geological Boring- South Section	Road Interference, move to one side	CMG

Figure 92: Example of review sheet for borehole conflicts

4.5.3 Excavation Techniques

The crossunders of interest for disposing of material through the pipe are located in the upper chamber locks and are referred to as crossunder 1 and crossunder 2. The upper chamber refers to locks closest to Lake Gatun and nearest to the Isla Represa/Monte Lirio disposal sites. The ACP used these locations to store the material excavated from the new locks. Because the Isla Represa site was used before, there is already a road from the Third Set of Locks, which is an advantage to running the pipe through the crossunder and then along the road to the disposal site.

The first crossunder analyzed was crossunder 1, the closest to the disposal site. Shaped like a U and symmetrical along the y-axis, the crossunder has two vertical uprights that house stairs, an elevator, utility shaft, inspection platforms, and an air shaft on each floor (Figure 93). Electrical ducts, telecommunication lines, and other pipes run the length of the upright along the walls. The vertical uprights of the crossunder reach an elevation of +110.3 ft (+33.6 m) up from level zero, then extend below to an elevation of -45.2 ft (-13.8 m). The horizontal piece of the crossunder rests between the elevations of -20.6 ft (-6.29 m) and -32.8 ft (-9.99 m) (Figure 93). In this piece, there are two electrical vaults on each end, located near the intersection of the vertical uprights and the horizontal piece, as shown in Figure 93. When crossunder 2 was examined, the same features were found.

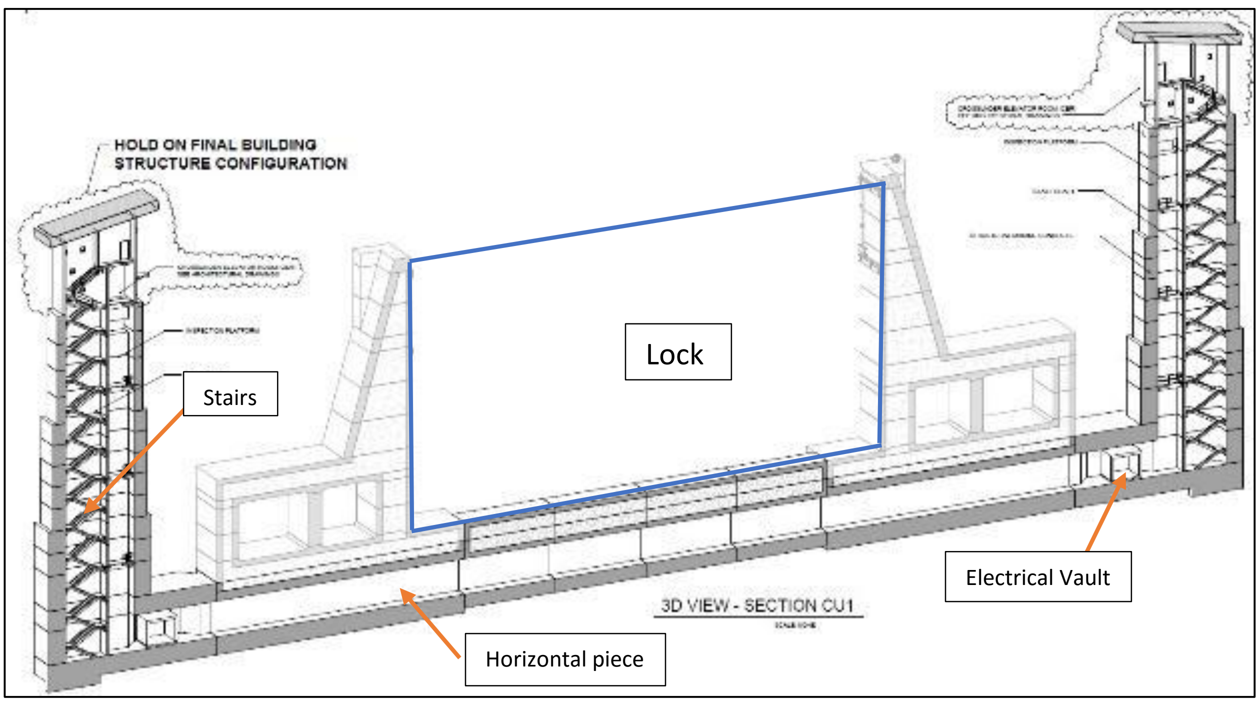

Figure 93: 3D view of crossunder 1 of Upper Chamber (Real, 2010)

The ACP devised two options for running the pipe through the crossunder. The first is to use both the vertical uprights and the horizontal piece to feed the pipe through, to minimize digging. The second option is to use only the horizontal section of the crossunder to run the pipe through, which would require a great deal of extra excavation. However, upon examination of the features of the crossunder, running a pipe through the structure is not feasible. The first option requires the inspection platforms on each floor of the vertical uprights to be punctured by the pipe and there would have to be enough pressure present in the pipe to move the material up the second vertical upright at a 90° angle (Figure 94). If only the second option was utilized, the elevator and air shaft would cause a problem unless the wall between the elevator and air shaft was to be cut through (Figure 95).

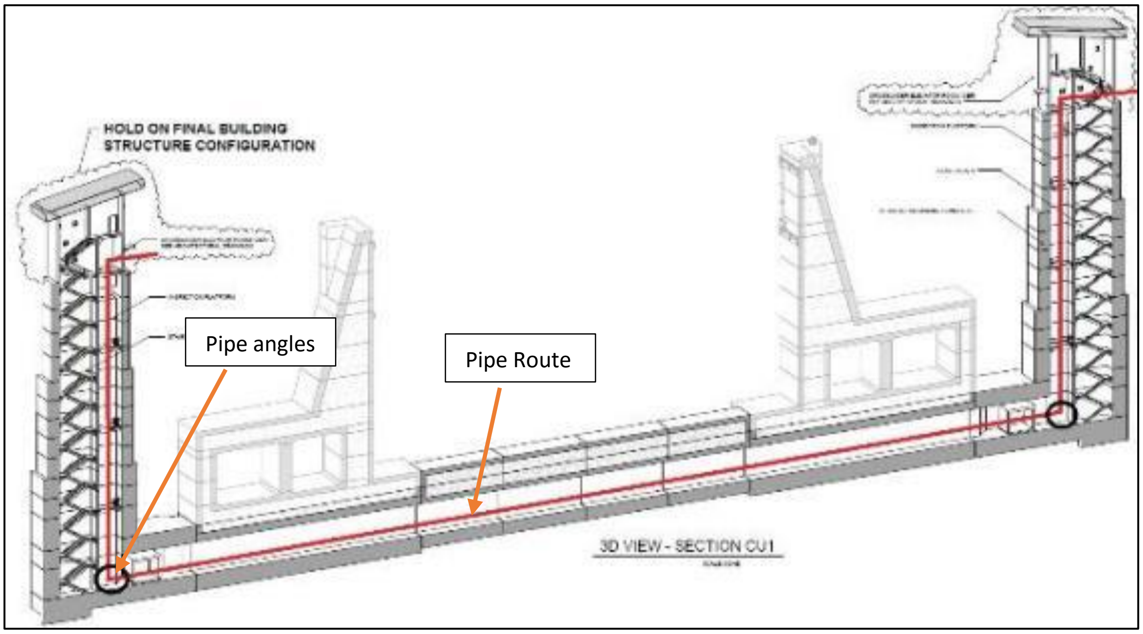

Figure 94: Option 1 (Real, 2010)

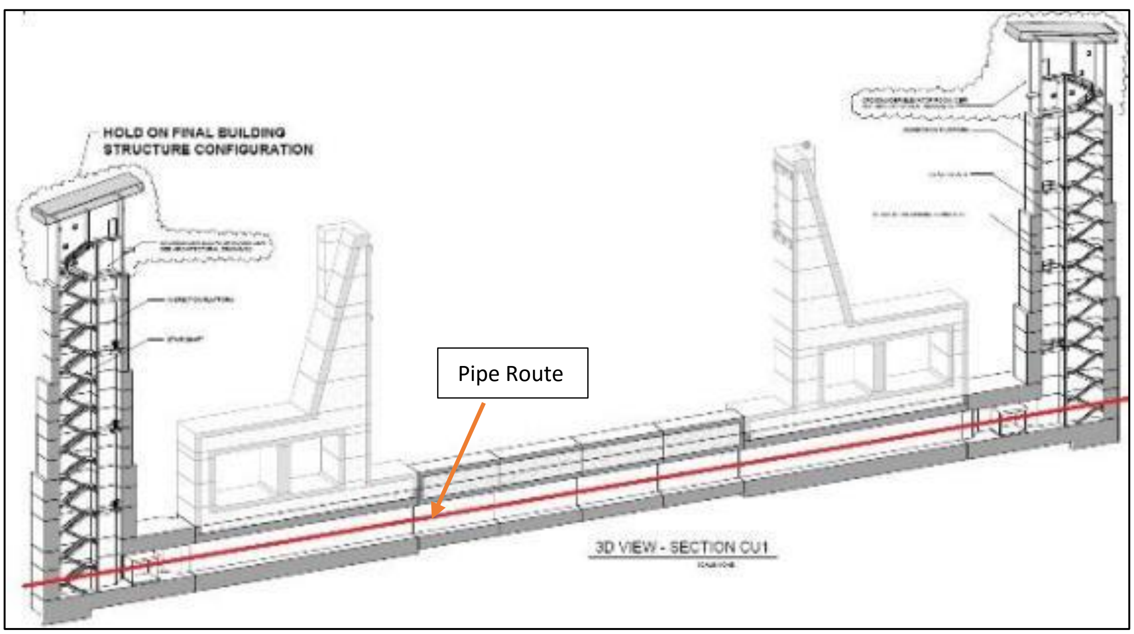

Figure 95: Option 2 (Real, 2010)

Considering these findings, alternative routes were investigated for excavation. The most viable option is to sink the pipe from the spillway site into Lake Gatun to bring the material to Isla Represa/Monte Lirio, a distance of 3.64 miles (5.85 km) (Figure 96). Another route is to sink the pipe under the Gatun locks to the Black Tank South disposal site, a distance of 1.68 miles (2.71 km) (Figure 97). The final closest route entails sinking pipe from the construction site into Limon Bay and transporting the material somewhere close to Isla Telfers, then having trucks haul the material the remaining distance to Isla Telfers, 2.26 miles (3.64 km) away (Figure 98). Sites such as Peña Blanca and Northwest Breakwater are located a distance of 8.70 miles (14 km) and 8.39 miles (13.5 km), respectively, away from the site. These distances are much longer than the other options and are therefore less practical. Barges to bring the excavated material offshore were also considered but in the area of Monte Lirio, there are many tree stumps and trunks buried underwater, which would cause problems for the transportation vessels.

Figure 96: Spillway site to Isla Represa/ Monte Lirio (Mapa General del Canal de Panamá, 2015)

Figure 97: Spillway site to Black Tank (Mapa General del Canal de Panamá, 2015)

Figure 98: Spillway site to Isla Telfers (Mapa General del Canal de Panamá, 2015)

Cost is a factor the ACP must consider for excavation. The cost depends on the quantity of pipes, pumps, and other necessary equipment. A sample pipe excavation cost estimate from the Third Set of Locks is shown in Figure 99. In this figure, the cost of reclamation equipment is listed, which includes mobilization and demobilization of land and submersible pipes. These materials are considered heavy machinery and are therefore very expensive. It is common for connections to spring a leak due to the pressure of the material passing through. In order to maintain the functionality of the pipes, it is important to keep the walls clean and sludge free, to not disturb energy flow. Less friction against the walls of the transport pipe creates fewer issues with buildup, leaks, and other expensive maintenance issues. If possible, less direction and elevation changes are better for keeping friction minimal (Dredge Source, LLC, 2011).

MOBILIZATION AND DEMOBILIZATION COSTS						
PROPOSED BY JAN DE NUL NV	MOB DATE	MOB		DEMOB		TOTAL
CSD	21/Sep/10	$720,000.00	60.0%	$480,000.00	40.0%	$1,200,000.00
BHD IL PRINCIPE	28/May/10	$227,600.00	40.0%	$341,400.00	60.0%	$569,000.00
Small TSHD LE BOUGAINVILLE	31/Jul/10	$420,000.00	60.0%	$280,000.00	40.0%	$700,000.00
Large TSHD FILIPPO BRUNELLESCHI	27/Nov/10	$360,000.00	60.0%	$240,000.00	40.0%	$600,000.00
SHB (Self-Propelled and non Self-Propelled split barges	20/May/10	$510,000.00	60.0%	$340,000.00	40.0%	$850,000.00
DRY PLANT	15/Jan/10	$600,000.00	60.0%	$400,000.00	40.0%	$1,000,000.00
RECLAMATION EQUIPMENT	31/Jan/10	$960,000.00	60.0%	$640,000.00	40.0%	$1,600,000.00
			Average		Average	
		3,797,600.00	57.1%	2,721,400.00	42.9%	6,519,000.00

CSD = Cutter Suction Dredger
TSHD = Trailing Suction Hopper Dredger
BHD = Backhoe Dredger
SHB = Split Hopper Barge
DRY PLANT — Dump truck, excavator, dozer
RECLAMATION EQUIPMENT — Pontoons, tug, floating pipeline, landpipes, submersible pipes, workshop.

Figure 99: Cost for pipes and equipment (Jan De Nul N.V., 2009)

4.6 Conclusions and Recommendations

The BEC Spillway project is scheduled to reach completion in 2019. This report details the preliminary work the ACP and hired contractors are currently undergoing. There are two primary phases of this project: planning and construction. In order to construct a spillway that will have a lifespan of over 100 years, a team consisting of many divisions from the ACP have come together to oversee the project and communicate with the hired design firm, INGETEC. This company is exploring the best design options for the spillway based on location and subsurface investigations. In tandem with INGETEC, the ACP is also looking into different options for the spillway through means of research and feasibility studies.

There are many aspects involved in choosing a spillway design such as location, soil type, seismicity, available materials, ease of construction, and cost. In this project, research was conducted on different types of spillways and how flow velocities affect the erosion of concrete-lined spillways, then discussed with the BEC Spillway Design project team and INGETEC. Because the Gatun region is made of soils such as clay, Atlantic muck, and silt, a stepped chute spillway with energy dissipation basins is being used, for a safer design with limited erosion.

To further reduce erosion, the new spillway channel will be concrete-lined. A higher strength concrete is better at resisting the effects of cavitation and abrasion and is recommended. For an improved compressive strength concrete, a lower water to cement ratio, water-reducing admixtures, and fine grained aggregate are the most effective options. Regular maintenance and inspections of the spillway for erosion are important for keeping the structure in a safe, operable condition and is recommended.

Before beginning construction, the ACP must evaluate different excavation routes for transporting material to disposal sites. The spillway site is located on an island between the existing Gatun Locks and the new Third Set of Locks, posing a problem for truck access to the site. Therefore, other potential options such as using large, steel pipelines or barges to bring the material to pre-approved disposal sites were examined. Upon studying drawings of the site and its utilities, it is recommended that the ACP sink pipelines in Lake Gatun to carry excavated material to the offshore disposal sites. Recommendations for alternative routes for sinking pipes are:

1. BLACK TANK SOUTH – pipe could be run under Gatun Approach then floated to the disposal site through the old French Channel, 1.68 miles (2.71 km)
2. ISLA REPRESA/MONTE LIRIO – pipe could be exposed once under the new locks channel, and run along the road to these disposal sites, 3.64 miles (5.85 km)
3. ISLA TELFERS – pipe sunk in the new locks approach channel, then exposed once under the channel and run along the road to Telfers, 2.26 miles (3.64 km)

When considering cost, mobilization and demobilization of the pipes, land pipes, submersible pipes, pumps, and maintenance are included in the estimate. These costs can easily reach over $1 million depending on selected routes and the amount of direction changes along the path.

In addition to methods of transporting excavated material, the ACP must also decide how to move other necessary materials to the site, such as concrete. If concrete trucks are not permitted to cross the new locks, other possible options include placing a batching facility on-site or transporting the concrete on barges to the island from nearby. Despite the option chosen by the ACP, the water to cement ratio must be checked frequently, especially if the concrete has a longer distance to travel.

This project encompasses a variety of research and information in relation to the construction of the new spillway. By providing the ACP with this material, the best design for the spillway was determined to be a stepped chute. Additionally, revisions of technical drawings for boreholes assisted the ACP and INGETEC in planning geological sampling in approved locations. This project also evaluated many possible options for pipe excavation routes. Although alternatives were given, costs for each route are difficult to determine without exact information on pipes and pumps. Therefore, more research should be done on pipe excavation by the ACP in order to prepare an accurate cost estimate and choose the best route(s).

In 2017, construction of the BEC Spillway Design project will begin. When it is completed, the level of Lake Gatun will be regulated by means of two spillways and lock culverts, if necessary. By having two structures to release water in the event of flooding, some pressure is released from both spillways, helping to extend their usable lifetimes.

Conclusion

Over the course of three months, the team completed four projects in conjunction with the ACP. With the completion of the projects outlined in this paper, the team seeks to contribute and develop ACP efforts towards sustainability and efficiency of the Canal. The team worked alongside professionals in several divisions of the ACP; specifically, in the Corporate Affairs (CO), Project Administration (IAP), and the Energy, Water, and Environmental Departments (EAA). Employees from the ACP offered invaluable guidance and assistance that contributed towards the completion of these projects.

These projects were created as a result of the expansion project and aligned with the ACP corporate mission of benefiting business, customers, country, and people. The four projects have withstanding positive impacts on society, sustainability, and technology. The first project supports the preservation of the land around Lake Gatun for any future development of the Canal. The next project, regarding alternative range tower structures, proposes improvements to ensure safe transit for customers and vessels through the Canal. The third project stresses the importance of supplying potable water to tugboats for the health and safety of the ACP employees. The final project aims to control the water level of Lake Gatun to guarantee continual supply of water for the operation of the Canal. Collectively, these projects have positive impacts on the environment, society, and safe transit of the Panama Canal to assure global operations.

The work carried out by these projects was not only beneficial to the ACP, but the experience was also critical to the team's undergraduate education. The completion of these projects fulfilled the requirements of WPI's design criteria for the Accreditation Board for Engineering and Technology. The team's final recommendation is to strengthen the link between the ACP and WPI through continued innovative student projects. This partnership has benefited both organizations to solve world problems using technology and collaboration between students and professionals.

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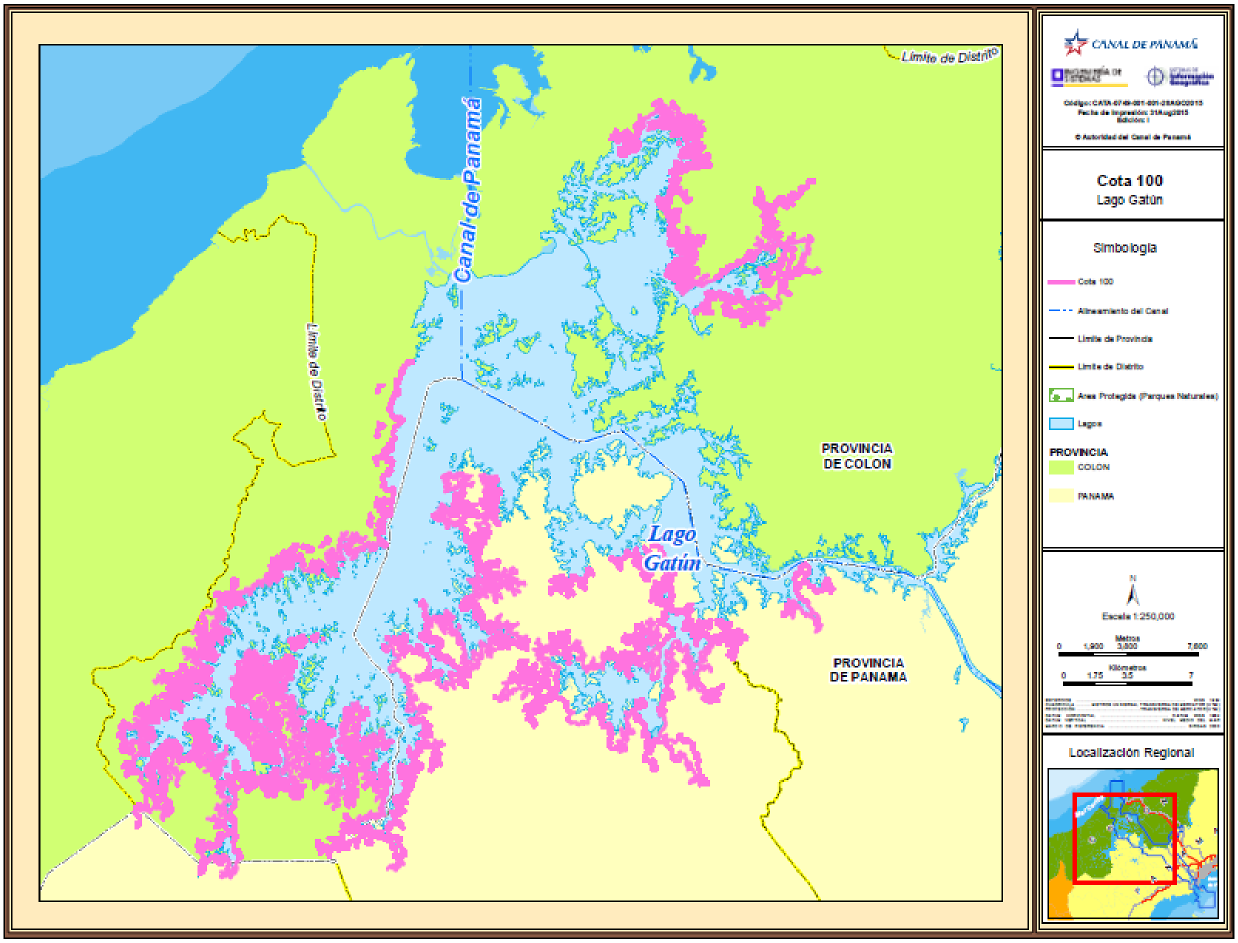
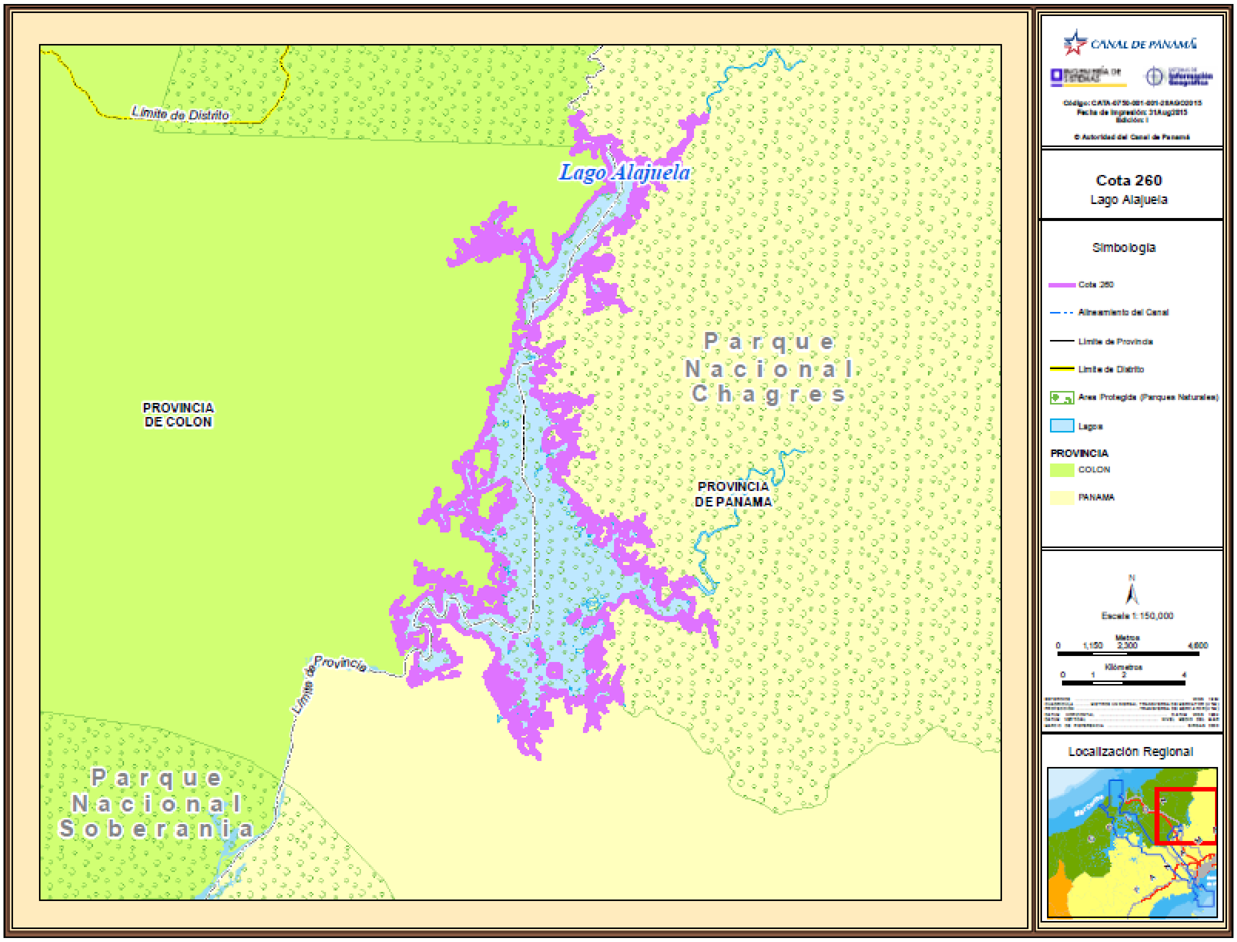
Appendix A

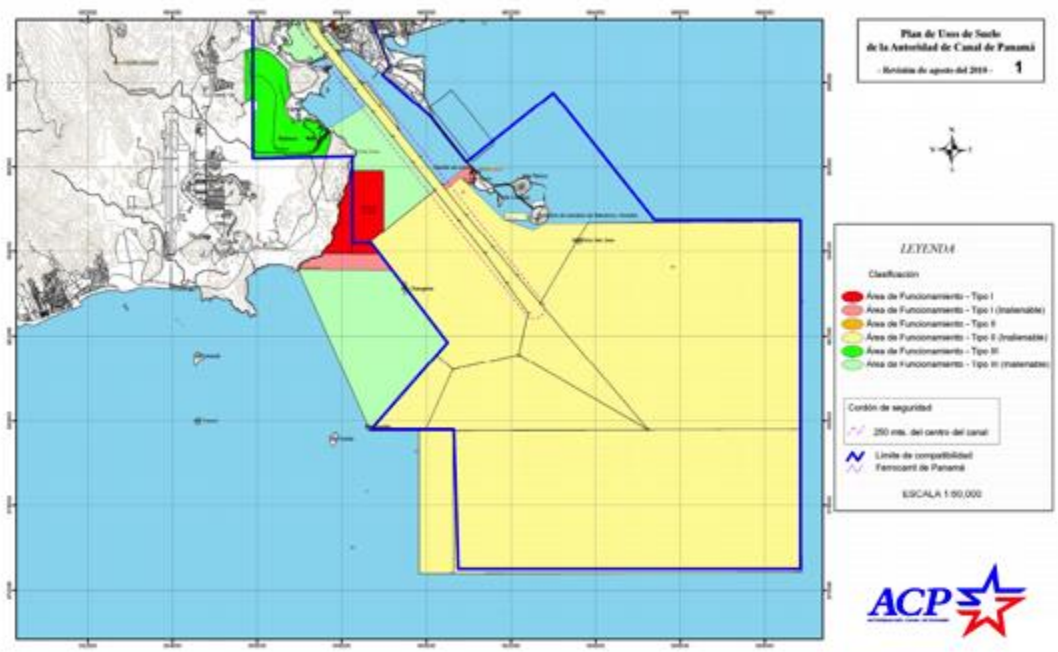


Canal de Panamá
Límite de Distrito
Límite de Distrito
PROVINCIA DE COLON
PROVINCIA DE PANAMA
Lago Gatún
CANAL DE PANAMÁ
Cota 100
Lago Gatún
Simbología
Cota 100
Alineamiento del Canal
Límite de Provincia
Límite de Distrito
Area Protegida (Parques Naturales)
Lagos
PROVINCIA
COLON
PANAMA
Escala 1:250,000
Metros
0 1,900 3,800 7,600
Kilómetros
0 1.75 3.5 7
Localización Regional


Límite de Distrito
Lago Alajuela
Parque Nacional Chagres
PROVINCIA DE COLON
PROVINCIA DE PANAMA
Límite de Provincia
Parque Nacional Soberania
CANAL DE PANAMÁ
Cota 260
Lago Alajuela
Simbología
Cota 260
Alineamiento del Canal
Límite de Provincia
Límite de Distrito
Área Protegida (Parques Naturales)
Lagos
PROVINCIA
COLON
PANAMA
N
Escala 1:150,000
Metros
0 1,150 2,300 4,600
Kilómetros
0 1 2 4
Localización Regional

Appendix B

This map is an example of the different types of land categorizations, at the Pacific entrance to the Canal.



Appendix C

ISO Standard 5667-1*: 2006*, *Water quality -- Sampling -- Part 1: Guidance on the design of sampling programmes and sampling techniques*

> "[S]ets out the general principles for, and provides guidance on, the design of sampling programmes and sampling techniques for all aspects of sampling of water (including waste waters, sludges, effluents and bottom deposits)" (International Organization for Standardization, 2006).

Environmental Protection Agency Method 180.1: *Determination of Turbidity by Nephelometry*

> "The method is based upon a comparison of the intensity of light scattered by the sample under defined conditions with the intensity of light scattered by a standard reference suspension. The higher the intensity of scattered light, the higher the turbidity. Readings, in NTU's, are made in a nephelometer designed according to specifications given in Sections 6.1 and 6.2. A primary standard suspension is used to calibrate the instrument. A secondary standard suspension is used as a daily calibration check and is monitored periodically for deterioration using one of the primary standards" (EPA, 1993).

ISO Standard 7393-2: 1985*, Water quality – Determination of free chlorine and total chlorine – Part 2: Colorimetric method using N,N-diethyl-1,4-phenylenediamine, for routine control purposes*

> "Specifies a procedure for water, readily applicable to field testing; it is based on measurement of the colour intensity by visual comparison of the colour with a scale of standards which is regularly calibrated. Sea water and waters containing bromides and iodides comprise a group for which special procedures are required. The procedure is applicable to concentrations, in terms of chlorine, from 0,000 4 to 0,07 mmol/l total chlorine and at higher concentrations by dilution of samples. Interferences of the procedure are noted" (International Organization of Standardization, 1985).

ISO Standard 9308-1: 2014*, Water quality -- Enumeration of Escherichia coli and coliform bacteria -- Part 1: Membrane filtration method for waters with low bacterial background flora*

> "[S]pecifies a method for the enumeration of *Escherichia coli* (*E. coli*) and coliform bacteria. The method is based on membrane filtration, subsequent culture on a chromogenic coliform agar medium, and calculation of the number of target organisms

in the sample. Due to the low selectivity of the differential agar medium, background growth can interfere with the reliable enumeration of *E. coli* and coliform bacteria, for example, in surface waters or shallow well waters. This method is not suitable for these types of water" (International Organization of Standardization, 2014).

Appendix D

LMT1				
Date	**Turbidity**	**Residual Chlorine**	**Total Coliforms**	**E.coli**
13-May	0.15	0.36	0.00	0.00
18-May	0.27	0.73	0.00	0.00
27-May	0.28	0.35	0.00	0.00
9-Jun	0.48	1.01	0.00	0.00
25-Jun	0.62	1.00	0.00	0.00
14-Jul	0.78	1.14	0.00	0.00
22-Jul	0.62	1.03	0.00	0.00

LMT2				
Date	**Turbidity**	**Residual Chlorine**	**Total Coliforms**	**E.coli**
13-May	0.24	0.54	0.00	0.00
18-May	0.37	0.93	0.00	0.00
27-May	0.26	0.68	0.00	0.00
9-Jun	0.55	1.03	0.00	0.00
25-Jun	0.47	0.95	0.00	0.00
14-Jul	0.98	1.24	0.00	0.00
22-Jul	0.72	1.01	0.00	0.00

LPT1				
Date	**Turbidity**	**Residual Chlorine**	**Total Coliforms**	**E.coli**
13-May	0.63	0.43	0.00	0.00
18-May	1.09	0.54	0.00	0.00
27-May	0.36	0.8	0.00	0.00
9-Jun	0.57	0.83	0.00	0.00
25-Jun	0.45	1.42	0.00	0.00
14-Jul	0.79	0.96	0.00	0.00
22-Jul	0.79	0.96	0.00	0.00

LPT2				
Date	**Turbidity**	**Residual Chlorine**	**Total Coliforms**	**E.coli**
13-May	0.39	0.43	0.00	0.00
18-May	1.69	0.64	0.00	0.00
27-May	0.48	0.79	0.00	0.00
9-Jun	0.67	0.86	0.00	0.00
25-Jun	0.47	1.16	0.00	0.00
14-Jul	0.93	0.96	0.00	0.00
22-Jul	0.93	0.96	0.00	0.00

LGA1				
Date	**Turbidity**	**Residual Chlorine**	**Total Coliforms**	**E.coli**
12-May	0.62	0.21	0.00	0.00

LGA3				
Date	**Turbidity**	**Residual Chlorine**	**Total Coliforms**	**E.coli**
12-May	0.43	0.36	0.00	0.00

LGA4				
Date	**Turbidity**	**Residual Chlorine**	**Total Coliforms**	**E.coli**
12-May	0.22	0.03	0.00	0.00

LGA5				
Date	**Turbidity**	**Residual Chlorine**	**Total Coliforms**	**E.coli**
12-May	0.14	0.04	0.00	0.00

LGT1				
Date	**Turbidity**	**Residual Chlorine**	**Total Coliforms**	**E.coli**
21-May	0.63	1.47	0.00	0.00
28-May	0.53	0.94	0.00	0.00
4-Jun	0.36	0.62	0.00	0.00
8-Jun	0.52	1.04	0.00	0.00
16-Jun	0.37	0.87	0.00	0.00
19-Jun	0.32	1.03	0.00	0.00
17-Jul	0.45	0.86	0.00	0.00
28-Jul	0.47	0.73	0.00	0.00
10-Aug	0.23	1.07	0.00	0.00
11-Aug	0.43	0.94	0.00	0.00
3-Sep	0.51	0.88	0.00	0.00
9-Sep	0.55	0.66	0.00	0.00

LGT2				
Date	**Turbidity**	**Residual Chlorine**	**Total Coliforms**	**E.coli**
21-May	0.54	1.23	0.00	0.00
28-May	0.45	0.99	0.00	0.00
4-Jun	0.32	0.92	0.00	0.00
8-Jun	0.46	1.09	0.00	0.00
16-Jun	0.34	0.87	0.00	0.00
19-Jun	0.33	1.06	0.00	0.00
17-Jul	0.45	0.86	0.00	0.00
28-Jul	0.52	0.77	0.00	0.00
10-Aug	0.21	0.98	0	0
11-Aug	0.44	0.81	0	0
3-Sep	0.48	0.88	0	0
9-Sep	0.61	0.65	0	0

LDT1				
Date	**Turbidity**	**Residual Chlorine**	**Total Coliforms**	**E.coli**
21-May	0.74	1.26	0.00	0.00
28-May	0.45	1.27	0.00	0.00
4-Jun	0.25	0.81	0.00	0.00
8-Jun	0.44	0.54	0.00	0.00
16-Jun	0.53	1.14	0.00	0.00
19-Jun	0.42	0.08	0.00	0.00
17-Jul	0.34	0.84	0.00	0.00
28-Jul	**	**	0.00	0.00
10-Aug	0.74	0.89	0	0
11-Aug	0.36	0.8	0	0
3-Sep	0.62	0.38	0	0
9-Sep	0.59	0.33	0	0

*Water was not tested for this parameter on this day

LDT2				
Date	**Turbidity**	**Residual Chlorine**	**Total Coliforms**	**E.coli**
21-May	0.75	1.6	0.00	0.00
28-May	0.40	1.37	0.00	0.00
4-Jun	0.30	0.79	0.00	0.00
8-Jun	0.48	0.52	0.00	0.00
16-Jun	0.51	1.12	0.00	0.00
19-Jun	0.43	0.42	0.00	0.00
17-Jul	0.33	0.82	0.00	0.00
28-Jul	**	**	0.00	0.00
10-Aug	0.93	0.86	0	0
11-Aug	0.36	0.83	0	0
3-Sep	0.68	0.44	0	0
9-Sep	0.62	0.3	0	0

*Water was not tested for this parameter on this day

Appendix E

Statistical Analysis of Turbidity Results: Landings					
Location	**Low**	**Mean**	**High**	**St. Deviation**	**n**
LMT1	0.15	0.46	0.78	0.23	7
LMT2	0.24	0.51	0.98	0.27	7
LPT1	0.36	0.67	1.09	0.25	7
LPT2	0.39	0.79	1.69	0.45	7
LGT1	0.23	0.45	0.63	0.11	8
LGT2	0.21	0.43	0.61	0.11	8
LDT1	0.25	0.50	0.74	0.16	7
LDT2	0.3	0.53	0.93	0.20	7

Statistical Analysis of Residual Chlorine Results: Landings					
Location	**Low**	**Mean**	**High**	**St. Deviation**	**n**
LMT1	0.35	0.80	1.14	0.33	7
LMT2	0.54	0.91	1.03	0.23	7
LPT1	0.43	0.85	1.42	0.32	7
LPT2	0.43	0.83	1.16	0.24	7
LGT1	0.62	0.93	1.47	0.22	8
LGT2	0.65	0.93	1.23	0.16	8
LDT1	0.08	0.76	1.27	0.39	7
LDT2	0.3	0.82	1.6	0.41	7

Appendix F

Water Quality Results: R-VER				
Date	Parameter			
	Turbidity	Residual Chlorine	Total Coliforms	E.coli
2-Jun	-	1.06	-	-
3-Jun	-	0.97	-	-
4-Jun	-	0.49	-	-
5-Jun	-	0.25	-	-
9-Jun	-	0.06	-	-
10-Jun	-	1.58	-	-
11-Jun	-	1.07	-	-
12-Jun	-	0.63	-	-
13-Jun	-	0.3	-	-
14-Jun	-	0.22	-	-
15-Jun	-	0.17	-	-
26-Jun	-	1.21	-	-
27-Jun	-	1.07	-	-
28-Jun	-	0.73	-	-
29-Jun	-	0.28	-	-
30-Jun	-	0.03	-	-
3-Jul	-	1.55	-	-
4-Jul	-	1.08	-	-
5-Jul	-	0.74	-	-
6-Jul	-	0.4	-	-
7-Jul	-	0.22	-	-
8-Jul	-	0.1	-	-
9-Jul	-	0	-	-
24-Jul	0.48	1.08	0	0
25-Jul	0.6	0.61	0	0
26-Jul	0.83	0.33	0	0
27-Jul	0.73	0.09	0	0

Water Quality Results: R-GUÍA				
Date	Parameter			
	Turbidity	Residual Chlorine	Total Coliforms	E.coli
24-Jul	0.8	0.8	0	0
25-Jul	13	0.25	0	0
26-Jul	9.24	0	6	0
27-Jul	*	0	*	*
30-Jul	4.05	0.55	0	0
31-Jul	3.3	0	0	0
5-Aug	2.57	2.93	0	0
6-Aug	4.51	1.18	0	0
7-Aug	2.52	0.83	0	0
25-Aug	*	3.42	*	*
26-Aug	0.84	5.13	0	0
28-Aug	1.26	0.53	0	0
29-Aug	0.97	0.13	0	0

*Water was not tested for this parameter on this day

Appendix G

Statistical Analysis of Results from R-VER					
Parameter	**Low**	**Mean**	**High**	**Std. Deviation**	**n**
Turbidity	0.48	0.66	0.83	0.15	4.00
Residual Chlorine	0	0.60	1.58	0.48	27.00
Total Coliforms	0	0.00	0	*	4
E.coli	0	0.00	0	*	4

*No standard deviation since all results are equal

Statistical Analysis of Results from R-GUÍA					
Parameter	**Low**	**Mean**	**High**	**Std. Deviation**	**n**
Turbidity	0.8	3.91	13	3.88	11.00
Residual Chlorine	0	1.21	5.13	1.60	13.00
Total Coliforms	0	0.55	6	1.81	11.00
E.coli	0	0.00	0	0.00	11.00

Appendix H

Panama Canal Maritime Safety Standards 2600SEG-307

1. Completely drain all of the water from the water distribution system, including storage tanks, and all lines, valves, keys and pumps. Then, close all valves and faucets.
2. Fill one-third of the storage tank with fresh water provided at the Panama Canal landings.
3. Prepare a five gallon bucket with 0.22 pounds (100 grams) of hypochlorite calcium solution (HTH) per 1000 gallons (3785.41 liters) of water. Dissolve all the HTH and pour the solution into the tanks.
4. Fill the remainder of the storage tank with potable water by immersing the hose about two feet under the surface of the water to improve the uniformity of the solution.
5. Open all faucets and valves of the water distribution system and check that a water solution containing 50 ppm of residual chlorine is flowing from all outputs. When this is confirmed, close all exits of the system for 24 hours.
6. Replenish the tank with a 50 ppm residual chlorine water solution.
7. Drain the entire water distribution system again.
8. Verify that chlorine consumption is less than 75% of the initial 50 ppm concentration. If chlorine decay has exceeded 75%, repeat the disinfection process.
9. If disinfection was successful, rinse the entire water distribution system by filling the tank with fresh water and draining until the water contains a residual chlorine concentration of greater than or equal to 2 ppm.
10. Refill the storage tank and allow the water to cool and let stand for 16 hours. Then, coordinate with the Miraflores Water Treatment Plant to sample and verify the water quality aboard the boat.

Appendix I

The document on the following pages is the Drinking Water Management Plan designed and developed by the project in Chapter 3: Assurance of Drinking Water Quality on Tugboats.

Panama Canal Tugboats

Drinking Water Management Plan

Adrienne Weishaar

On February 25, 2015, the Quality Water Division of the Energy, Environment, and Water Unit (EAA-CA) at the ACP established a new plan for the assessment of potable water quality on tugboats of the Panama Canal. The following management plan was designed based on established health targets, results of a drinking water system assessment, and proposed control measures outlined by this report.

Health Target Parameters

Turbidity:	Less than 1.00 NTU
Residual Chlorine:	Between 0.80-1.50 ppm
Total Coliforms:	Less than 1 colony per 100 mL sample
Escherichia Coli:	Less than 1 colony per 100 mL sample

Sampling Location and Frequency

Water should be collected from all takes at all five tugboat landings along the Panama Canal and from the water distribution system aboard the tugboat. The landings include Miraflores, Paraiso, Gamboa, Gatun, and Davis. At each take, water should be collected and tested directly from the faucets and from the hoses. It is recommended that water be sampled and tested at a location where consumers are likely to retrieve water.

Water should be collected and sampled after filling the tanks and several days after to ensure residual chlorine levels are being maintained within the health targets.

Sampling and Assessment Methods

Water Sampling

Equipment:

1- 100 mL collection container

1- 100 mL sterile collection container

1- Cooler

Procedure:

1. Turn on the water system to maximum flow and let the water run for five minutes before collecting a sample.
2. After five minutes, rinsed the collection bottle for testing residual chlorine and turbidity three times by the faucet water before collecting a 100mL sample. After collecting the sample, tightly screw back on the cap.

3. Immediately fill the sterile collection bottle for microbiological tests, without rinsing, after removing the sterilized seal.
4. Transport samples to the lab in coolers as to minimize factors that may alter the results of water testing

Turbidity Testing

Equipment:

1- Turbidimeter

1- Sample Cell

Procedure:

1. Fill the sample cell provided with the Turbidimeter to the line etched on the outside of the cell and replaced the cap.
2. Wipe the outside of the sample cell to remove any water residue or finger prints.
3. Place the sample cell into the instrument cell compartment of the Turbidimeter and close the cover.
4. The Turbidimeter will display a reading of the turbidity of the sample.

Residual Chlorine Testing

Equipment:

1- Spectrophotometer

1- Syringe

1- 50 mL plastic beaker

1- Phosphate buffer

1- N,N-diethyl-p-phenylenediamine (DPD)

1- 1 cm sample cuvette

Procedure:

1. Rinse a syringe three times with water from the 100 mL sample, then collected 10 mL and empty the contents of the syringe into a 50 mL plastic beaker.
2. Add 0.5 mL of phosphate buffer and 0.5 mL N,N-diethyl-p-phenylenediamine (DPD) to the 10 mL sample of water.
3. Depending on the amount of residual chlorine, the water will begin to change to a red color. A deeper red corresponds to a higher residual chlorine concentration.
4. Swirl the sample for 10-15 seconds and then pour the solution into a 1 cm sample cuvette.
5. Wipe the outside of the cuvette to remove any water residue or fingerprints and insert the cuvette into the vacuum sealed compartment of the spectrophotometer.
6. The spectrophotometer will print a reading of the residual chlorine of the water sample.

Microbial Tests

Equipment:

1- Sterile membrane

1- Agar plate

1- Incubator

Procedure:

1. Filter 100 mL of water through a sterile membrane.
2. Cautiously place the membrane into an agar plate, and incubate the sample for 24 hours at 95-98.6° F (35–37 °C).
3. If no colonies develop after 24 hours of incubation at this temperature then the water is not contaminated with total coliforms or E.coli. However, if the presence of total coliforms is indicated, then the sample must be incubated for another 24 hours at 111.2-113° F (44–45 °C).
4. If the water sample is harboring E.coli, then the sample will develop coliforms on the media at this temperature.

Schedule for Sampling and Assessment

Water should be sampled and assessed after every time the tank is filled. Additionally, the water should be tested several days after filling the tank to ensure that the water is maintaining residual chlorine levels.

Quality Assurance and Validation of Results

It is vital to frequently test the water quality from the potable water tanks on the tugboats to ensure that the potable water system is delivering drinkable water in terms of the established health targets. When water quality tests reveal that the water does not meet health targets, the water should be drained and refilled with fresh water. After refilling, the water must be tested again. If the health targets are still not met, then the system should be cleaned in accordance with the Panama Canal Maritime Safety Standards 2600SEG-307 titled, *Maritime Safety Standard Cleaning Procedure for Drinking Water Storage Tanks Aboard Floating Equipment*. After cleaning, retest the water, and if the health targets are still not met, then control measures should be taken to clean and epoxy paint the interior walls of the potable water storage tanks. Then, water should be collected and tested once more. If health targets are still not met then a full system assessment and investigation should be carried out.

Also, since time was a constraint of this project, water should continue to be collected and tested from the landings to ensure that the water used to fill the potable water storage tanks meet health targets.

Checking and Interpreting Results

All water tests should be carried out by a trained chemist of the ACP. If the conductor of the tests notice a trend in the system to not meet health targets, further control measures should be investigated.

Documentation and Management of Results

All water quality results should be recorded in a laboratory notebook specifically for documenting results of this project. The notebook should identify whether the sample was collected from a tugboat or landing, which tugboat or landing, the date the sample was collected, the date the sample was tested, and the results for turbidity, residual chlorine, total coliforms, and *E. coli*. Also, dates that the potable water tanks were drained, cleaned or painted should be recorded. Additionally, all data should be copied into Excel for data interpretation. On the next page, there is a template for documenting results.

Reporting and Communicating Results

Monthly meetings should be held between the ACP divisions assigned to assuring the water quality on the Panama Canal tugboats. At the meetings, water quality results ought to be reviewed and any trends or hazards must be identified. If any hazards arise in the drinking water quality, potential control measures should be discussed and actions taken to improve the potable water quality.

Panama Canal Tugboat Water Quality Documentation

Collector:	Collection Location:

Dates Tank Drained

Dates Tank Cleaned

Dates Tank Painted

Water Quality Testing					
		Results			
Date Collected	Date Tested	**Turbidity (NTU)**	**Residual Chlorine (ppm)**	**Total Coliforms**	***E. coli***

Notes:

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Date Recorded into Excel:	Initials: