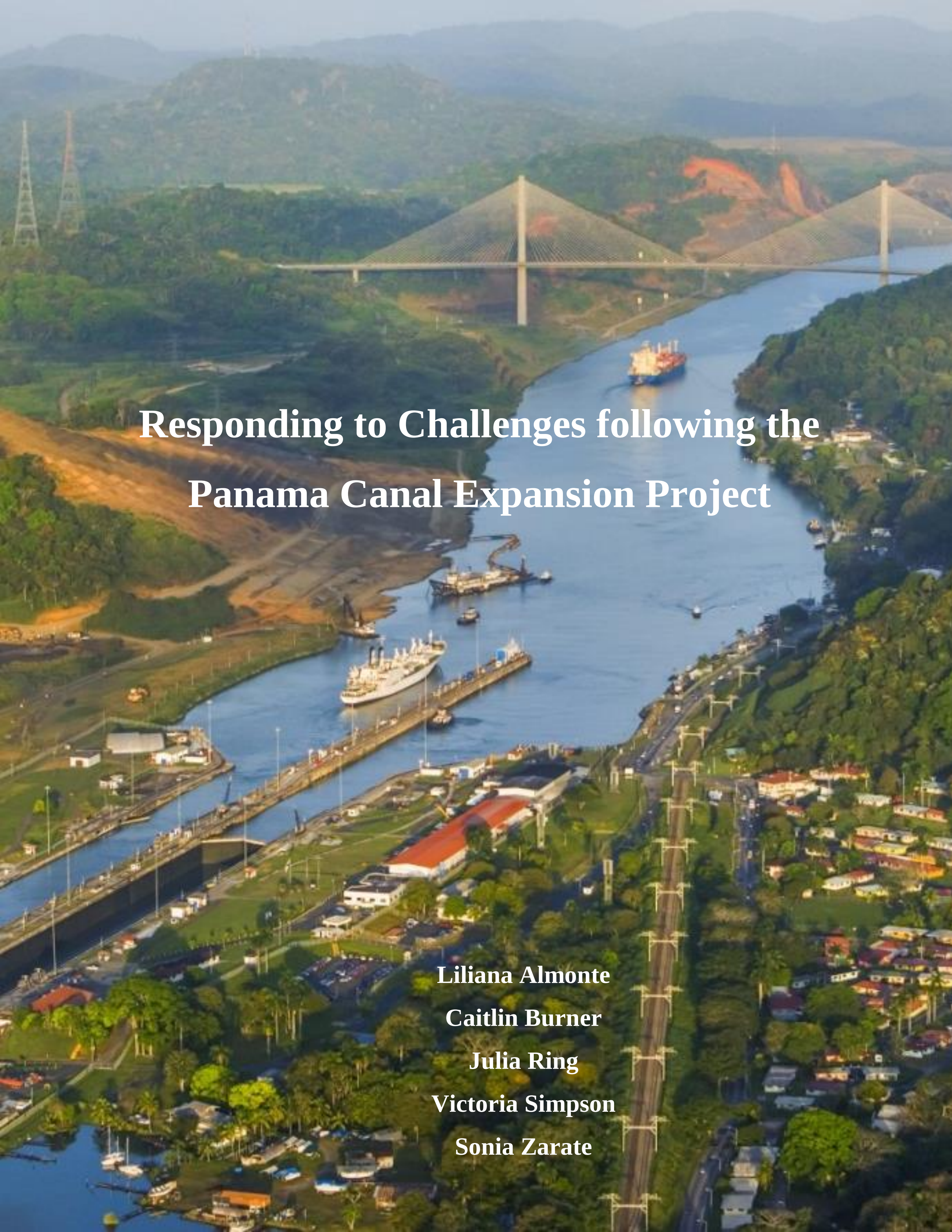

Responding to Challenges following the Panama Canal Expansion Project

Liliana Almonte

Caitlin Burner

Julia Ring

Victoria Simpson

Sonia Zarate

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A Major Qualifying Project Report:

Submitted to the faculty of the

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in partial fulfillment of the requirements for the

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in cooperation with the Autoridad del Canal de Panamá

Submitted October 14, 2016

Submitted By:

Liliana Almonte

Caitlin Burner

Julia Ring

Victoria Simpson

Sonia Zarate

Project Advisors:

Dr. Aaron Sakulich

Dr. Tahar El-Korchi

Abstract

The Panama Canal has shaped the global shipping industry since 1914, but recently expanded its operations to respond to increasing world trade. Projects completed in collaboration with the Autoridad del Canal de Panamá over the course of three months in Panama focused on the treatment of potable water originating in the canal and the maintenance of its aging structures following the expansion. Recommendations were provided to aid in preserving the sustainability of the canal.

Authorship

In order to achieve the collaborative writing goals set forth by the Worcester Polytechnic Institute (WPI) Major Qualifying Project (MQP) guidelines, the team adopted a methodology by which the alternative roles of writer and editor were assumed by each member. While different subsections of the report were written individually, all five students critically reviewed their teammates' writing, editing the sections to improve clarity, tone, and the overall flow of the report. This ensured equal contribution and a cohesive voice throughout the paper.

The four projects presented in this report were grouped into two chapters; one focused on water purification, and the other focused on dams and spillways. Within the water purification chapter, Liliana Almonte and Sonia Zarate completed the project entitled *Analysis of Chemical Consumption Patterns at Miraflores Filtration Plant*, and Julia Ring completed the project entitled *Process Analysis of Mount Hope Water Filtration Plant*. Within the dams and spillways chapter, Caitlin Burner completed the project entitled *Evaluation of the ACP's Formal Inspection Program of Dams and Spillways*, and Victoria Simpson completed the project entitled *Risk Analysis of Madden Dam and Spillway Drum Gates*. The background, methodologies, results, analyses, conclusions, and recommendations for each of the four separate projects were written by the respective student researchers.

Acknowledgments

This report was made possible through the help, guidance, and support of the many people met through our time working with the Autoridad del Canal de Panamá (ACP – Panama Canal Authority). Each person played an important role in our efforts to adapt to a new culture and our development as young professional engineers. To our WPI advisor, Dr. Aaron Sakulich, thank you for your constant advice, criticism, and feedback on our report. This work was partially funded by Grant #1357667, made available by the National Science Foundation's Office of International Science and Engineering, titled "IRES: Environmental Impact of the Panama Canal Expansion Project" (PI: Aaron Sakulich). Additionally, thank you to Dr. Tahar El-Korchi for offering your support throughout the development of our projects. To our ACP supervisors, Patricio Lyew, Roberto Bruno, Marietta Ng, and Ana Lucía Lim Cárdenas, thank you for welcoming us to your teams, inviting us to field visits to see incredible civil engineering structures, and providing answers to all of our questions. To our many friends met through work, thank you for giving us tips about your beautiful country, making us feel at home and part of the ACP family. Additionally, we would like to thank:

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Thank you for going out of your way to answer our questions, helping our projects develop, and providing a home for us during this incredible opportunity.

Licensure Statement

Professional licensure certifies that a person is qualified to create, sign, and seal engineering designs. In addition to having the ability to perform their engineering responsibilities thoroughly and to a high standard of quality, Professional Engineers (PEs) are also expected to work carefully and ethically. Licensure indicates a certain level of competency, experience, and expertise. It allows others to confidently put their trust in the PE's work (National Society of Professional Engineers, 2016).

Professional licensure is important on several levels, including to the individual, to the profession, and to the public. For the individual engineer, a PE License opens the door to promotions within their current companies and better job opportunities in their respective fields. For the engineering profession, PE Licenses provide credibility. By mandating licensure restrictions, engineers are held to a high standard, allowing the engineering profession to be regarded with respect. For the public, PE Licenses ensure a degree of safety. PE licensure is required to practice legally, and if an engineer wishes to maintain their license, they must adhere to industry-set regulations and safety restrictions when designing and approving plans (National Society of Professional Engineers, 2016).

In the United States of America, PE licensure is regulated by the National Council of Examiners for Engineering and Surveying (NCEES). The exact requirements necessary to earn a PE License varies on a state-by-state basis; however, there are four main conditions to be met that are mandatory across the country. First, the individual seeking the license must have attended and received a bachelor's degree from a university accredited by the Engineering Accreditation Commission (EAC) or Accreditation Board for Engineering and Technology, Inc. (ABET) (NCEES). These two organizations certify that education programs properly prepare their students for the workforce (ABET). Next, the individual must pass the Fundamentals of Engineering (FE) exam geared towards their specific engineering field, earning them the title of Engineer Intern (EI) or Engineer-in-Training (EIT). The FE exam is a six hour, 110 multiple-choice question test given over computer that evaluates a spectrum of topics that an engineer must be proficient in to pass. After passing the FE exam, an EIT must work under the supervision of a PE for a minimum of four years. Finally, the EIT must pass the Principles and Practice of Engineering (PE) exam, an eight hour, open-book test that evaluates an individual's "ability to practice in a particular engineering discipline completely" (NCEES). Once all of these requirements are accomplished, in addition to the various ones set by the state, the EIT will be awarded their PE License. Each PE has their own assigned number that appears on their license and seal for identification and verification purposes. In order to maintain a PE License, one must continue taking courses and engaging in opportunities that will further educate and improve their engineering skills (National Society of Professional Engineers, 2016).

In Panama, licensure is regulated by the government entity Junta Técnica de Ingeniería y Arquitectura (JTIA - Technical Board of Engineering and Architecture). Similar to NCEES in the U.S., JTIA is the only body that can certify a Panamanian engineer. In order to receive their Certificado de Idoneidad (Certificate of Suitability), a graduate must first submit their diploma to the Universidad de Panamá (University of Panama) for review. The individual is not required to be a Universidad de Panamá graduate to seek certification. The university verifies that the diploma and respective school are both credible. For graduates that studied outside of Panama, extra stamps of approval from organizations in the U.S. must be included as well. The university checks that the proper number of credits were met and that the proper types of courses were taken by the student. Once the paperwork is cleared, the Universidad de Panamá sends the information to JTIA for processing. While graduates are not required to wait a certain number of years before applying for certification, like in the U.S., the approval process can take up to one year to complete. During this time, the individual must practice under the guidance and supervision of a certified engineer. After the review process has been completed and JTIA determines that the documentation is valid, the engineer receives their Certificado de Idoneidad, along with their seal. The seal usually comes in the form of a stamp, but can also be a punch that creates a raised impression on papers. Both the certificate and the seal display the engineer's professional registration or identification number. This number is unique to the engineer and serves as proof of their credibility when they place their seal on a document. Panamanian engineers are not required by law to continue their education to maintain their certificate, as PEs are in the U.S.; however, it is strongly recommended and practiced by most (Lyew, 2016a). Some companies, such as the ACP, present their employees with further educational opportunities by offering several courses on various topics throughout each year.

Executive Summary

In 1914, the opening of the Panama Canal changed both the global shipping industry and the country of Panama. The Canal Expansion Project, completed in June of 2016, further developed the waterway, making it accessible to new markets. Due to the increasing age of the original structures and the different operational procedures for the third set of locks, new challenges arose that needed to be addressed to preserve the longevity of the system. This report contains the findings of four separate projects related to these challenges.

The Panama Canal Expansion has increased the number of transits and size of ships passing through the new set of locks, thus increasing the inflow of water into Gatún Lake from the Pacific and Atlantic Oceans. As Gatún Lake is a large supplier of potable water to the residents of Panama, the Autoridad del Canal de Panamá (ACP - Panama Canal Authority) has been monitoring its water quality, paying specific attention to salinity. The *Analysis of Chemical Consumption Patterns at Miraflores Filtration Plant* project entailed collecting and analyzing chemical consumption data and water samples for the fiscal year. The goal of this project was to assess the effect of salinity and other related water quality parameters on water treatment at the Miraflores Filtration Plant before and after the opening of the expansion project. To achieve this goal, an understanding of the plant operations was established; data regarding chemical consumption and water quality parameters were collected; consumption patterns pre- and post-expansion operations were established and the chemicals that had increased in dosing were identified; and potential relationships between water quality parameters and chemical dosing were investigated. Through a combination of statistical analyses, it was found that post-expansion operations have not significantly increased consumption of chlorine or alum. Furthermore, a correlation analysis determined that, across all periods, turbidity levels and volume of influent have a significant, positive relationship with alum consumption, while salinity levels have a significant, positive relationship with chlorine consumption. Finally, it was concluded that post-expansion operations have only impacted salinity levels, and although these have not reached the maximum value permitted for human consumption, a significant increase has occurred since pre-expansion operations. To guarantee that water treatment within the plant continues to be effective, it has been recommended that the monitoring of salinity levels at all seven distribution points continues, a necessary measure to ensure that levels do not surpass the

freshwater limit. In addition, the further investigation of the chemical relationship between chlorine consumption and salinity was advised to determine the effectiveness of using chlorine to treat salt concentration. Lastly, an investigation on how seasonal changes affect salinity levels in Gatún Lake was recommended as only salinity data during the rainy season was available for this analysis.

Due to population increase and higher potable water demands, the ACP's water treatment plants currently operate under different flows than those for which there were originally designed. The Mount Hope Water Filtration Plant, responsible for supplying potable water to the northern region of Panama, is in need of an evaluation of the facility's efficiency based on differences between particle speeds in the water. The goal of the *Process Analysis of Mount Hope Water Filtration Plant* project was to analyze the flow of water through specific components of the plant. To achieve this goal, the layout of the plant was analyzed, the velocity gradients were calculated for the rapid mix chamber and flocculation basin, and the detention time was calculated for the sedimentation basin. Based on the current daily discharge of the plant, the calculated velocity gradient in one pathway (of three) of the rapid mixing chamber ranged between 146.69 and 154.81 s^{-1}, which fell below the recommended ranges of 300 – 1000 s^{-1}. It was suggested that the dimensions of the structure be reviewed and potentially modified, as volumetric decreases would increase the velocity gradient of the water passing through the chamber, improving the purification at that step. Based on the current shaft rotational velocity of 1.49 rpm, the velocity gradient in the flocculation basin was calculated to be between 6.75 and 7.12 s^{-1}. It was recommended that a motor be acquired that can operate at a higher rate and across a range of rotational velocities. This would allow operators to achieve a wider range of targeted velocity gradients, responding to the variations in water quality at any given time. Depending on the water volume within the sedimentation basin, the detention time in the structure at the time of analysis was between 83 and 100 min. It was recommended that modifications to the sedimentation basin be considered to increase its volume. A final option would be to consider other types of sedimentation basins, using newer technology.

The water that is processed by the various filtration plants originates in Gatún Lake, an artificial body of water created and maintained by a system of dams and spillways. Inspections are conducted on these structures to ensure that they remain in working order and to identify points of loss before a failure occurs. The ACP implemented a formal, detailed, inspection program in 2015 but encountered unexpected difficulties due to the complexity and age of the structures. The *Evaluation of the ACP's Formal Inspection Program of Dams and Spillways* project focused on revising the formal inspection protocol and providing suggestions to further improve their processes. To achieve this goal, the meaning of "formal inspection" in the context of other regions was researched, the ACP's current inspection process was reviewed, U.S. standards and the ACP protocol were compared, and suggested checklists were created to be followed by the ACP during future inspections. It was concluded that the ACP follows the correct steps to complete a formal inspection; however, their protocol was in need of updating to allow for ease of inspection. Additionally, it was determined that the formatting of prior reports was inconsistent and difficult to navigate. Checklists of items to be inspected were modified to increase the efficiency of the inspections and an outline was created to allow personnel to complete the inspection report in the required 15-day period. Finally, suggestions were provided for the preparation processes of the inspections in order to help ensure the sustainability of the structures being inspected.

Risk analysis is a tool used to increase the productivity of inspection and maintenance programs and can be used to prioritize specific repairs before failures occur. Madden Dam and Spillway is considered to be the most high-risk water retention structure in the Panama Canal System because it operates with drum gates, a design not used in modern construction. The goal of the *Risk Analysis of Madden Dam and Spillway Drum Gates* project was to improve the current maintenance program and allow for preemptive repair of the drum gates using a risk-based analysis methodology. To achieve this goal, the structural condition of the Madden Spillway drum gates over time was analyzed, maintenance programs aimed at preserving adequate reliability of spillway gates were researched, the capacity of the drum gate's structural components were calculated and compared to their demand, and suggestions were made to improve the current maintenance program. After reviewing historical inspection and maintenance reports from 1982 to 2015, a historical maintenance log was created to record the structural condition of each drum gate. The upstream and bottom skin plates were considered the most critical elements because they experience direct water pressure from Alhajuela Lake and the flotation chamber, respectively, and were analyzed further. The stress acting on the upstream plate was calculated to be 14.9 ksi (102.7 MPa), while the stress on the bottom plate was found to be 10.1 ksi (69.6 MPa). The allowable stress, or capacity, was evaluated to be 19.8 ksi (136.5

MPa). The critical thickness of each plate was calculated, assuming capacity was equal to demand, and given a factor of safety in order to provide a warning indicator for the ACP to begin planning repairs or replacements. While it was concluded that the drum gates remain in good condition, recommendations were presented for updating the maintenance log annually, improving inspection records, and conducting a risk analysis based on thickness of the plates over time.

These projects were completed over the course of three months in collaboration with ACP engineers and the support of WPI faculty. Background knowledge from previous coursework, experience from prior internships, information gathered from extensive research, lab work, and field visits came together to make this work possible. Based on the results, suggestions were provided to the ACP in hopes of improving the projects' respective systems.

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I. Preface

This report was written over the course of a three month partnership with the Autoridad del Canal de Panamá (ACP – Panama Canal Authority) by five Civil Engineering students to fulfill Worcester Polytechnic Institute's (WPI) requirements for a Major Qualifying Project (MQP). An MQP is a cumulative project completed in a student's senior year that meets the standards set forth by the Accreditation Board for Engineering and Technology, Inc., for engineering design capstones.

The five students worked in various engineering divisions of the ACP to complete four separate projects. Liliana Almonte and Sonia Zarate were responsible for the section entitled *Analysis of Chemical Consumption Patterns at Miraflores Filtration Plant*. Julia Ring was responsible for the section entitled *Process Analysis of Mount Hope Water Filtration Plant*. Caitlin Burner was responsible for the section entitled *Evaluation of the ACP's Formal Inspection Program of Dams and Spillways*. Victoria Simpson was responsible for the section entitled *Risk Analysis of Madden Dam and Spillway Drum Gates*. This report contains the methods, findings, and recommendations for all four projects.

The common themes underlying all four projects stemmed from the effects of the recently completed Expansion Project and the Panama Canal's age overall. The first two reports explore how the new locks have affected the water quality drawn from the canal and how it is processed before public distribution. The remaining reports explore concerns related to evaluating and maintaining the quality of the structures that are more than 100 years old.

II. Background

The country of Panama is known globally for its marine trade route, connecting the Atlantic and Pacific Oceans. While the canal has been operational for over 100 years, the ACP is constantly seeking opportunities to improve. This chapter presents information about the canal system and its procedure for safely shipping goods through the waterway. The Third Set of Locks Project, completed in June 2016, is also evaluated in terms of both engineering design and the controversy surrounding the construction and operation.

1.0 Panama Canal

The Panama Canal intersects the Continental Divide and cuts through the Isthmus of Panama from Colón to Panama City. The first ship passed through the Panama Canal on September 26, 1913, but the official opening did not occur until August 15, 1914 (Panama Canal Museum, 2014). The canal stretches for about 50 miles (82 km) from the Atlantic Ocean to the Pacific Ocean. Shipping vessels traveling from the Atlantic to the Pacific enter the approach channel in Limón Bay, which extends for 7 miles (11 km) to Gatún Locks (Figure 1). The

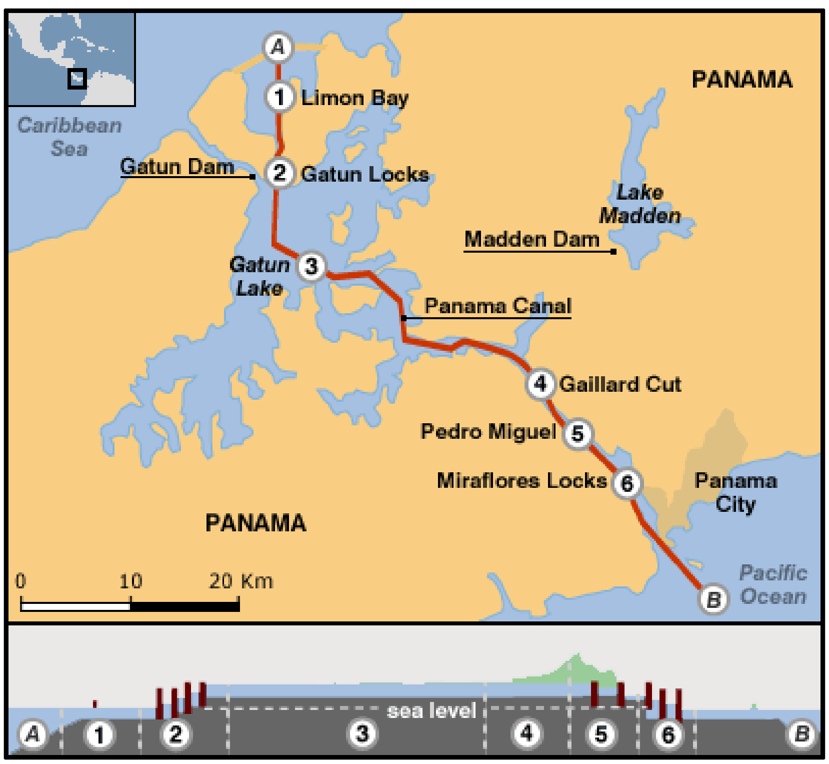


Figure 1: Map of Panama Canal (BBC News, 2006)

Gatún Locks consist of three steps that lift vessels 85 ft (26 m) to Gatún Lake. Once in the lake, ships travel for 23 miles (37 km) to Gamboa, the beginning of the Culebra (Gaillard) Cut. The Culebra Cut passes through the Continental Divide and extends for 8 miles (13 km) to the Pedro Miguel Locks. The Pedro Miguel Locks have one step that lowers vessels 30 ft (9 m) to Miraflores Lake. Ships pass 1.2 miles (2 km) through the lake to the Miraflores Locks, which consist of two steps that lower vessels back to sea level. Finally, ships travel 7 miles (11 km) through the approach passage to the Pacific Ocean (Padelford, 2016). This entire journey takes between 8 and 10 hours to complete (Panama Canal Museum, 2014).

The operation of the locks is controlled by the gravity flow of water from Gatún, Alhajuela, and Miraflores Lakes, which are fed by the Chagres River, among others. The flooding and emptying of the lock chambers is controlled by a set of hinge gates that are operated from a control tower (Padelford, 2016). The lock chambers are 1,000 ft (300 m) long, 110 ft (33 m) wide, and 42 ft (13 m) deep (Panama Canal Museum, 2014).

The opening of the Panama Canal for commercial trade helped change the global shipping industry. Prior to the canal's opening, trade between the East and West Coasts of the United States had three options for travel: the transcontinental railroad; travel by ship to Mexico or Panama for transfer via the Tehuantepec or Panama railroads, followed by another ship; or travel by ship around Cape Horn in South America (Maurer & Yu, 2011). By using the canal, the voyage was shortened by about 8,000 nautical miles (15,000 km) (Padelford, 2016). Other trade routes were also significantly shortened with the creation of the Panama Canal (Table 1).

Table 1: Representative distances of shipping routes in miles (Maurer & Yu, 2011)

	Shortest alternative	*Via Panama Canal*
U.S. routes		
U.S. East to U.S. West	13,277	6,146
U.S. East to Canada West total	14,054	6,925
U.S. East to South America West total	8,512	5,515
U.S. East to Asia total	16,746	11,471
U.S. East to Australasia total	12,762	10,573
U.S. West to Europe total	13,841	7,825
Non-U.S. routes		
Europe to Canada West	13,251	8,602
Europe to Australasia	11,514	12,250
Europe to South America West	11,841	7,192
Europe to Asia	10,465	13,148
Mexico East to South America West	9,088	4,785

Source: Distances.com, "World Ports Distances Calculator," www.distances.com.

While the United States initially supported the creation of the canal for their own benefit, they permitted other countries to ship goods through the isthmus, making different shipping routes possible (Maurer & Yu, 2011). Although between 1923 and 1937 about 41% of the traffic traveling through the canal was American intra-continental goods, it also allowed countries such as Japan and Chile to join the global trade economy by creating a shorter route to their markets. By 1939, over 7,000 ships were transiting the canal annually and global trade has continued to increase since (The American Experience, 2013).

2.0 Development of the Shipping Industry

During early operation, many ships were built to fit within the locks to allow their passage through the Panama Canal. Early ships to transit the canal passed through the locks with plenty of open air between their hull and the concrete sidewalls. As the shipping industry developed, larger ships were built in order to increase efficiency (Rodrigue, 2016). These ships were 965 ft (294 m) long, 106 ft (32 m) wide, and 39.5 ft (12 m) deep. They were known as Panamax vessels, the maximum size ship that could fit through the Panama Canal (Figure 2) (Panama Canal Museum, 2014). The first Panamax standard was established in 1985 and allowed a capacity of 4,000 twenty-foot equivalent units (TEUs). A twenty-foot equivalent unit refers to the size of a 20 ft (6 m) long shipping container and is a standard measure for the capacity of a container ship. This standard was increased to allow a capacity of about 5,000 TEUs by enlarging the width, or beam, of the ships.

Figure 2: Early ship transiting the canal (PSN, 2011) vs. container ship passing through Miraflores Locks (Eric, 2015)

In 1934, however, the RMS Queen Mary became the first known post-Panamax ship (Maurer & Yu, 2011). Post-Panamax describes the size of ship that would not be able to fit through the Panama Canal. In 1940, the Japanese launched their Yamato-class battleships, which were the first warships unable to use the canal. The United States soon followed, abolishing their size limit on battleships on February 12, 1940. By 1996, post-Panamax container ships became standard and were too wide to fit through the Panama Canal (Rodrigue, 2016). After the initial development of post-Panamax ships, container ships continued to increase in size in order to improve the efficiency of transporting large amounts of cargo globally.

3.0 Responding to Increasing World Trade

Throughout its history, the Panama Canal has consistently faced competition from both the United States intermodal system and the Suez Canal. Based on the locations of the distributor and the destination of the goods, some routes are more favorable than others. For example, shipping between Europe and Asia is most efficient when cargo is sent overseas through the Suez Canal. Other trade partners, however, have the ability to choose their shipping routes. The US intermodal system is the Panama Canal's largest competitor due to the large number of passages traveling from Asia to the Eastern Coast of the United States. Ships traveling from Asia have the option of using the canal and unloading at East Coast ports or unloading at a West Coast port and having the cargo shipped the remainder of the journey by either truck or railway (Figure 3). Both systems have advantages; the Panama Canal route takes about 26 days while the Transcontinental Railway route takes only 21 (15 days by ship and 6 by rail). However, the Panama Canal is $600 less expensive per TEU (Webster, 2015). With the introduction of Post-Panamax ships, the canal route became less convenient. In order to use the canal, Post-Panamax ships had to unload at one end of the canal and have the cargo transported by the Panama Canal Railway Company to another Post-Panamax ship on the other side, or loaded into Panamax vessels to finish the journey to the Eastern United States.

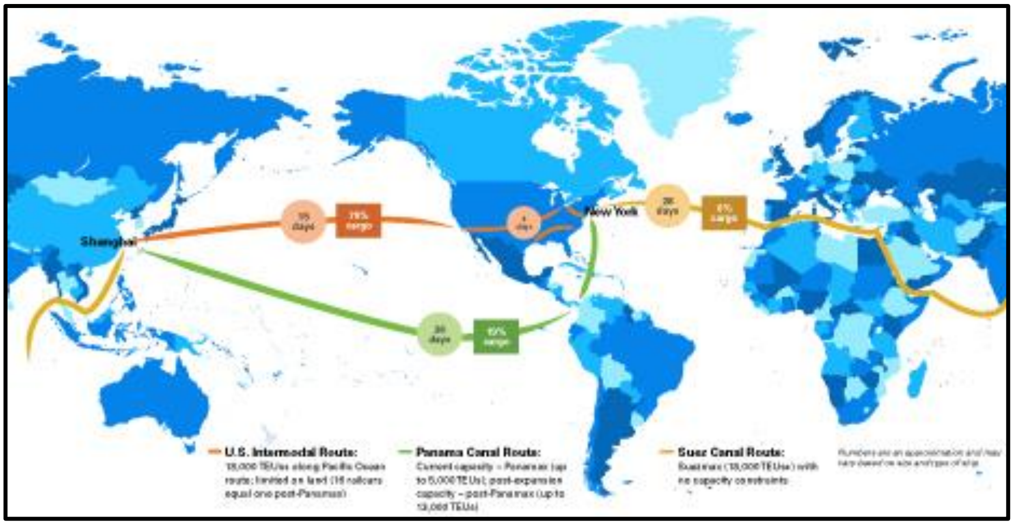


Figure 3: Competitor No. 1 - Intermodal: East Asia through Continental U.S. (Webster, 2015)

Expanding the Panama Canal with a "Third Set of Locks" was first considered by the Americans in 1939 to allow larger ships, including new American warships, to pass through the channel (Maurer & Yu, 2011). The United States began excavation for the project but abandoned the expansion at the outbreak of World War II. However, as post-Panamax ships became more widely used in world trade, the ACP again considered expansion to stay relevant. A study conducted by the ACP in 2005 estimated that the Panama Canal would reach its "maximum sustainable capacity" of about 330 to 340 million tons (299 to 308 million tonnes) of cargo between 2009 and 2012 (Aguirre, 2010). After the canal reached maximum capacity, it would not be a competitive member of global trade, as it would not be flexible with increasing demands by shipping companies. The canal would also be missing out on revenue from not being able to accept larger ships (Webster, 2015). With the advent of post-Panamax container ships in the 1990s, the more efficient ships became increasingly more common (Figure 4). In 2015, more than a third of the world's container vessels, bulk carriers, and tankers were too large to fit through the existing locks. It was projected that by 2030, two thirds of container ships would be unable to pass through the canal (Rodrigue, 2010).

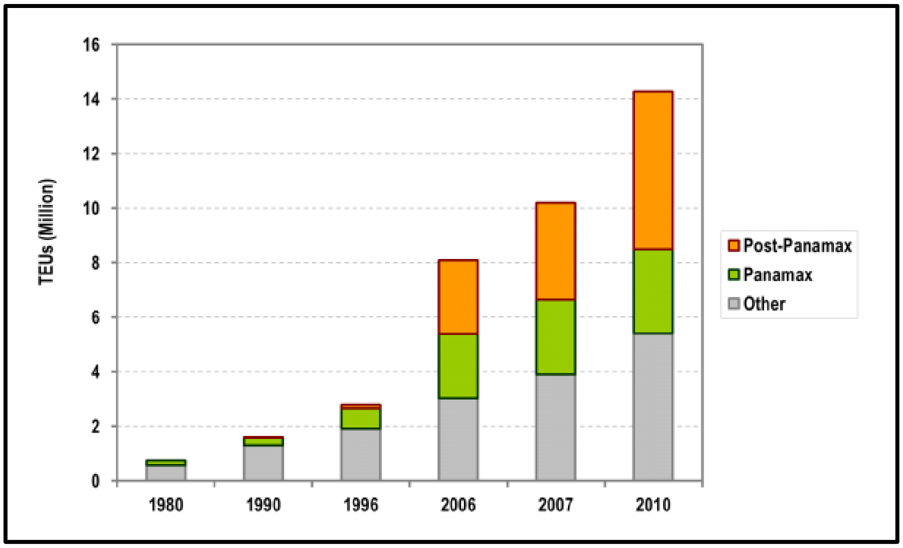


Figure 4: Evolution of the world's containerized carrying capacity, 1980-2010 (Rodrigue, 2010)

In order to achieve long-term sustainability and growth, maintain the waterway's competitiveness, and increase the canal's capacity to meet growing demand, the ACP determined that a third set of locks needed to be constructed on the Panama Canal (Panama Canal Museum, 2016). For six months, the ACP conducted an education and outreach program to the citizens of Panama about the benefits of the expansion project. On October 22, 2006, a referendum was held to allow Panamanians to vote on whether the canal should undergo the expansion project or should continue to operate as normal. Although less than half of Panama’s population voted, the project passed with 76.8% of the votes in favor of expanding the canal. With the announcement of the expansion project, ports along the East Coast of the United States, such as Miami, Savannah, and New York, began planning dredging projects in order to be able to accept the larger ships that would pass through the new canal (Rodrigue, 2010).

4.0 Bid Process

Considering the magnitude and engineering complexity of the expansion, professional advisory assistance was sought from international specialists providing services such as financial legal advisory, construction-contracting legal advisory, and program management. With $3.48 billion of internal allocated funds, the ACP issued an international announcement in August 2007 to pre-qualify a maximum of four tenderers interested in the design and construction of the Panama Canal Expansion (Autoridad del Canal de Panamá, 2010a). Four different consortiums composed of over 30 companies, representing 13 different countries, were pre-qualified by the

ACP to participate in the bidding process (Table 2) (Autoridad del Canal de Panamá, 2009b). In December of 2007, each consortium received the Request for Proposals (RFP) on the "design-build" contract for the new locks under the Canal's Expansion Program (Canal de Panamá, 2007). Various individual and plenary meetings were executed with each tenderer to address questions and suggestions regarding the RFP, which led to 24 different amendments to the document (Autoridad del Canal de Panamá, 2009a).

On March 3, 2009, several months after the initial submission deadline of August 2008, three of the four pre-qualified consortiums submitted their proposals to the ACP (Autoridad del Canal de Panamá, 2009b). Representatives from Bechtel-Taisei-Mitsubishi, C.A.N.A.L, and Grupos Unidos por el Canal (GUPC) attended a public ceremony covered by local and international media at ACP grounds following a proposal-receipt process. Tenderers' submissions were composed of a technical proposal and a price proposal, each closed and sealed. While the technical proposals were transferred to a secure building awaiting private revision by a contracting officer, the price proposals were deposited in a vault at Banco Nacional de Panamá, in addition to an envelope containing the amount of ACP allocated funds (Autoridad del Canal de Panamá, 2009a).

Table 2: Pre-Qualified consortia for Third Set of Locks Construction Project (Autoridad del Canal de Panamá, 2009a)

Pre-Qualified Consortia			
Consortium	**Members**	**Designers**	**Gate manufacturer**
C.A.N.A.L.	ACS Servicios, Comunicaciones y Energía S.L. (leader)	Sener Ingeniería y Sistemas	ACS Servicios, Comunicaciones y Energía S.L.
	Acciona Infraestructuras S.A.		
	Fomento de Construcciones y Contratas S.A.	Haskoning Nederland BV	
	Hochtief Construction AG	Mott MacDonald Limited	
	Constructores ICA S.A. de C.V.	Hochtief Consult	
Atlántico-Pacifico de Panamá	Bouygues Travaux Publics. (leader)	AECOM (leader)	ALSTOM Hydro Energía Brasil
	Bilfinger Berger		
	VINCI Construction Grands Projets		
	Construcoes e Comercio Camargo Correa S.A.		
	Constructora Andrade Gutierrez S.A.		
	Constructora Queiroz Galvao S.A.		
	ALSTOM Hydro Energía Brasil		
	BARDELLA Ind. Mecânicas		
Bechtel, Taisei, Mitsubishi Corporation	Bechtel International Inc. (leader)	Bechtel International Inc. (leader)	Wuchang Shipyard
	Taisei Corporation		
	Mitsubishi Corporation		
Grupos Unidos por el Canal (GUPC))	Sacyr Vallehermoso S.A. (leader)	Montgomery Watson Harza (MWH) (leader)	Heerema Fabrication Group
	Impregilo S.p.A.		
	Jan de Nul n.v.	IV-Groep	
	Constructora Urbana S.A.	Tetra Tech	

The evaluation for the contractor selection process aimed to be fair, impartial, transparent, and holistic (Zubieta, 2009). As explained by Alberto Alemán Zubieta, CEO and Administrator of the ACP, "…we stand committed to hiring a consortium that meets all technical requirements and provides the best value for the project" (Canal de Panamá, 2009). In addition to fully complying with criteria established by the RFP, the process was executed by experts in a confidential manner. Three teams, each with a different area of focus, independently reviewed proposals submitted by each tenderer. Utilizing a non-negotiated best value process, a weight of 55% and 45% was assigned to the technical proposal and price proposal, respectively (Zubieta, 2009).

In July of 2009, having concluded the review process for technical proposals, the ACP called for a public ceremony where the winning contractor was selected. After disclosing the scores for the technical proposals and opening the price proposals, a best value proposal was calculated automatically (Zubieta, 2009). GUPC, led by Sacyr Vallehermoso, S.A. of Spain, won the Panama Canal Expansion competition with a bid of $3.1 billion (Latin American Herald Tribune, 2015). The price offer, which was lower than the $3.48 billion target price calculated by the ACP, was approximately $1 billion less than the Bechtel-Taisei-Mitsubishi bid and $3 billion less than the C.A.N.A.L bid (Table 3) (Kriel & Dowsett, 2014). Differences in construction design explain the low price proposal made by GUPC; in comparison to Bechtel-Taisei-Mitsubishi, whose design incorporated 18 water-saving basins and larger gates, the winning proposal had nine water-saving basins for each lock (Canal de Panamá, 2016).

Table 3: Participating consortia proposals and scores (Autoridad del Canal de Panamá, 2010a)

PARTICIPATING CONSORTIA PROPOSALS AND SCORES

Consortium	55%	40%		5%		Total Price Proposal	45%	100%
	Technical Score (Maximum 5,500)	Price Proposal	Price Score (Maximum 4,000)	Provisional Sum Price Proposal	Provisional Sum Score (Maximum 500)		Price Proposal Total Score (Maximum 4,500)	Total Score (Maximum 10,000)
Bechtel, Taisei, Mitsubishi Corporation	3,789.5	$ 4,185,983,000.00	2,980.3	$ 93,836,670.00	-	$ 4,279,819,670.00	2,980.3	6,769.8
C.A.N.A.L.	3,973.5	$ 5,981,020,333.00	2,085.9	-	500	$ 5,981,020,333.00	2,585.9	6,559.4
Grupo Unidos por el Canal	4,088.5	$ 3,118,880,001.00	4,000.0	$ 102,751,383.00	-	$ 3,221,631,384.00	4,000.0	8,088.5

Amount of Allotted Funds - ACP $ 3,481,000,000.00

Differences in the bid price and design by GUPC caused concern among local officials (Kriel & Dowsett, 2014). An analyst from Hill International described the project as a "high risk situation" considering the "little room in the budget for execution errors or significant inefficiencies" (Bogdanich, Williams, & Méndez, 2016b). As a result of poor quality concrete and water leaks, GUPC filed claims for $1.6 billion in cost overruns (Leach, 2016). However, the ACP claimed that "GUPC has failed to support or validate the claims for cost overruns" (Canal de Panamá, 2016).

5.0 Construction of the Panama Canal Expansion

Construction of the Panama Canal Expansion began on September 3, 2007 and lasted for approximately nine years (Funke, 2016). During this time, two new sets of locks were built while the original three still operated normally. Expansion phases needed to be coordinated to prevent interference with the international trade system.

5.1 Design of the Third Set of Locks

The most drastic changes to the canal took place where the Cocolí and Agua Clara Locks were built. Agua Clara Locks are located at the Atlantic side of the canal, opening directly into Gatún Lake. They are situated east of the Gatún Locks, and their access channels converge at the inlet from the Atlantic Ocean (Figure 5). Cocolí Locks are located at the Pacific entrance to the Panama Canal, parallel to and southwest of the Miraflores Locks. The two access channels join together as they approach the Culebra Cut (Corporate Communications Office of the Panama Canal Authority, 2009). Aside from these access channels, the routes vessels take through the canal are the same.

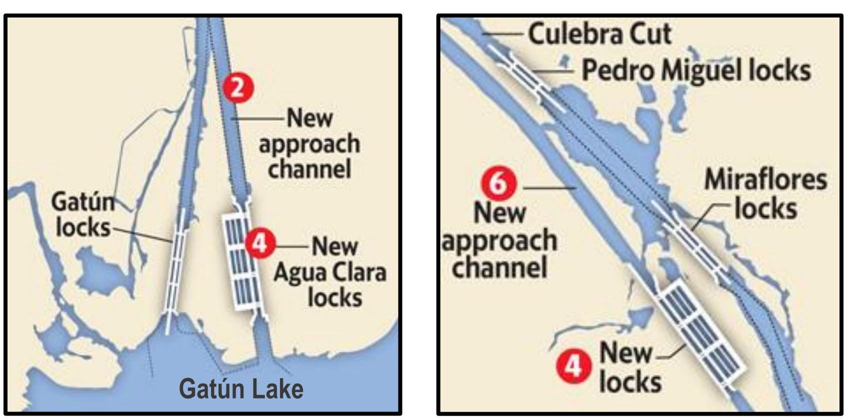


Figure 5: Locations of Agua Clara Locks (left) and Cocolí Locks (right) in relation to the original locks (Whitefield, 2016)

The new locks were designed to have three consecutive steps, just as in the original Gatún Locks, but they were larger in all dimensions. The chambers are each 1,400 ft (427 m) long, 180 ft (55 m) wide, and 60 ft (18.3 m) deep. In comparison to the old locks, this meant increases of 400 ft (122.2 m) in length, 70 ft (21.5 m) in width, and 18 ft (5.5 m) in depth (Figure 6) (Corporate Communications Office of the Panama Canal Authority, 2009). Not only are these larger locks able to fit most post-Panamax ships, but they have led to the classification of neo-Panamax ships, which have been specifically dimensioned for the two new sets of locks.

Miraflores, Pedro Miguel, and Gatún Locks all have two lanes for transit. Cocolí and Agua Clara Locks, however, have one lane each, hence their nickname, the "Third Set of Locks." Where the old lock chambers were separated by hinged miter gates, the new ones use rolling gates that slide open, receding perpendicularly into the chamber walls (Figure 6). Water-reutilization basins are located on the same side of the lock towards which the gates recede. Each chamber is connected to three side-by-side basins (18 in the total expansion project) that are partially responsible for filling and draining the lock lane while a ship is traveling through it (Alarcón, Ashley, de Hanily, Molenaar, & Ungo, 2011). The basins help conserve the water required in every passage, saving up to 60% of the water used for each lockage (Figure 7).

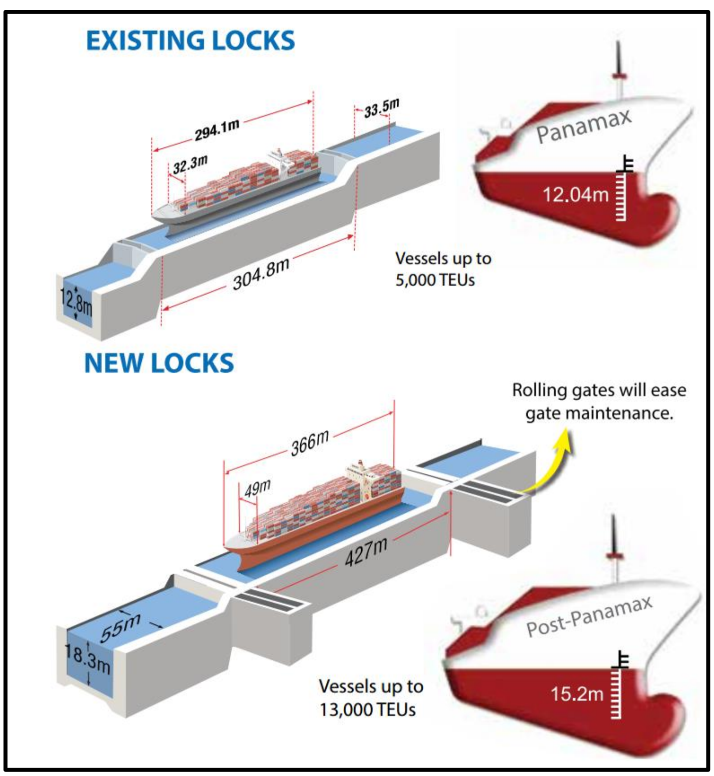


Figure 6: Comparison between the dimensions relating to the old and new locks (Autoridad del Canal de Panamá, 2012)

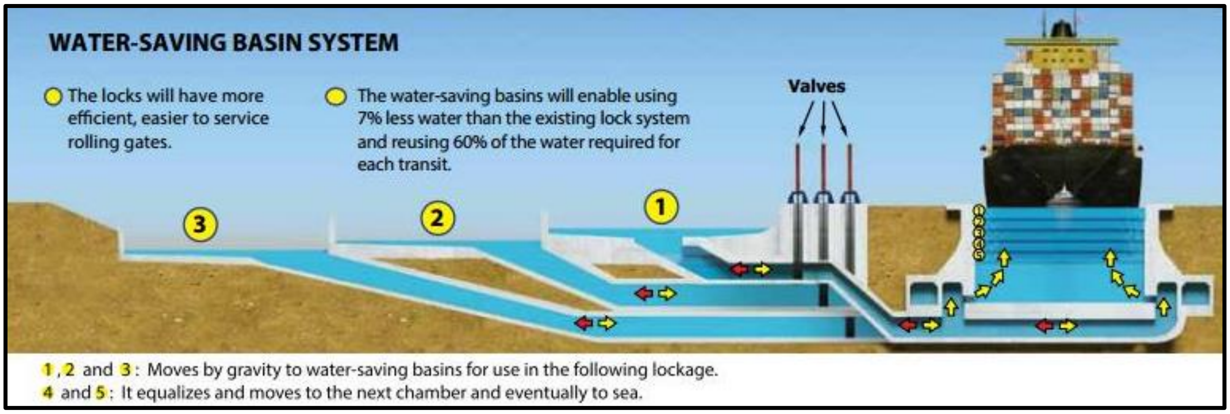


Figure 7: Water-saving basin system (Autoridad del Canal de Panamá, 2012)

5.2 Construction Process

During the attempted expansion project by the United States in the early 1940s, excavation was begun and abandoned on both the Pacific and Atlantic sides of the Panama Canal. These previous excavation sites became the locations of the Cocolí and Agua Clara Locks (Alarcón et al., 2011).

Despite this initial construction, a great deal of work remained (Figure 8). Before efforts could begin on the Pacific side of the canal, 198 acres (80.1 hectares) of land west of the locks needed to be cleared of debris, as they sat on the site of a former testing range for experimental weapons (House, 2013). While the U.S. military still occupied the Panama Canal Zone, they

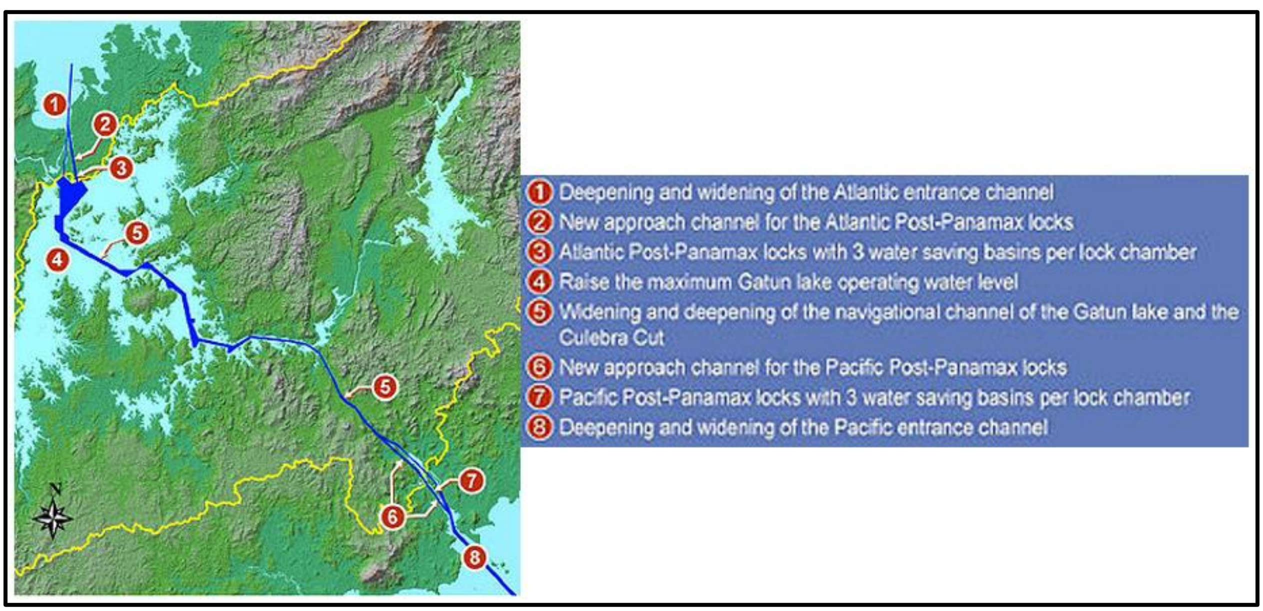


Figure 8: Components of the expansion project (Panama Canal Expansion Project, n.d.)

launched munitions prototypes towards the test range. When it came time for expansion, the region needed to be cleared of weaponry remnants, such as unexploded bombs, shrapnel, and chemicals, to ensure the safety of all those who would be traveling through and excavating the area (Lyew, 2016b). Once the danger had been eliminated, construction began.

In order to accommodate the ever-increasing ship sizes, the access channels on both the oceanic and lake sides of the locks needed to be dredged and widened. Originally 650 ft (198 m) wide, both the Atlantic and Pacific sea entrance navigation channels were widened to 738 ft (225 m) (House, 2013). At the lowest tide, these channels were deepened to 51 ft (15.5 m). Access channels connecting the new locks to the oceans and Gatún Lake were cut to a width of 715 ft (218 m) (Alarcón et al., 2011).

Modifications to the interior section of the Panama Canal focused on expanding the pathways taken by vessels through the Culebra Cut and Gatún Lake. These routes were dredged, adding an extra 4 ft (1.2 m) of depth, allowing ship drafts up to 50 ft (15.2 m) to cross. In the lake itself, passageway widths were increased to allow post-Panamax ships to pass one another safely while traveling in opposite directions. Straightaways were broadened to a minimum of 919 ft (280 m) and curved sections were increased to 1,200 ft (366 m). Furthermore, the water level in Gatún Lake was raised by 1.5 ft (0.5 m) to increase the volume of water available for both the locks and consumption by residents of surrounding cities (Alarcón et al., 2011).

The dredging process also served to provide aggregate for the construction of the Agua Clara and Cocolí Locks. Aggregate is a key component in concrete and is composed of stones of various grades that give the mix its strength and stability. Aggregate was gathered from the material dredged from the Pacific side of the project. With the construction of a concrete manufacturing plant at each end of the canal, both the Agua Clara and Cocolí Locks were mixed and poured using aggregate from the project site itself (Bogdanich et al., 2016b).

In addition to the lanes that the ships travel, surrounding infrastructure needed to be constructed to support the project. Access roads were created at several points along the Panama Canal to allow contractors, employees, and heavy equipment entry to the new construction sites and points of expansion. Drainage channels were created to direct rainwater away from the sites and to remove water used in various tests on the lock structures at different stages in the building process (House, 2013). Because the water in the Cocolí Locks access channel was designed to sit 29.5 ft (9 m) higher than that for Miraflores, the two paths needed to be separated by an earth dam (Figure 9) (Lyew, 2016b). A 0.9 mi (1.5 km) containment structure made up of cofferdams was first built on the southwest edge of the access channel leading to the Miraflores Locks in order to be able to build the earth dam without interfering with ongoing transit through the canal. Once in place, a dam constructed of multiple layers and materials was laid southwest of the cofferdams, ensuring the permanent separation between the Miraflores and Cocolí access channels. The dam is 1.8 mi (2.9 km) long, 492 ft (150 m) wide, and 85 ft (26 m) high (House, 2013).

Figure 9: Cofferdam and earth dam during construction and rendering of after construction (Autoridad del Canal de Panamá, 2015)

5.3 Challenges during Construction

Given its sheer magnitude, the Panama Canal Expansion Project ran into unexpected challenges and delays. Some problems arose as a result of controversial decision-making, while others resulted from natural causes that were out of project managers' control.

One of the issues of highest concern was related to the quality and durability of the concrete used to form the new locks. Prior to the selection of the winning consortium, the groups were able to perform preliminary calculations that would help determine their bid values. While the calculations from several of the consortiums, including those from GUPC, determined that the material dredged from the Pacific side of the canal would not serve as a suitable aggregate, GUPC members still opted to use this source. They chose this aggregate because the portion of the project budget allotted to concrete was very small and using the dredged matter was cheaper than importing aggregate from an outside source. The mix proved insufficient when large cracks started opening up at several points along the new locks. Some simply remained damp, while water surged from others. Repairs, in the form of added reinforcing steel bars and seals, were made and construction continued (Bogdanich et al., 2016b).

Other concerns arose regarding the water in the canal. Towards the end of 2015 and the beginning of 2016, as the expansion project neared completion, water levels in Gatún Lake started dropping significantly. Some attributed the decrease in supply to unforeseen increases in household consumption, while others blamed the problem on El Niño, a recurring weather event that leaves Panamá in drought and lasts between one and two years (Bogdanich et al., 2016b; Henson, Rae, Masters, & Brown, 2016). Regardless of the causes, the ACP periodically issued warnings worldwide beginning in February of 2016, directing distributors to lighten the loads of the ships intended to pass through the canal. By reducing the amount of cargo, ships reduced the risk of hitting the bottom of the passages in Gatún Lake. The load restrictions were lifted after sufficient rainfall, but there were still concerns about how much the Agua Clara and Cocolí Locks would further impact the water level and quality through the Panama Canal. People worried that a third set of locks would deplete Gatún even more rapidly, while also disturbing salinity levels in the water (Bodganich et al., 2016b; Maritime Gateway, 2012). They feared the additional lockages would alter the ratio of salt water entering Gatún Lake's fresh water, negatively affecting the drinking water that is derived from the lake (Maritime Gateway, 2012).

The overall timescale allotted to the Panama Canal Expansion Project suffered as a result of the challenges along the way. Initially, the Cocolí and Agua Clara Locks were scheduled to be completed and transporting post-Panamax ships by 2014. This inauguration date would pay homage to the Panama Canal's 100th year in operation. Unfortunately, delays, such as those from cracks in the concrete, repairs, and miscommunications, caused the project to run past the projected date (Bogdanich et al., 2016b). The construction ended up closing two years late, officially opening for transit in 2016.

5.4 Operational Changes

From the initial planning stages, the Cocolí and Agua Clara Locks were designed to operate very differently than the Miraflores, Pedro Miguel, and Gatún Locks. When ships use the original sets of locks, tugboats guide them in from the ocean to the access channels. Once at the locks, the ships shut off their engines and are attached to locomotives by taut wires to help guide them through the channels safely. The locomotives keep the vessels moving in a straight line, preventing collisions between the hulls and the canal walls or lock gates (Bogdanich et al., 2016b).

Conversely, Agua Clara and Cocolí were built without locomotive tracks. Instead, tugboats guide the ships through the entire length of the locks. One tug ties to the bow and one to the stern. While the tugboats help guide them and try to prevent wall collisions, the ships also progress through the channel under some of their own power. As can be seen in the ACP's informational video *A New Experience - Transits Through Expanded Panama Canal* (2016), vessels are tied down at each step in the locks to hold them in place, the step is drained (or filled), and the vessels are untied and guided to the next step. The differences in the operation of the new locks caused many canal pilots and tugboat captains to voice concern and request more training. They feared that complications could arise as the result of several different factors including vast increases in ship sizes, cargo stacks acting as sails, and unpredictable currents created from the mixing of fresh and salt water (Bogdanich et al., 2016b). Some training was provided to the pilots and captains, but much of their experience would have to be gained in the first several months of operation.

6.0 Current Operation

On June 26, 2016 the Panama Canal Expansion was officially inaugurated. The first commercial vessel to successfully pass through the expanded canal was a Chinese container ship, called Cosco Shipping Panama (Mufson, 2016). The vessel set sail on June 11th carrying 9,472 TEUs. It measured 984 ft (300 m) long and 158 ft (48 m) wide (Autoridad del Canal de Panamá, 2016d). Despite the success of the first transit, there were many concerns regarding the feasibility and safety of the expanded canal. These included doubts about the "new canal's long term viability because of water availability and changes in shipping patterns" (Bogdanich, 2016). Other concerns related to the pilot's ability to safely navigate through the lock chambers because of the tight fit between the neo-Panamax ships and the expanded canal (Mufson, 2016). Additionally, "the height of the bigger container ships - capable of carrying 14,000 containers, more than double previous maximums - could leave them susceptible to wind gusts" (Mufson, 2016).

After one month of operations, the concerns about the expanded canal became more prevalent as several minor collisions were reported. The most severe collision occurred on July

21, 2016 when Chinese container ship, Xin Fei Zhou, collided with the corner of the lock wall. The collision tore holes in its hull, forcing it out of service. A potential cause was the lack of an approach wall that is present at all other entrances. Approach walls are designed to properly align vessels and combat currents and winds (Bogdanich, Williams, & Méndez, 2016a). Another collision occurred in late June of 2016 with Lycaste Peace, the first liquefied petroleum gas (LPG) tanker to pass through the expanded canal. It was reported that a fender, which protects the lock walls and ship hulls in case of collisions, was ripped off, resulting in minor damage to the railing of the ship (Hampton & Parraga, 2016). In addition to these notable collisions, other vessels had "sheared or badly damaged up to 100 buffering fenders". As a result of these incidents, Jorge Quijano, Canal Administrator, commented that it was unfair to assume that damage to the fenders were a result of poor conditions, because the fenders are designed to lessen the severity of collisions and are expected to fall off and be replaced. However, Mr. Quijano has mentioned that he believes in working towards continuous improvements and is pushing for further captain training to satisfy increased demand in the future (Bogdanich et al., 2016a).

Aside from the collisions, the opening of the Panama Canal Expansion has welcomed many positive achievements. For example, on July 23, 2016 the Panama Canal announced the launch of the Green Connection Award as a "new initiative to recognize customers who demonstrate excellent environmental stewardship, and to encourage others to implement technologies and standards to help reduce greenhouse gas emissions" (Autoridad del Canal de Panamá, 2016f). The Panama Canal strongly supports the effort towards sustainability by providing opportunities for ships to reduce traveling distance and thereby reducing carbon dioxide (CO_2) emissions. The original Panama Canal has contributed by reducing 650 million tons (590 million tonnes) of CO_2 emissions. It has been estimated that the expanded canal will reduce "160 million tons of CO_2 emissions in the next ten years" (Autoridad del Canal de Panamá, 2016f). The first recipient of the Green Connection Award was Maran Gas Apollonia and Shell International Trading & Shipping Company for their contribution to reducing CO_2 emissions as a result of utilizing the Panama Canal (American Journal of Transportation, 2016).

Another notable achievement includes the first liquefied natural gas (LNG) tanker that passed through the expanded locks on July 25, 2016 (Autoridad del Canal de Panamá, 2016c). The expansion of the canal allows 88% of the LNG tankers to pass through, compared to the 9%

that were able to fit through the old facilities (Horn, 2016). This change in accessibility will have a major impact on global LNG trade. Specifically, the expanded canal will allow the export of LNG from the United States to Asian markets in a significantly shorter amount of time, up to 22.8 days of reduced voyage time roundtrip (Autoridad del Canal de Panamá, 2016c). In addition to these achievements, the Panama Canal celebrated several successful transits thus far. As of August 3, 2016, the expanded canal had 69 neo-Panamax vessels transit the locks, including 40 container ships, 24 LPG vessels, three vehicle carriers, and two LNG carriers. At that time, there were more than 250 reservations from neo-Panamax vessels to pass through the expanded canal (American Journal of Transportation, 2016). These accomplishments illustrate the positive impact that the Panama Canal Expansion has on environmental sustainability and the fast growth of global trade.

7.0 Summary

The age of the canal structures, as well as the expansion of the waterway, created new challenges for the ACP. With a higher number of transits and larger ships, there was an increase in salinity in Gatún Lake, which provides water to residents of Panama. The Mount Hope Water Filtration Plant is now operating at a higher volume than it was initially designed for, and as updates are being made to the plant, the water flow through the system must be analyzed under the new conditions. Due to the raised level of Gatún Lake and the increased traffic through the canal, maintaining the dam and spillway structures has become even more important. To sustain this global trade enterprise, all components need to be fully operational and in proper working condition. The following projects work towards solving these new challenges.

III. Analysis of Water Purification Plants of the ACP

1.0 Design Statement

This chapter contains two projects related to water quality and purification processes in water treatment plants, performed in conjunction with the ACP. Both projects adhered to specific requirements set forth by Worcester Polytechnic Institute and ABET to complete a design capstone, known as the MQP. According to ABET, an engineering design capstone must be open-ended, include analysis and synthesis in an iterative cycle, and consider engineering standards and realistic constraints.

The first project, *Analysis of Chemical Consumption Patterns at Miraflores Filtration Plant*, completed by Liliana Almonte and Sonia Zarate, combined applied statistics experience from undergraduate coursework, knowledge gained from extensive literature review, and fieldwork to identify changes in chemical consumption during water treatment at the Miraflores Filtration Plant. Concern has been raised over the quality of water in Gatún Lake and its effect on water treatment following the expansion of the Panama Canal.

With an increasing number of transits and larger ships passing through the third set of locks, a higher volume of ocean water is displaced into Gatún Lake, potentially causing changes to water quality parameters. Maintaining the quality of water in Gatún Lake is essential for the safe distribution of drinking water to 35% of Panama's residents. This analysis, requested by the ACP Water Quality Division, identified chemical dosing trends, both pre- and post-expansion, and relationships between consumption patterns and water parameters. In order to complete this project, economics, climate, and health and safety constraints were considered.

Economic constraints were considered for alternative treatment recommendations that were cost-effective and feasible given, the current quality of the raw water. Climate constraints were taken into account because seasonal changes in Panama impact the quality of water being treated and thus, changes in the dosing of chemicals had to be accounted for in the analysis. Finally, the health and safety of the public was considered, as changes in water quality and the amount of chemicals used during treatment could affect the safe distribution of potable water. As a result, a protocol was designed that outlines steps for water sampling within the plant and methods to statistically analyze patterns of chemical consumption and their relationships to different water quality parameters. This protocol will facilitate the further investigation of changes in water quality and its impact on the treatment process as a result of the Panama Canal Expansion.

The second project, *Process Analysis of Mount Hope Water Filtration Plant*, completed by Julia Ring, incorporated knowledge of fluid mechanics from previous coursework with information from an extensive literature review and field visits to evaluate the flow patterns through three structures in the Mount Hope Water Filtration Plant. This assessment contributed to a larger study of the plant performed by the Hydraulics Engineering Unit of the ACP.

The treatment plant reached 100 years of operation in 2014. After providing the surrounding regions with clean water for more than a century, plant operators have requested that calculations describing flow and analyses of the structures' productivity be performed. This project consisted of the evaluation of the rapid mixing chamber, flocculators, and sedimentation basin. Over the course of completion, several design constraints were encountered and acknowledged, including physical restrictions, sustainability, economics, and health and safety.

While there were numerous solutions to the problems mathematically, real world constraints limited the number of recommendations that could be provided to ACP personnel. In terms of physicality, the rapid mixer, flocculators, and sedimentation basin are already built and in place, therefore only small modifications to their designs could be recommended. These recommendations were made with caution, however, as economics and sustainability would play a role in such changes. The expenses associated with renovations would require thorough cost-benefit analyses. Furthermore, the structures have proved to be sturdy and sustainable, meaning that modifications to them would also be expected to stand the test of time. Finally, the health and safety of the public was of concern when considering the Mount Hope Water Filtration Plant because it provides potable water to the residents of Colón. Taking these constraints into consideration, CAD drawings were made using field measurements and a series of spreadsheets, used to calculate the flow of water through different components the plant, was designed.

Collectively, these projects explored the quality of the water in Gatún Lake and purification methods prior to public distribution. This chapter provides recommendations to ensure effective water treatment through continuous monitoring, contingency plans, and design updates.

2.0 Background

In addition to acting as a maritime passage between the Atlantic and Pacific Oceans, the water contained within the Panama Canal serves as a major source of drinking water for Panama's residents. The ACP manages three filtration plants – Miraflores, Mount Hope, and Mendoza – to treat raw water drawn from the canal prior to public distribution. These plants continuously undergo operational updates and their proper functioning is integral to the community's well-being.

2.1 Conventional Water Treatment

Raw water must be purified by passing it through a series of progressively refined steps before it is potable, or safe for human consumption. Purification involves the removal of suspended solids, colloidal matter, and dissolved matter (Water Treatment Handbook, 2007). In conventional water treatment, filtration plants commonly process raw intake through aerators, rapid mixers, flocculators, sedimentation basins, and filters to produce a final product that can be distributed and used safely.

Aeration is often one of the first steps in the water purification process. During this procedure, the water is brought into contact with air to facilitate the transfer of dissolved gases and volatile substances. Depending on the contents of the influent water, this transfer can either introduce substances to or remove substances from the water. Contents that need to be treated via aeration include hydrogen sulfide, carbon dioxide, methane, oxygen, iron, manganese, and organic compounds. By employing this step in the filtration process, operators can ensure that the water traveling further into the plant is more oxygen rich, contains less taste- and odor-producing matter, and contains fewer substances that may increase treatment costs in subsequent phases of purification (Department of the Army Corps of Engineers, 1984).

Waterfall aerators use nozzles to spray influent water vertically upward (Department of the Army Corps of Engineers, 1984). They facilitate the increase of the contact surface area between the water and air, encouraging more gaseous diffusion, and therefore elevating the number of chemical reactions that occur to purify the water (Figure 10). The aerated water falls back down into the aeration basin and exits towards the next stage in the filtration procedure (Water Treatment Handbook, 2007).

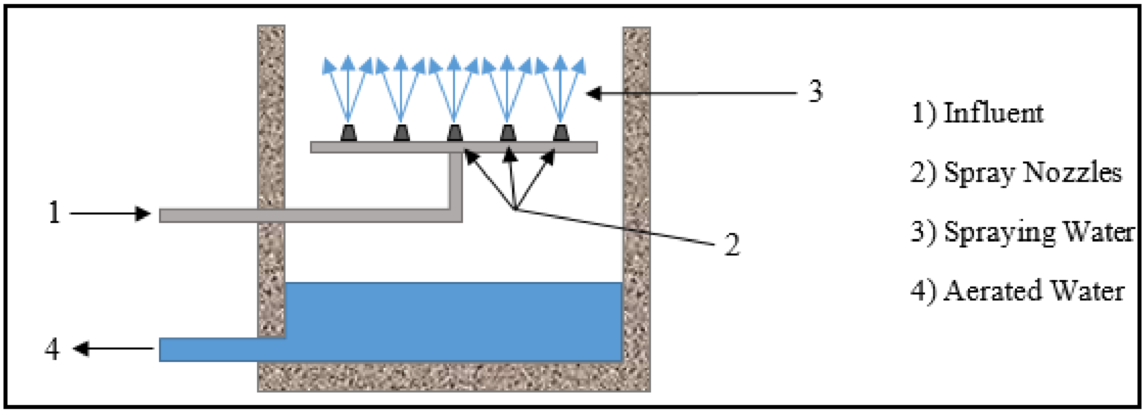


Figure 10: Simple schematic of a spray nozzle waterfall aerator (Water Treatment Handbook, 2007)

Rapid mixing chambers exist to introduce coagulants and other chemicals to the influent water as quickly and uniformly as possible. A coagulant is a chemical that reacts with the suspended particles that cause turbidity and color in the water. They are considered effective when they reduce the repellent inter-particulate forces enough that the gravitational forces between the particles dominate, causing them to clump together. These clumps are called micro-flocs (Department of the Army Corps of Engineers, 1984). This formation is essential to the water treatment process, because individually, the suspended particles are too small in diameter to be mechanically filtered out, and are too low in density to settle out of the water fast enough to be cost efficient (Table 4) (Water Treatment Handbook, 2007).

Table 4: Relationship between increasing sedimentation times and decreasing particle diameters
**for water depth of 3.38 ft (1 m) (Water Treatment Handbook, 2007, p. 186)*

Particle Diameter (in)	Particle Diameter (mm)	Particle Type	Sedimentation Time*	Classification
0.39	10	Gravel	1 second	Settleable Suspended Solids
0.039	1	Sand	10 seconds	
$3.9x10^{-3}$	10^{-1}	Fine Sand	2 minutes	
$3.9x10^{-4}$	10^{-2}	Silt	2 hours	
$3.9x10^{-4}$	10^{-2}	Protozoa Cysts	20 hours	Colloids
$3.9x10^{-5}$	10^{-3}	Clay	2 days	
$3.9x10^{-5}$	10^{-3}	Bacteria	8 days	
$3.9x10^{-6}$	10^{-4}	Colloid	2 years	
$3.9x10^{-7}$	10^{-5}	Colloid	20 years	

Detention times for rapid mixers generally last up to two minutes and the velocity gradients, or the differences between particle speeds, must be high (Department of the Army Corps of Engineers, 2001). When detention times in rapid mixing chambers become much longer, the effects start counteracting the purification process. Although the turbulence within a rapid mixer encourages initial micro-floc formation, the frequency of particle collisions and the forces when such impacts occur are too high for larger flocs to withstand. Instead, flocs that are too large will shear apart, re-introducing smaller matter to the water (Kocamemi, n.d.).

Flocculation, "the joining together of smaller particles into larger, settleable, and filterable particles," is a direct result of coagulation and generally takes place in the beginning sections of a sedimentation basin (Department of the Army Corps of Engineers, 1984, p. 3.4). Flocculators mix water at much lower velocity gradients for longer detention times than rapid mixers in order to encourage low-shear collisions that facilitate floc formation. The slow mixing through a flocculator can be achieved by baffles or mechanically rotating stirrers (Kocamemi, n.d.). Baffles offer the advantage of compartmentalizing a flocculator to prevent some of the water traveling faster through the process, therefore not being cleaned as well. Rotating flocculators offer the advantage of having easily adjustable speeds to maintain certain purification standards.

It has been observed that flocculation basins with progressively decreasing velocity gradients across their length are more productive. Flocculators are considered productive when the flocs created are either large enough to settle out of the water on their own in sedimentation basins, or to be removed as the water passes through filters (Department of the Army Corps of Engineers, 1984). According to the Water Treatment Handbook (2007), particles at least 3.9×10^{-4} in (10^{-2} mm) in diameter are considered settleable suspended solids (Table 4).

After spending between 10 and 60 minutes in a flocculator, the water traverses the length of the sedimentation basin over the course of two to four hours, during which time the flocs and other sediment in the water can settle to the bottom of the structure (Crittenden, Trussell, Hand, Howe, & Tchobanoglous, 2012; Department of the Army Corps of Engineers, 1984). It is important that the velocity through this section is very low, allowing enough time for the matter to sink and preventing already separated particles from being stirred back up into the passing water (Department of the Army Corps of Engineers, 1984). Similar to some flocculators, sedimentation basins can be baffled to keep the water velocity down.

The most common types of sedimentation basins are either rectangular or circular. Both require sludge removal methods in place, whether they be mechanical or manual. Sedimentation basins found in the ACP water treatment plants are horizontal flow, rectangular static settling tanks. These designs require the basins to be periodically shut down, drained, and manually rinsed clean with pressurized water jets. The complicated, labor-intensive maintenance and longer detention times are drawbacks that need to be considered when designing a rectangular sedimentation basin (Water Treatment Handbook, 2007).

Filtration often follows sedimentation and is one of the last purification steps. It is the process by which a "solid-liquid mixture is percolated through a porous medium (filter) which ideally screens out solid particles, letting the liquid (filtrate) through" (Water Treatment Handbook, 2007, p. 252). Generally, the solid particles removed at this stage have diameters no smaller than $3.9 \times 10^{-8} - 2.0 \times 10^{-3}$ in (0.001 – 50 μm). The most commonly used types are rapid sand filters, which are an example of granular filters (Department of the Army Corps of Engineers, 1984). Granular filters clean passing water by catching and holding pollutant particles in the inter-granular spaces (Water Treatment Handbook, 2007).

Filters composed of several different layers are referred to as "multimedia filters." The materials in a multimedia filter are layered in order of grade size and vary in thickness (Figure 11). Underdrains made of perforated pipes and covered in gravel run underneath the granular matter, often forming a grid pattern. Influent flows through the finest layers first, gradually making its way to the gravel and underdrains, directing the purified water to a clear basin (Department of the Army Corps of Engineers, 1984).

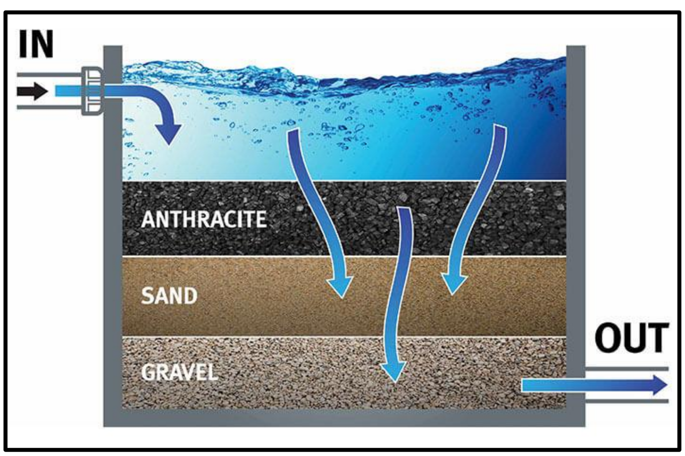


Figure 11: Simple schematic of a multimedia filter (Desal Process)

Filters need to be cleaned on a regular basis to ensure that the quality of the water produced by the purification plant is maintained. Multimedia filters respond best to successive water and air washes. In this method, air first scours the granular filter material to detach the trapped impurities, such as mud balls, from the inter-granular spaces. After that, wash water is passed through the filter in reverse to remove the pollutants, in addition to regrading and expanding the layers. Depending on the filter, this cleaning process may need to be repeated multiple times before it can begin purifying water again (Water Treatment Handbook, 2007).

2.2 Velocity Gradients

The velocity gradient of a flowing fluid measures the relative velocity between two particles over the distance between them (Figure 12) (Kocamemi, n.d.). This parameter is often used in the study of fluids, especially when discussing hydraulics. In terms of the hydraulic flows through a water treatment plant, the velocity gradient parameter provides facility operators with information about the motion of the water. It is applicable when analyzing rapid mixers and flocculators. High velocity gradients are more commonly found in rapid mixers, where the fluid particles have high energies and collide with one another roughly and frequently. Low velocity gradients indicate a gentle flow pattern with low energy, often sought after when designing flocculators.

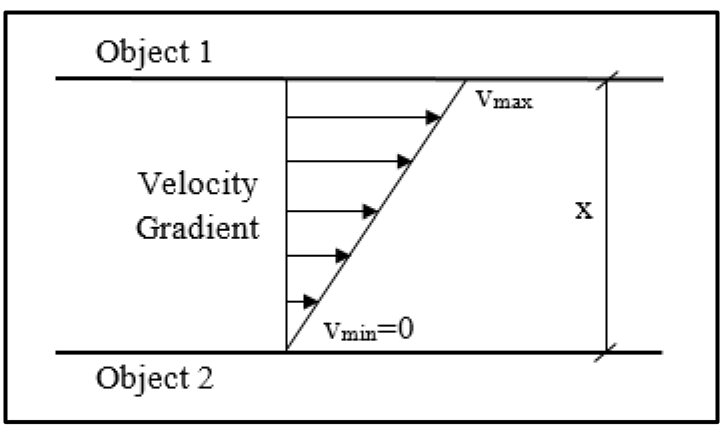


Figure 12: Velocity gradient between two objects (Ring, 2016b)

2.3 Water Filtration Plants

Of the three water filtration plants managed by the ACP, Mount Hope and Miraflores were the two established during the construction of the Panama Canal to provide clean water to laborers working in the Canal Zone. The Mount Hope Water Filtration Plant, opened on

February 23, 1914, is located in the city of Columbus on the Atlantic side of the Panama Canal, in the province of Colón (Office of the Governor, 1916). It produces 36 MGD (136 ML/day), of which 30 – 35 MGD (113 – 132 ML/day) are sold to the National Institute of Aqueducts and Sewers (IDAAN), a company that then distributes the clean, potable water to Mount Hope, Colón, Randolph, Gatún, and Gulick (Appendix A) (Bramwell, 2016; Autoridad del Canal de Panamá, 2010b). The Miraflores Filtration Plant, opened on March 14, 1915, is located on the Pacific side of Panama (Office of the Governor, 1916). It produces an average of 48 – 50 MGD (182 – 189 ML/day) and thus is the largest of the ACP water production sites. A maximum of 45 MGD (170 ML/day) are purchased by IDAAN to supply potable water to residents of Ancón, Arraijan, Avenida Nacional, Bella Vista, Calidonia, Casco Antiguo, Chorrillo, Curundu, El Chorrillo, San Felipe, Santa Ana, and Perejil, all neighborhoods of Panama City (Autoridad del Canal de Panamá, 2010b). The rest of the water produced by Miraflores is utilized for internal operations in the Panama Canal. Although both filtration plants follow conventional water treatment, there are some differences between their two layouts (Appendix B).

The water supplied to both plants originates in Gatún Lake, where it is drawn from various intake points and then carried by gravity to the plants. The raw water supplied to the Mount Hope plant stops intermittently in the Brazos Brook Reservoir, where three conduction pipes transport it to the waterworks center. As they enter the facility, all three supplies are metered to monitor the water's flow and initial turbidity (Bramwell, 2016). The raw water being supplied to the Miraflores plant is obtained from two intake points: Gamboa and Paraiso. Gate valves are utilized to regulate water flow and allow for an initial mix between raw water from both intake points (Acevedo, 2011). From this point forward, the raw water in both plants is treated through conventional water purification processes.

First, the raw water travels to the aeration basins where it passes through spray nozzle waterfall aerators. At Mount Hope, the basin is a 60 ft by 66 ft (18 m by 20 m) concrete structure containing five batteries with 17 cone nozzles each, for a total of 85 nozzles (Figure 13). At Miraflores, the basin is 86 ft by 130 ft (26 m by 40 m) and equipped with seven batteries of 15 nozzles each, for a total of 105 nozzles (Figure 14). In both locations, the angles that the nozzles are tilted to can be adjusted based on the water conditions at any given time (Office of the Governor, 1916).

Figure 13: Aerial view of Mount Hope Water Filtration Plant (Autoridad del Canal de Panamá, 2016e)

Figure 14: Aerial view of Miraflores Filtration Plant (Autoridad del Canal de Panamá, 2016e)

Following aeration, the water travels to three concrete rapid mixing chambers designed with alternating vertical baffles to ensure coagulant dispersion in a matter of seconds (Office of the Governor, 1916). At both plants, chemicals including chlorine, aluminum sulfate (alum), activated carbon, and fluoride are added during rapid mixing. In addition, polymers are added at this step at the Miraflores plant. Each chemical has a distinct role in the water treatment process (Table 5). Regulations state that chlorine levels should fall in the range of 0.8 – 1.5 ppm and fluoride levels within 0.6 – 0.8 ppm. At Miraflores, the usual applied dose of alum falls within 10 – 50 ppm, activated carbon within 0 – 0.7 ppm, and polymers within 0 – 1.0 ppm (Autoridad del Canal de Panamá, 2016a). If the monitors detect levels outside of the prescribed ranges, operators must adjust the amount of chemicals being added to ensure proper water quality (Bramwell, 2016).

Both the distance and time spent in the mixing chambers are short before the water goes through the flocculation and sedimentation stages. The influent at both plants is directed to three cross-connected parallel sedimentation basins by weirs at the entrances. The weirs allow operators to control to which pathways the water is diverted. In the Mount Hope plant, the basin as a whole measures 171 ft by 171 ft (52 m by 52 m) with a total volume capacity of 2.5 million gal (9.5 ML). These basins are divided into three square compartments by two pressure baffle walls. Between each set of pressure walls are three light baffle walls that are offset horizontally from one another, allowing water to pass through the basin in a side-to-side pattern. In each of the first two compartments of the sedimentation basin, there are three paddle-wheel flocculators, connected by a horizontal axis. Because the water is fairly clean upon entry, the six total wheels are only utilized during heavy storms that result in turbidity increases in Gatún Lake. Otherwise, the compartments where the flocculators are located serve as additional sedimentation space. In the Miraflores plant, the basin as a whole measures 300 ft by 125 ft (91 m by 38 m). These

Table 5: Chemicals utilized during water treatment at Miraflores

Chemical	Purpose	Point of Dosing
Chlorine	Disinfects to kill bacteria and algae. Helps to eliminate taste and odor problems.	Rapid Mix, Recollection Chamber
Aluminum Sulfate	Neutralizes negative charge of solids to allow them to combine and create floc particles. Helps to eliminate solids.	Rapid Mix
Activated Carbon	Helps to eliminate taste and odor problems.	Rapid Mix
Polymers	Three different types utilized: coagulant aid, flocculation aid, and filtration aid. Dosing is not consistent and only used when necessary.	Rapid Mix, Sedimentation
Fluoride	Contributes to good dental health	Rapid Mix

basins are divided into seven rectangular compartments by two pressure baffle walls and four light baffle walls. The pressure baffle walls contain five rectangular openings and the light baffle walls contain four arched openings, all of which allow water to pass through (Office of the Governor, 1916). In the first compartment of each basin, there are nine paddle-wheel flocculators. In the next six compartments, the water goes through the sedimentation process.

After exiting the final sedimentation compartment, the water travels through rapid sand gravity filters. In both plants, the filters consist of a gravel base, overlain by sand, and topped with anthracite coal (Bramwell, 2016). At Mount Hope, there are ten filters laid out into two rows of five (Bramwell, 2016), while Miraflores has 20 filters, organized in two rows of ten. The filtration process is regulated through connected monitoring software and hydraulic valves (Office of the Governor, 1916). Once filtered, the potable water travels to the clear water basins for storage, then distributed through pumping stations to the community.

2.4 Water Quality in Gatún Lake

At the Miraflores Filtration Plant, certain parameters are monitored daily to ensure safe drinking water standards are met (Table 6). Following the opening of the third set of locks, special concern was raised regarding the quality of water in Gatún Lake, as it supplies the influent treated at Miraflores. Prior to the expansion, Gatún Lake had an operating range of 81.5 – 87.5 ft (24.9 – 26.7 m) (Bunch, Johnson, & Sarruff, 2003). The maximum operating level has since been raised to 89 ft (27.1 m) to increase the water supply (Autoridad del Canal de Panamá, 2015). Currently, Gatún Lake is able to store nearly 52.8 billion gal (200 GL) of water,

Table 6: Parameters measured daily for safe drinking water (Dirección General de Normas y Tecnología Industrial; Comisión Panameña de Normas Industriales y Técnicas, 1999)

Parameter	Maximum Permissible Value	Unit
Alkalinity	120	Mg $CaCO_3$/L
Bacteria: Total Coliforms (Including Fecal Coliforms and E. coli)	0	N° of colonies/100mL
Fluoride	0.6 – 0.8	mg/L
pH	6.5 – 8.5	pH unit
Residual Chlorine	0.8 – 1.5	mg/L
Salinity	≤ 0.20	ppt
Turbidity	< 1.0	NTU
Total Dissolved Solids	0-500	mg/L

which allow for “approximately 1,100 additional transits every year” (Autoridad del Canal de Panamá, 2015).

Operational changes have impacted salinity levels in the water from Gatún Lake. Salinity can be defined as the amount of dissolved salt in water and is usually measured in parts per thousand (ppt). As explained by the U.S. EPA (), the average ocean salinity is 35 ppt, meaning that in every kilogram (2.2 lbs) of seawater, 35 grams (0.08 lbs) are salt. For river water, salinity is usually 0.5 ppt or less.

Salt intrusion, the movement of seawater into freshwater, is a factor that increases salinity in Gatún Lake. As ships sail in or out of the locks, “density flows will occur from lock chambers containing water that is either saltier or fresher than the water into which the gates are opened” (Parchure, Wilhelms, Sarruff, & McAnally, 2000). With an increasing number of transits and larger ships passing through the third set of locks, a higher volume of mixed salt and fresh water, will be displaced into Gatún Lake, potentially causing undesirable salinity levels.

The State Water Resources Control Board in California (2016) explains that “high concentrations of salts can damage crops, affect plant growth, degrade drinking water, and damage home or industrial equipment.” Maintaining suitable levels of salinity in Gatún Lake is essential for the distribution of drinking water to approximately 35% of Panama’s residents (Worldmark Encyclopedia of Nations, 2007). Prior to the Panama Canal Expansion, salinity levels in Gatún Lake were recorded to be less than 0.1 ppt. However, a report by DHI Water Environment (2005) predicted that after the expansion, a variation in salinity levels would occur and recommended new measurements to be executed in the Gatún area.

Salinity values can be determined by measuring the ability of electrically charged particles to pass through water. This property, also called electrical conductivity, is directly related to the total dissolved solids (TDS) found in a given volume of water. The more salt that is dissolved in the water, the higher the electric conductivity. TDS are charged ions such as minerals, salts, metals, cations, or anions dissolved in water (Oram). The dissolved solids come from a variety of organic sources, including leaves, silt, plankton, and industrial waste and sewage (TDS Meter, 2005). TDS is measured by “evaporating a known volume of water to dryness, then weighing the solid residue remaining” (Cummings & Anderson, 1999). Depending on the total amount of dissolved salts calculated, water can be classified and used for different purposes (Table 7).

Table 7: Salinity status classifications, by total salt concentration (Western Australia Department of Water)

Salinity Status	**Salinity (ppt)**	**Description and Use**
Fresh	<0.5	Drinking and all irrigation
Marginal	0.5 – 1	Most irrigation, adverse effects on ecosystems become apparent
Brackish	1 – 2	Irrigation for certain crops only; useful for most livestock
Saline	2 – 10	Useful for most livestock
Highly Saline	10 – 35	Very saline groundwater, limited use for certain livestock
Brine	>35	Seawater; some mining and industrial uses exist

3.0 Analysis of Chemical Consumption Patterns at Miraflores Filtration Plant

3.1 Methodology

The goal of this project was to evaluate the relationship between certain water quality parameters, including salinity, and chemical consumption patterns at the Miraflores Filtration Plant before and after the inauguration of the Panama Canal Expansion. To achieve this goal, the following research objectives were outlined:

1. Establish a complete understanding of the day-to-day plant operations.
2. Collect data regarding water quality parameters and chemical consumption.
3. Establish consumption patterns pre- and post- expansion operations and identify if dosing of chemicals has increased.
4. Determine if a relationship exists between salinity, among other parameters, and chemical consumption patterns through statistical analyses.

3.1.1 Establish Complete Understanding of Operations

To gain a complete understanding of operations within the Miraflores Filtration Plant, a technical tour was completed to enable the visualization of each process. The tour was conducted by the plant operator and senior chemist. To ensure full comprehension, the plant operator led the tour in Spanish and the senior chemist provided English translations when necessary. The tour began with a brief overview of plant operations as a whole before providing specific details about each step. The tour had five primary stops, including the water aeration basin, chemical dosing station, rapid mixing chamber, flocculation and sedimentation basins, and filtration basins.

To understand how field and laboratory data are managed and stored at the plant, a one-hour introductory course on Water Resources Database (WRDB) was presented by the software developer. WRDB is a Microsoft Windows application designed to meet the demand for practical and effective management of familiar water resource data (Wilson Engineering, 2016). The course covered understanding the database’s organization, locating desired information through advanced queries, importing and exporting information in multiple ways, and conducting data analyses through graphs and reports.

3.1.2 Collect Water Quality Parameters and Chemical Consumption Data

To determine which chemicals would be involved in the analysis and identify parameters that potentially affect the consumption of chemicals, an investigation outline was established. Of the five chemicals used at the Miraflores plant, chlorine and alum were chosen due to their critical roles in the water treatment process as a disinfectant and coagulant. Although activated carbon eliminates taste and odor problems and fluoride provides dental health benefits, these are secondary concerns after the elimination of bacteria and solids. Polymers were not included in the investigation due to infrequent use of any specific type of polymer. For parameters, turbidity of raw water and volume of influent were selected, in addition to salinity, to include in the study, as they directly relate to the consumption of chemicals.

A variety of water quality parameters were collected through field measurements starting on July 5, 2016 (Table 8). Utilizing a YSI Professional Plus multi-parameter instrument, water samples were analyzed within the Miraflores plant distribution system. Seven different stations were sampled daily; two containing raw water and five containing treated water (Figure 15). Faucets at each station were opened to let water run for an average length of three to five minutes

Table 8: YSI multi-parameter instrument specifications (YSI, 2012)

Parameter	Sensor Type
Temperature	Thermometer
pH	Glass combination electrode
Conductivity	Four electrode cell
Salinity	Calculated from conductivity and temperature
Total Dissolved Solids (TDS)	Calculated from conductivity and temperature
Dissolved Oxygen	Polarographic or galvanic
Dissolved Oxygen	Polarographic or galvanic

Figure 15: Water collection stations at Miraflores Water Treatment Plant (Google Maps, 2016)

in order to flush standing water in the pipes. The instrument container was then filled with water to ¾ of its allowable capacity and closed off with a four-port sensor cable that determines the parameters. Finally, once the values had stabilized, the data were captured on a printable spreadsheet named "Datos de Campo," provided by the ACP.

Chemical consumption data from October 1, 2015 to September 15, 2016 were obtained from the Miraflores Filtration Plant personnel, accounting for a majority of operations during the fiscal year. Operators measure turbidity levels for raw water and consumption of chemicals for treated water daily. This information is recorded on an hourly basis and manually written in confidential spreadsheets. Through coordination with the Miraflores Filtration Plant Superintendent, specific data were extracted from these spreadsheets and utilized for analysis. Furthermore, data on the volume of raw water entering the plant were provided. An Excel spreadsheet was then created to record all of the data obtained in one cohesive document.

3.1.3 Establish Chemical Consumption Patterns

Descriptive statistics were first performed with the chemical consumption data to create a box-and-whisker plot using STATISTICA 12, a data analysis software. The plot provided information regarding the mean, median, standard deviation, minimum and maximum, and interquartile range. This enabled the summarization and basic understanding of the information collected. The data were organized into four time periods to account for seasonal weather, operations prior to and after the expansion, and to ensure equal sample sizes. Period 1 (Oct 1, 2015 – Dec 31, 2015) represented frequent rainfall. Period 2 (Jan 1, 2016 – Mar 31, 2016) represented dry conditions. Period 3 (Apr 1, 2016 – Jun 26, 2016) represented dry conditions throughout April and frequent rainfall from May onwards. Period 4 (Jun 27, 2016 – Sep 15, 2016) represented data from after the expansion with frequent rainfall. Due to higher water contamination during the rainy season, the consumption of chemicals was expected to be greater during water treatment. Finally, a graph of chemical consumption over time was created using Excel to visually identify patterns with consideration to the different weather conditions and operational changes.

Chemical consumption histograms that illustrated the frequency of data points within a specific range were created using STATISTICA 12. A curve was superimposed over the histograms to indicate if the data followed a normal distribution. Normal distribution refers to when the mean, median, and mode of a data set are equal and values are distributed evenly around a central value (Martin Martin, Cabero Moran, & Paz Santa, 2008). Understanding if the dataset followed a normal distribution was important to determine if a parametric or non-parametric test should be performed to identify significant statistical changes and create correlations between different variables (Table 9).

To statistically prove if the data followed a specific distribution, the Anderson-Darling (A-D) test was performed. This test uses a specific distribution to calculate critical values and results in a final acceptance or rejection of the null hypothesis, H_0. If the null hypothesis is rejected, then the data are said to favor the alternative hypothesis, H_a. The significance level (α) of this test was defined as 0.05. Significance level is the probability that the null hypothesis is rejected when it is true (The Pennsylvania State University, 2016a). If the probability was calculated to be less than or equal to the significance level of 0.05, then the null hypothesis was rejected. This probability value, p, is defined as the likelihood of observing a test statistic that favors the alternative hypothesis (The Pennsylvania State University, 2016b). After the distribution was identified and the corresponding tests were performed, graphical comparisons of chemical consumption patterns from Periods 1, 2, and 3 to Period 4 were created using Excel to illustrate the results of the tests.

3.1.4 Determine Relationship between Salinity and Chemical Consumption Patterns

To investigate whether a relationship exists between possible chemical consumption changes and salinity, turbidity, and volume, a correlation analysis was carried out. Correlations are a measure of the linear association between two variables (Encyclopaedia Britannica, 2016). The analysis outputs correlation coefficients that vary between +1 and -1. The closer the coefficient is to ±1, the higher the association between variables. The type of correlation analysis utilized depends on the nature of the data (Table 9). Graphical representations of correlations between chemical consumption patterns and the investigated parameters were created using Excel to display the results of the analysis.

Table 9: List of parametric and non-parametric tests (Hoskin, n.d.)

	Parametric	**Non-parametric**
Assumed distribution	Normal	Any
Central Measure	Mean	Median
Compare means between two distinct/independent groups	Two-sample t-test	Wilcoxon rank sum test
Estimate the degree of association between two quantitative variables	Pearson coefficient of correlation	Spearman's rank correlation

3.2 Results and Analysis

Descriptive statistics, illustrated through box and whisker plots, provided values for the mean, median, minimum and maximum, standard deviation, and interquartile range for chlorine and alum consumption at the Miraflores Filtration Plant (Figure 16 and Figure 17). Mean values for chlorine, 1,060 lbs (481 kg) per day, and alum, 12,386 lbs (5,618 kg) per day, indicate that the highest amount of chemical consumption occurred during Period 1 (Oct 1, 2015 – Dec 31). During Period 2 (Jan 1, 2016 – Mar 31, 2016), the average amount of consumption decreased by 190 lbs (86 kg) per day for chlorine and 2,015 lbs (914 kg) per day for alum. While chlorine consumption increased through Period 3 (Apr 1, 2016 – Jun 26, 2016) and Period 4 (Jun 27, 2016 – Sep 15, 2016), alum consumption continued to decrease after Period 1. The most significant minimum and maximum variances for chlorine and alum consumption occurred during Period 4. For chlorine, a maximum amount of 1,278 lbs (580 kg) was utilized on July 5, 2016, days after the expansion inauguration occurred. For alum, a maximum amount of 17,612 lbs (7,989 kg) was utilized on July 4, 2016.

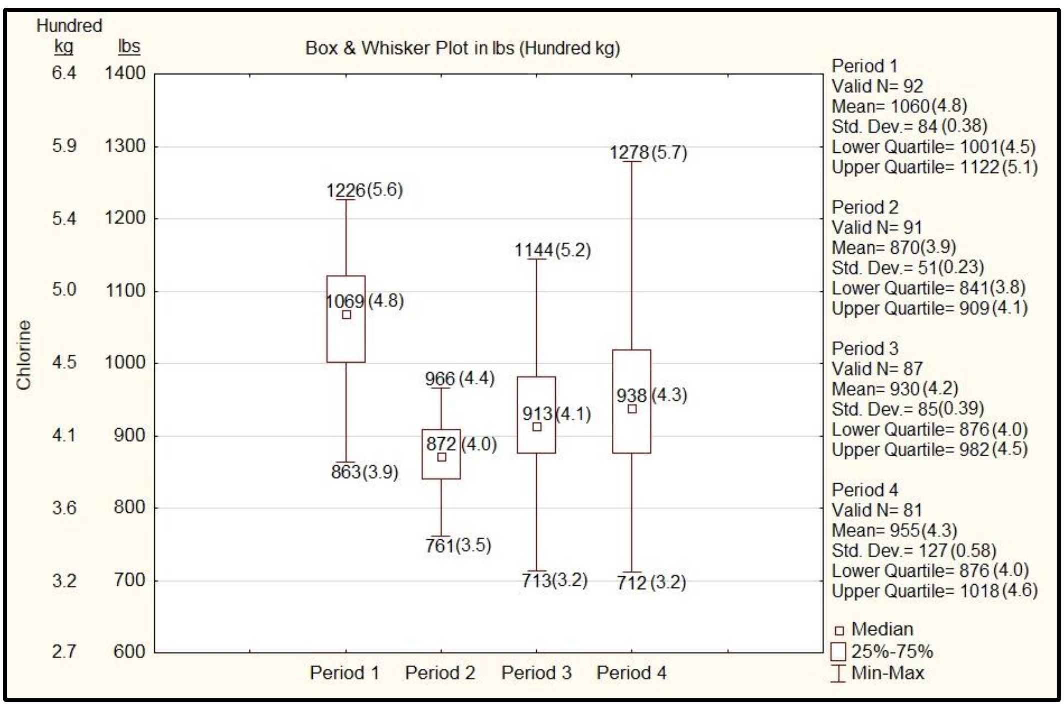


Figure 16: Box and whisker plot of chlorine consumption

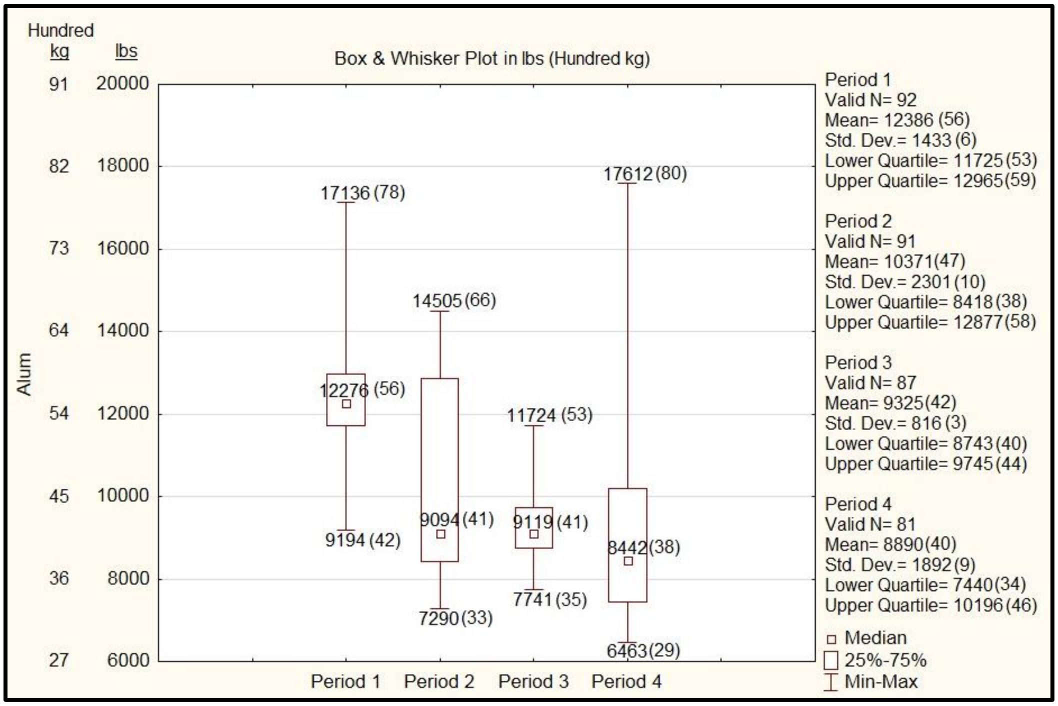


Figure 17: Box and whisker plot of alum consumption

For chlorine, the highest range of consumption, 800 – 1,200 lbs (363 – 544 kg), was attained during Period 1 (Figure 18). While during Period 2, the range decreased gradually to 700 – 900 lbs (318 – 408 kg), an increase in range of 700 – 1,100 lbs (318 – 499 kg) occurred during Period 3 and of 700 – 1,200 lbs (318 – 544 kg) during Period 4. Similarly, the highest range of consumption for alum, 9,000 – 17,000 lbs (4082 – 7711 kg), was attained during Period 1, and was maintained through Period 2, until February 2016. The range then decreased to 8,000 – 12,000 lbs (3629 – 5443 kg) and 6,000 – 17,000 lbs (2722 – 7711 kg) during Periods 3 and 4, respectively. Within Period 4, alum consumption presented an outlier on July 4, 2016 with a value of 17,612 lbs (7989 kg). Without this value, the range of consumption, 6,000 – 13,000 lbs (2722 – 5897 kg), explains the decrease in mean from Period 3.

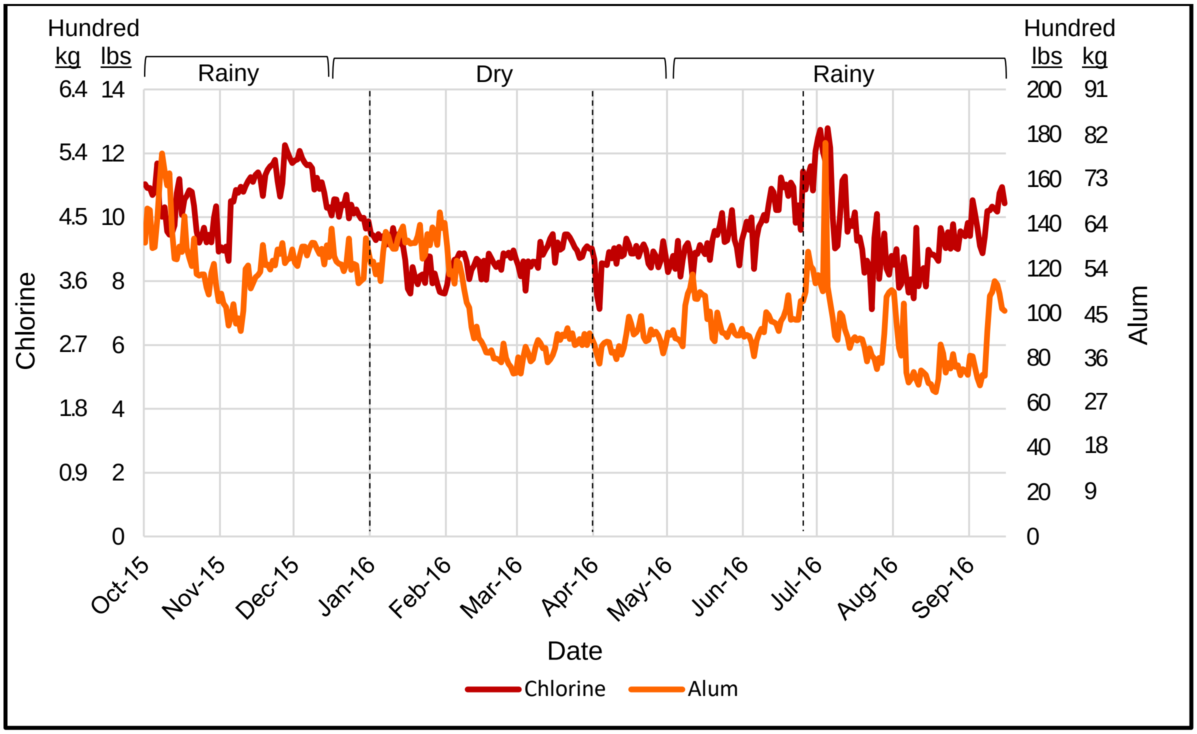


Figure 18: Consumption patterns of chlorine and alum during water treatment at Miraflores

Chemical consumption was expected to be higher during the rainy season. Rainfall causes runoff to enter Gatún Lake and thus increases levels of contamination in the water. Furthermore, it dilutes the concentration of chemicals in the sedimentation basins, as they are exposed to the elements. These factors potentially affect the amount of chemicals utilized during the water treatment process. The chemical consumption patterns of chlorine met the expectations based on seasonal weather. As Periods 1 and 4 encompassed rainy conditions, it was expected that the highest level of consumption would occur during these phases. Meanwhile, the lowest level of consumption occurred during dry weather conditions in Period 2. A combination of dry and rainy conditions was represented by Period 3, explaining the intermediate level of consumption. For alum, the decrease of the interquartile range from Periods 1 to 2 was the only pattern to meet consumption expectations. In Period 2, the consumption of alum maintained higher levels throughout January, despite the dry season starting in mid-December. Finally, the opposite pattern from chlorine was observed as alum consumption continued to decrease after Period 2.

The Anderson-Darling test was performed to prove if the data followed a specific distribution, resulting in a final acceptance or rejection of the null hypothesis, H_0. The null hypothesis stated that the data followed a normal distribution. Contrarily, the alternative hypothesis, H_a, stated that the data did not follow a normal distribution. Anderson-Darling results showed that the consumption of chlorine, $p = 0.0043$, and alum, $p = 0.0015$, did not follow a normal distribution, and therefore resulted in the rejection of the null hypothesis. This can also be seen through the lines superimposed over the histograms; the data lack the symmetry necessary for the distribution to be considered normal (Figure 19 and Figure 20).

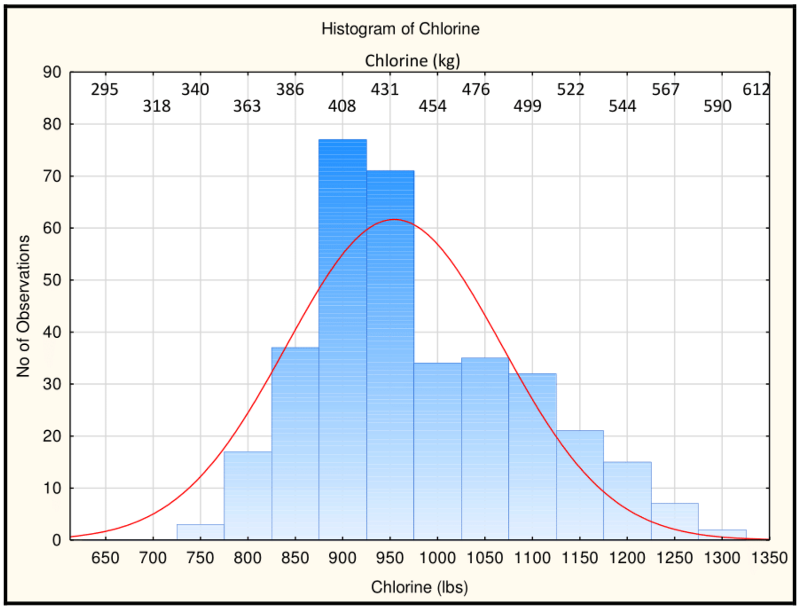


Figure 19: Histogram of chlorine with Anderson-Darling test results

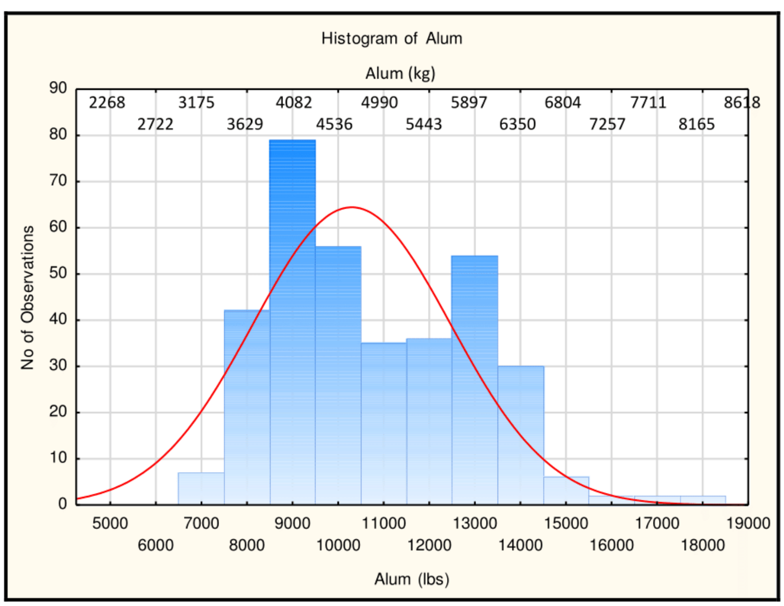


Figure 20: Histogram of alum with Anderson-Darling test results

By concluding that the data set did not follow a normal distribution, a Wilcoxon rank sum test was chosen. This test determines whether two sets of non-normally distributed data are significantly different by comparison of medians, $\tilde{x}$, and results in a final acceptance or rejection of the null hypothesis, H_0. The null hypothesis stated that a significant difference did not occur between the consumption of chemicals before and after the canal expansion. Contrarily, the alternative hypothesis, H_a, stated that there was a significant difference between the consumption of chemicals before and after the canal expansion. The significance level, α, of this test was defined as 0.05. This test compared Periods 1, 2, and 3 to Period 4, which represents post-expansion operations.

The Wilcoxon rank sum test was performed to identify significant changes between periods. Due to the large sample size of chemical consumption data, a z-statistic, Z, was used to calculate the p-value, p. This test showed that the consumption of chlorine, $p = 0.00$, and alum, $p = 0.00$, during Period 1 presented a statistically significant change from consumption during Period 4 (Table 10). Similarly, consumption of chlorine, $p = 0.00$, and alum, $p = 0.00$, during Period 2 also presented a statistically significant change from consumption during Period 4 (Table 11). Lastly, while consumption of alum, $p = 0.04$, during Period 3 presented a statistically significant change from consumption during Period 4, consumption of chlorine, $p = 0.47$, did not present a statistically significant change (Table 12). During Periods 3 and 4, consumption remained within the same general range of values of 3, 700 – 1,100 lbs (318 – 499 kg) and 4, 700 – 1,200 lbs (318 – 544 kg) (Figure 21). In summary, the null hypothesis was rejected for all, excluding chlorine consumption between Periods 3 and 4. Graphs were created to display comparisons of chemical consumption patterns from Periods 1, 2, and 3 to Period 4 (Appendix C).

Table 10: Wilcoxon Matched Pairs Test for chlorine and alum between Period 1 and Period 4

	Wilcoxon Matched Pairs Test Marked tests are significant at p <.05000		
Pair of Variables (Periods)	Valid N	Z	p-value
Chlorine (1&4)	81.00	5.36	0.00
Alum (1&4)	81.00	7.65	0.00

Table 11: Wilcoxon Matched Pairs Test for chlorine and alum between Period 2 and Period 4

Pair of Variables (Periods)	Wilcoxon Matched Pairs Test Marked tests are significant at p <.05000		
	Valid N	Z	p-value
Chlorine (2&4)	81.00	5.84	0.00
Alum (2&4)	81.00	5.52	0.00

Table 12: Wilcoxon Matched Pairs Test for chlorine and alum between Period 3 and Period 4

Pair of Variables (Periods)	Wilcoxon Matched Pairs Test Marked tests are significant at p <.05000		
	Valid N	Z	p-value
Chlorine (3&4)	81.00	0.72	0.47
Alum (3&4)	81.00	2.03	0.04

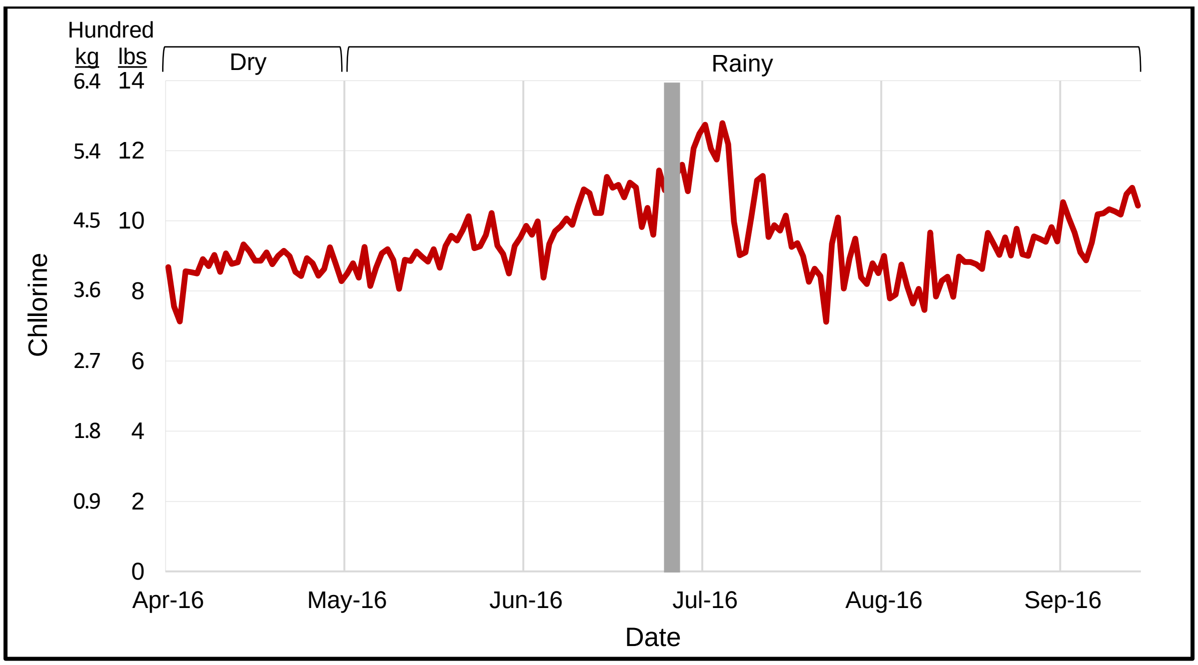


Figure 21: Consumption of chlorine between Period 3 and 4 (gray line represents expansion inauguration date)

As determined using box and whisker plots, the statistically significant change for chlorine consumption between Periods 1 and 4 was a decrease and between Periods 2 and 4 was an increase. The increase from Periods 3 to 4 was found to be statistically insignificant and thus, was not explored further. The decrease between Periods 1 and 4 was of particular importance as both encompass rainy conditions and contained the highest levels of consumption. Overall, the decrease between periods suggests that the expansion of the Panama Canal has not caused chlorine consumption to increase. For alum, all statistically significant changes were decreases. Similarly to chlorine, this suggests that the expansion of the Panama Canal has not caused alum consumption to increase. However, in addition to the effects of seasonal weather, the source of variations of chemical consumption was investigated further by the assessment of salinity, turbidity, and volume.

A Spearman's rank-order correlation was run to estimate the degree of association, ρ, between chemical consumption changes and salinity, turbidity, volume. This analysis encompassed the correlation between Period 4 and Periods 1, 2, and 3. Between Periods 1 and 4, there was a significant, positive correlation between chlorine consumption and turbidity, ρ = 0.40, salinity, ρ = 0.32, and volume, ρ = 0.57 (Table 13). For alum consumption, a significant, positive correlation only occurred with turbidity, ρ = 0.72, and volume, ρ = 0.61, whereas salinity, ρ = -0.24, presented a negative value. This negative correlation represents an inverse relationship, meaning that when one variable increases, the other decreases. Between Periods 2 and 4, there was only a significant, positive correlation between chlorine consumption and salinity, ρ = 0.57 (Table 14). For alum consumption, significant, positive correlations occurred with turbidity, ρ = 0.72, and volume, ρ = 0.61, and a negative, non-significant correlation occurred with salinity, ρ = -0.15, similar to the relationship found during Period 1. Between Periods 3 and 4, there was a significant, positive correlation between chlorine consumption and turbidity, ρ = 0.25, salinity, ρ = 0.44, and volume, ρ = 0.16 (Table 15). For alum consumption, a significant, positive correlation only occurred with turbidity, ρ = 0.51, and volume, ρ = 0.37, while salinity, ρ = -0.15, continued to present a negative correlation. Graphs were created displaying correlations of chemical consumption with the different parameters analyzed between Periods 1, 2, and 3 and Period 4 (Appendix C).

Table 13: Spearman Rank Order Correlations between Periods 1 and 4

	Spearman Rank Order Correlations (Periods 1 vs. 4) Bolded correlations are significant at p <.05000				
Variable	Chlorine	Alum	Turbidity	Salinity	Volume
Chlorine	1.00				
Alum	**0.62**	1.00			
Turbidity	**0.40**	**0.72**	1.00		
Salinity	**0.32**	-0.24	**-0.33**	1.00	
Volume	**0.57**	**0.61**	**0.59**	-0.06	1.00

Table 14: Spearman Rank Order Correlations between Periods 2 and 4

Variable	Spearman Rank Order Correlations (Periods 2 vs. 4) Bolded correlations are significant at p <.05000				
	Chlorine	Alum	Turbidity	Salinity	Volume
Chlorine	1.00				
Alum	0.07	1.00			
Turbidity	0.06	**0.60**	1.00		
Salinity	**0.57**	-0.15	-0.13	1.00	
Volume	-0.03	**0.32**	0.01	-0.14	1.00

Table 15: Spearman Rank Order Correlations between Periods 3 and 4

Variable	Spearman Rank Order Correlations (Periods 3 vs. 4) Bolded correlations are significant at p <.05000				
	Chlorine	Alum	Turbidity	Salinity	Volume
Chlorine	1.00				
Alum	**0.47**	1.00			
Turbidity	**0.25**	**0.51**	1.00		
Salinity	**0.44**	-0.15	**-0.30**	1.00	
Volume	**0.16**	**0.37**	**0.32**	-0.14	1.00

Across all periods analyzed, alum consumption presented a significant, positive correlation with turbidity (Figure 22). During Period 1, the positive correlation can be seen until November 2015, where both alum consumption and turbidity decreased. A stronger linear relationship can be seen during Period 2, where both variables decreased until March 2016. During Period 3, an increase in both alum consumption and turbidity occurred until mid-May 2016. Afterwards, the variables decreased until the conclusion of Period 4, excluding June 2016 where an increase of both can be seen. Overall, the graph shows that high values of alum consumption were associated with high values of turbidity. In addition, alum consumption presented a significant, positive correlation with the volume of influent. While the correlation coefficients between alum consumption and volume are lower than those of turbidity, the relationship was still considered significant and can be understood because a higher volume of influent water requires an increase of chemicals during water treatment.

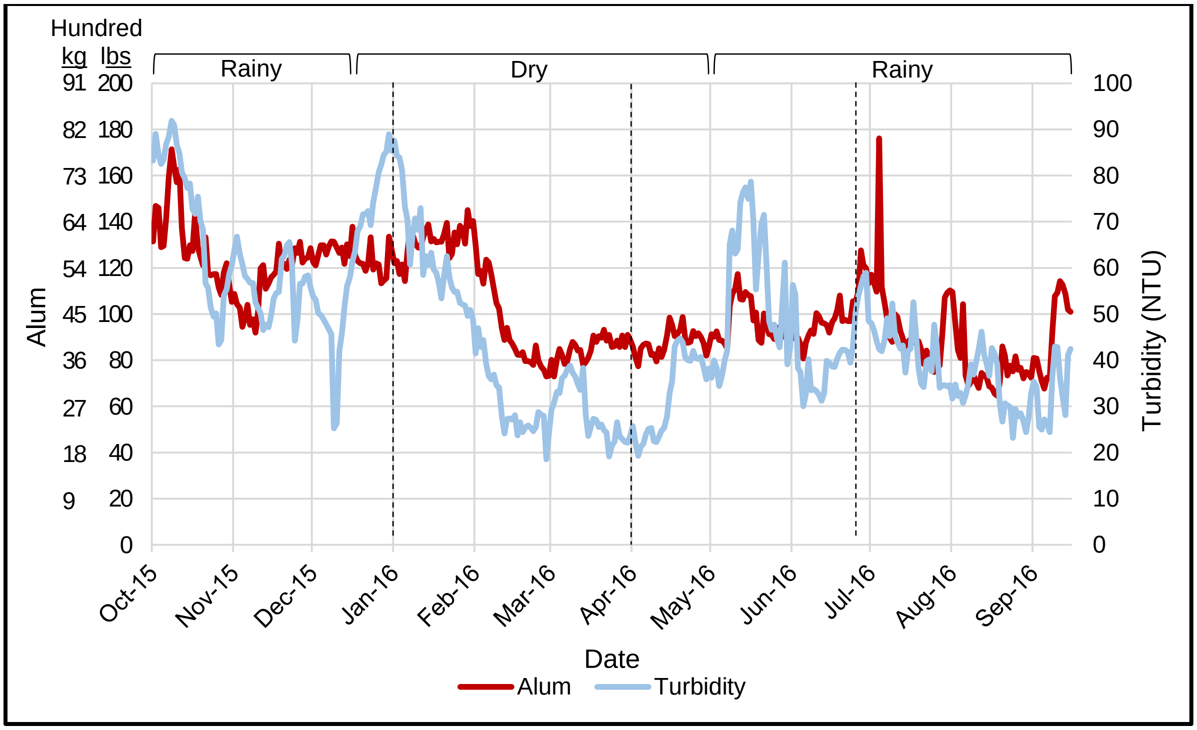


Figure 22: Alum consumption in relation to turbidity levels at Miraflores

Finally, chlorine consumption presented a significant, positive correlation with salinity across all periods, despite limited values for salinity prior to the expansion (Figure 23). During Period 1, chlorine consumption and salinity showed a decrease after December 2015. During Period 2, both variables remained consistent, with neither variable presenting distinctive variations. This same behavior continued through Period 3, with an increase occurring after June 2016. During Period 4, chlorine consumption decreased after the expansion but, similarly to salinity levels, presented a continuous increase after August 2016.

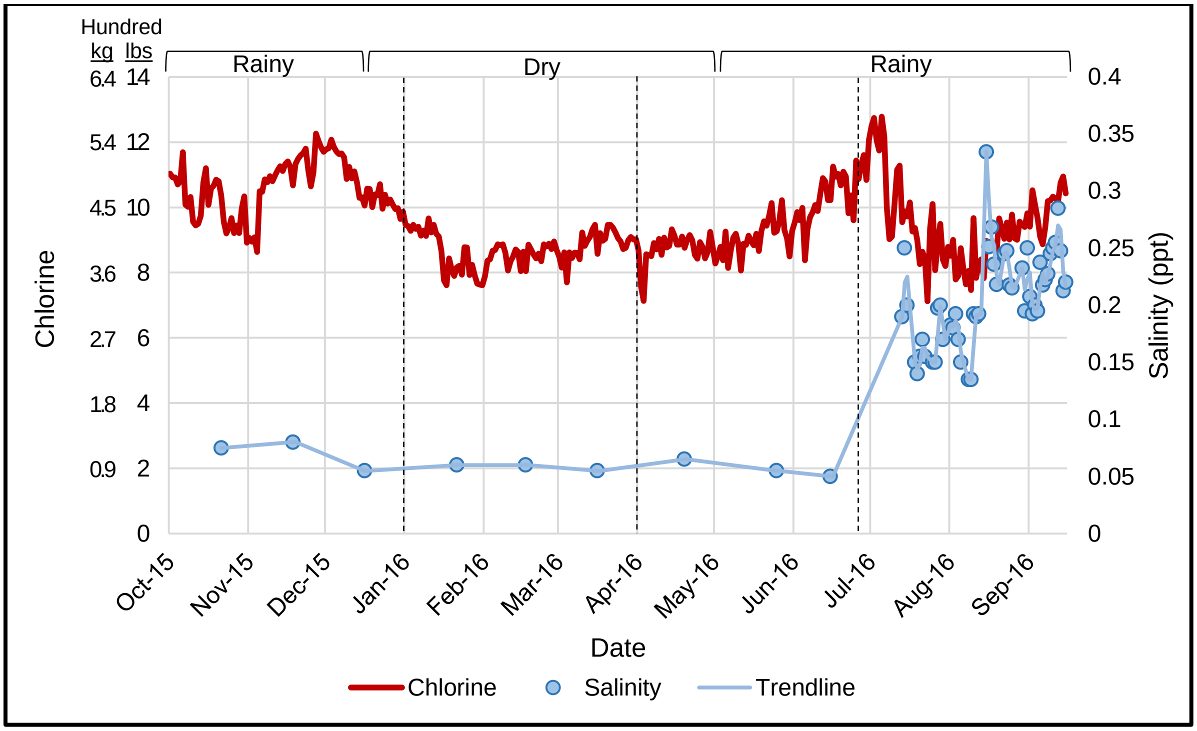


Figure 23: Chlorine consumption in relation to salinity levels at Miraflores

Recognizing that a relationship exists between chemical consumption and the water quality parameters analyzed, it is important to understand how post-expansion operations have affected the parameters. A mean value of 63 NTU (Nephelometric Turbidity Units) for turbidity indicates that the highest levels occurred during Period 1 (Figure 24). A comparison of maximum values explain that, following Period 1, turbidity levels have continuously decreased, with the lowest mean value, 38 NTU, occurring during Period 4. Contrarily, a mean value of 0.21 ppt for salinity indicates that the highest levels occurred during Period 4 (Figure 25). While salinity levels remained within a mean range of 0.06 – 0.07 ppt during Periods 1, 2, and 3, an increase occurred during Period 4. Through this analysis, it can be assumed that post-expansion operations have impacted salinity levels but not turbidity levels.

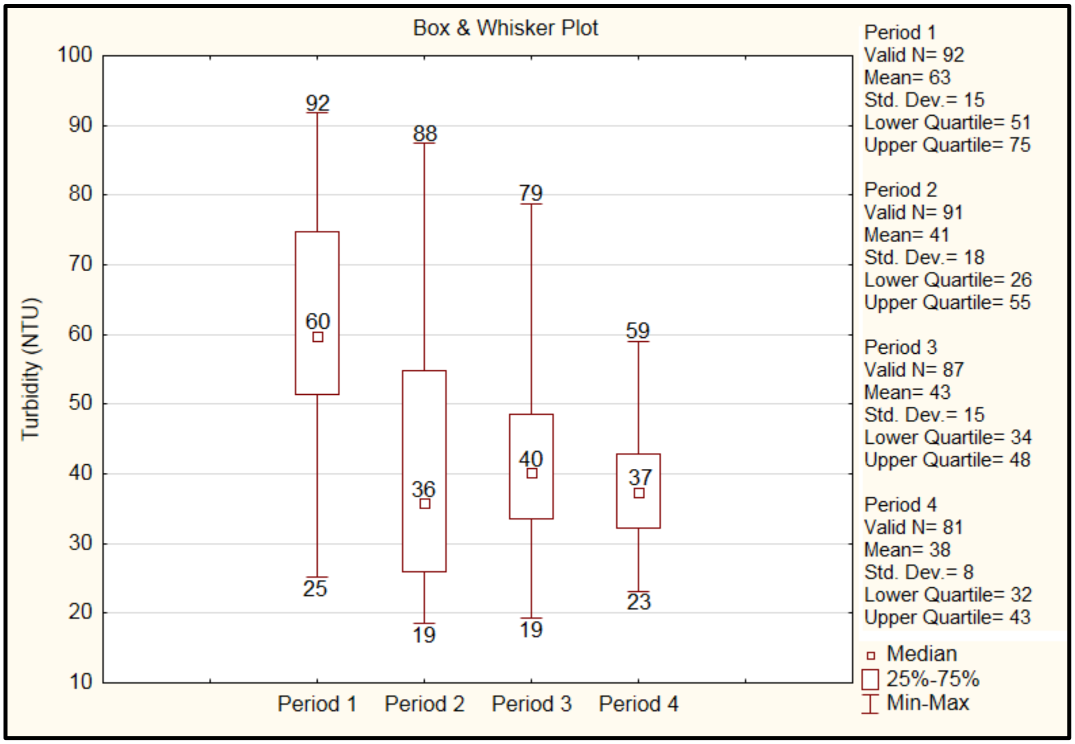


Figure 24: Box and whisker plot of turbidity levels

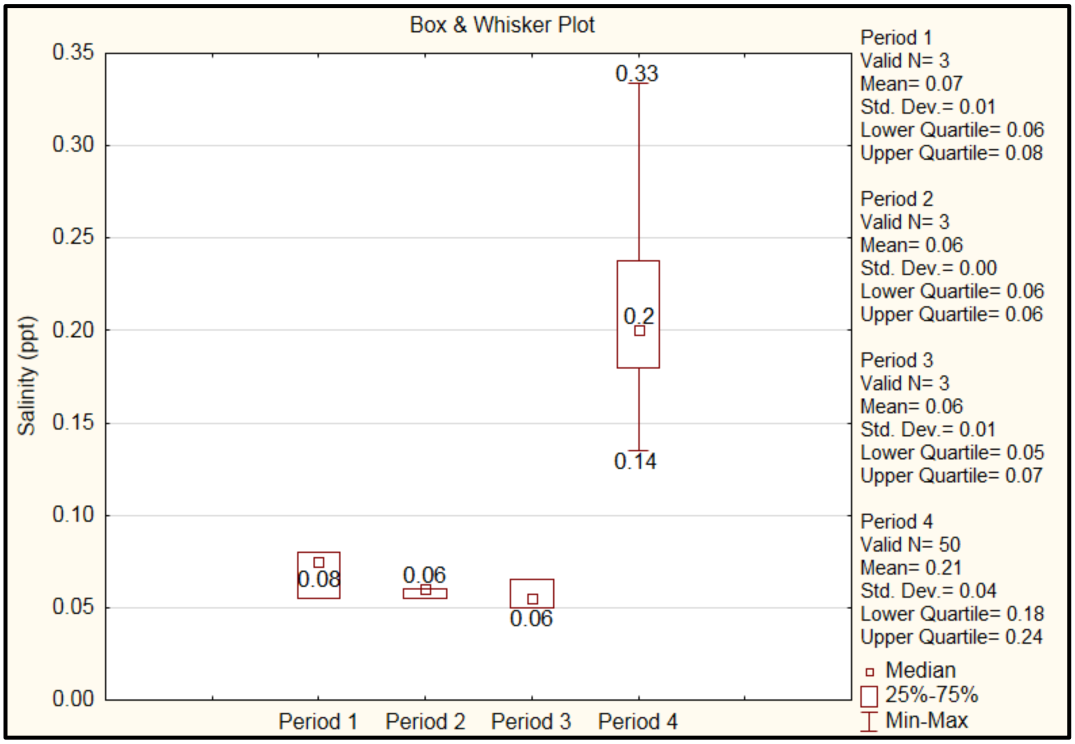


Figure 25: Box and whisker plot of salinity levels

Water is considered safe for human consumption when salinity levels are less than or equal to 0.50 ppt. A maximum value of 0.33 ppt during Period 4 indicates that, although salinity levels did not exceed the maximum permissible value for potable water, they increased following expansion operations. At Miraflores, a plan to monitor salinity levels was created to ensure that the raw water obtained from Gatún Lake remains within the acceptable ranges to be considered a source of freshwater (Autoridad del Canal de Panamá, 2016b). The plan described a normal value for salinity in raw water as less than or equal to 0.20 ppt. It states that if salinity levels are measured to be greater than or equal to 0.55 ppt, the pumping of raw water from the intake points at Gatún Lake will be discontinued. The increase of salinity levels poses a threat to the production of potable water within the plant, and thus, affects future distribution to residents of Panama.

3.3 Conclusions and Recommendations

Different statistical methods were utilized to identify changes in chemical consumption and correlations between chemicals and the quality of water. Through results obtained from the Wilcoxon rank sum test, it was concluded that both chemicals analyzed, chlorine and alum, presented a statistically significant change in consumption across all periods analyzed, excluding Period 3 for chlorine consumption. Descriptive statistics and a graph of chemical consumption over time were used to determine that chlorine and alum were consumed the most during Period 1, before the expansion. During Period 4, following the expansion, chlorine consumption levels increased although they did not exceed the interquartile range of Period 1. For alum, consumption levels decreased gradually. Overall, post-expansion operations have not significantly increased consumption of either chemical.

Through a Spearman's rank-order correlation, it was concluded that turbidity levels and volume of influent have a significant, positive relationship with alum consumption across all periods. It was also concluded that salinity levels have a significant, positive relationship with chlorine consumption across all periods. Descriptive statistics were used to determine that post-expansion operations have only impacted salinity levels. While salinity levels have not reached the maximum value permitted for water to be considered safe for human consumption, it has shown an increase from levels during pre-expansion operations. Maintaining suitable levels of salinity is essential for the safe distribution of potable water to residents of Panama, thus, recommendations have been created to ensure that water treatment within the Miraflores Filtration Plant continues to be effective.

First, the continuous monitoring of salinity levels at all seven distribution points within the plant is recommended. Although salinity measurements indicate that the influent and effluent remain within freshwater range, the results suggest that levels may continue to increase. Due to the recent opening of the expansion of the canal at the time of data collection, limited salinity data was available for analysis. Therefore, it is difficult to predict if salinity will continue to increase past safe ranges or reach a plateau before then. Continuous monitoring is necessary to ensure that salinity levels do not surpass the freshwater limit of 0.50 ppt. If limits are exceeded, it is advised to follow the ACP’s plan to discontinue the pumping of raw water from the intake points and notify all affected associates, such as IDAAN.

Second, the further investigation of the chemical relationship between chlorine consumption and salinity is recommended. While the correlation analysis showed a significant association between both variables, the effectiveness of using chlorine to treat salinity was not investigated. Thus, measured salinity levels at the potable water distribution points should be analyzed to determine if a decrease in salt concentration occurs after treatment. If salinity levels continue to increase and it is found that the use of chlorine is ineffective, it is advised that alternative treatments methods, such as electrodialysis reversal and reverse osmosis, are implemented.

Finally, additional research on how seasonal changes affect salinity levels in Gatún Lake is recommended. Due to time constraints, only salinity data during the rainy season were available during this investigation. Examination of this relationship during different seasons can follow a similar methodology as outlined for this project. First, salinity data should be collected for a full year after the opening of the expansion and organized by periods according to the seasons. Then, descriptive statistics should be performed to provide initial insight to trends within the data. Finally, according to the type of distribution, a hypothesis test should be performed to identify statistically significant changes of salinity levels between different periods. Together, these recommendations provided suggestions to the ACP Division of Water Quality to guarantee that good quality water is distributed to the public.

4.0 Process Analysis of Mount Hope Water Filtration Plant

4.1 Methodology

The goal of this project was to analyze the flow of water through specific components of the Mount Hope Water Filtration Plant. This goal was achieved through the following objectives:

1. Analyze the layout of the facility to gain an understanding of the water filtration system.
2. Calculate the velocity gradient through the rapid mix chamber using a range of discharges.
3. Calculate the velocity gradient through the flocculation basin using a range of rotational velocities.
4. Calculate the detention time in the sedimentation basin using a range of discharges.

4.1.1 Analysis of Facility Layout

The first step in understanding the specifics of the Mount Hope Water Filtration Plant entailed a review process of the design plans for the facility's various buildings and structures. The earliest plans for the rapid mixer and sedimentation basin date back to 1912, when the plant was first being considered. The plans detail aspects ranging from building foundations, to pipe dimensions and layout, to wall elevations and thicknesses. The dimensions of the rapid mixing chambers and sedimentation basins were of particular interest, and were crucial in being able to calculate the velocity gradients and detention times, respectively, through these stages of filtration.

Furthermore, the ACP stresses the importance of site visits, as they encourage communication and ensure that the work being done in the office aligns with the current conditions in the field. In the context of this project, field visits facilitated communication between the research team and plant operators. The first trip to the Mount Hope Water Filtration Plant, on July 20, 2016, consisted of a tour of the facility, given by the plant supervisor. Walking through the plant step-by-step, he explained how the water is cleaned by each successive process. He provided firsthand knowledge of various measurements, such as Mount Hope's total daily discharge.

The second trip to the facility was made on September 13, 2016. The purpose of this visit was to verify the dimensions of the rapid mixer, flocculators, and sedimentation basin. While the plans on record included some of the structural changes that had been made since the plant's opening in 1914, a collection of measurements ensured that the dimensions being used in the calculations would be as updated as possible. The visit was planned in advance, allowing the operators to drain one of the pathways. With the rapid mixer, flocculator, and sedimentation basin empty, it was possible to enter the structures and measure their various components. Two Mount Hope employees helped with the process, holding the tape measure and climbing into tighter, harder to reach spaces to collect the necessary data. The measurements from this visit were compiled into three separate CAD drawings, one for each of the three structures.

4.1.2 Calculation of Velocity Gradient through Rapid Mix Chamber

Due to an assortment of variables, such as water quality and maintenance schedules, the exact discharge produced by the Mount Hope Water Filtration Plant slightly varies on a day-to-day basis. As a result, all calculations were performed using ranges of the independent variables, rather than assuming one specific value. The ranges chosen were large to provide more comprehensive results. In the event that flow rates change, these ranges of calculations will allow operators to make adjustments in other sections of the plant accordingly to ensure the quality of the water being distributed to the surrounding areas. Similarly, the calculations were iterated three times over water temperatures of 77.0°F (25°C), 80.6°F (27°C), and 86.0°F (30°C). These specific temperatures were chosen based on a similar analysis of the Miraflores Filtration Plant conducted by the ACP.

The ranges of independent variables contained ten data points each. Therefore, 30 data points were produced for each calculation. In order to maximize time efficiency, separate Excel spreadsheets were designed for the rapid mixer, flocculator, and sedimentation basin to help analyze the data (Appendix D). Each equation had its own table with columns for the ten iterations, and rows listing the different variables required. The values across the rows only changed for the independent variable. The final row in each table performed the respective equation by relating the variables in the rows above. In some cases, additional tables were created to calculate a value necessary in a different table. Considering a spreadsheet as a whole, each column of tables performed the same calculation, with all variables the same, except those related to water temperature (i.e. dynamic viscosity and fluid density). Each row of tables performed the overall analysis of the plant component for one specific temperature.

Hydraulic baffled rapid mixers, like those found in the Mount Hope Water Filtration Plant, are similar to hydraulic baffled flocculators, with the exception of the speeds and detention times of the water passing through them. Therefore, the equation solving for the velocity gradient in a vertical flow flocculator can be also be applied to a vertically baffled rapid mixing chamber and was applied as follows:

$$G = \sqrt{\frac{\rho g Q h_L}{\mu V}}$$

where G is the velocity gradient through the rapid mix chamber (s^{-1}), ρ is the fluid density at a specific temperature (lb_f/ft^3; kg/m^3), g is the acceleration due to gravity (ft/s^2; m/s^2), Q is the volumetric flow rate of the fluid (ft^3/s; m^3/s), h_L is the fluid's head loss as a result of flow through the rapid mixer (ft; m), μ is the dynamic viscosity of the fluid at a specific temperature ($lb_f/ft\cdot s$; $kg/m\cdot s$), and V is the volume of the rapid mixing train (ft^3; m^3) (CEPIS, 2004). Before the velocity gradient could be calculated, however, equations solving for the total head loss, frictional head loss, fluid velocity through the channels, hydraulic radius of the basin, turning head loss, and velocity around the turns needed to be carried out.

The total head loss, h_L, required in the equation above, was computed by:

$$h_L = h_1 + h_2$$

where h_1 is the head loss due to friction with the walls of the chamber (ft; m) and h_2 is the head loss due to turns around the baffles (ft; m).

The frictional head loss, h_1, was calculated by:

$$h_1 = \left(\frac{n v_1}{R_h^{\frac{2}{3}}}\right)^2 l$$

where n is the Manning coefficient of the chamber walls ($s/ft^{1/3}$; $s/m^{1/3}$), v_1 is the fluid velocity in the channels (ft/s; m/s), R_h is the hydraulic radius of the channels in the basin (ft; m), and l is the total channel length in the section (ft; m) (CEPIS, 2004).

The fluid velocity through the channels, v_1, was determined using:

$$v_1 = \frac{Q}{ab}$$

where Q is the volumetric flow rate of the fluid (ft^3/s; m^3/s), and a and b are the dimensions of the channels normal to the direction of flow (ft; m) (CEPIS, 2004).

The hydraulic radius of a channel in the basin, R_h, is determined by dividing the fluid's cross-sectional area as it flows through the channel by the wetted perimeter of the channel. In this case the hydraulic radius was calculated by:

$$R_h = \frac{ab}{2a + 2b}$$

where a and b are the dimensions of the channels normal to the direction of flow (ft; m), ab is the cross-sectional area (ft^2; m^2), and $2a + 2b$ is the wetted perimeter (ft; m) (CEPIS, 2004).

The turning head loss, h_2, was calculated by:

$$h_2 = \frac{(m+1){v_1}^2 + m{v_2}^2}{2g}$$

where m is the number of compartments in the rapid mixing chamber (unitless), v_1 is the fluid velocity in the channels (ft/s; m/s), v_2 is the fluid velocity through the passages or holes between adjacent compartments (ft/s; m/s), and g is the acceleration due to gravity (ft/s^2; m/s^2) (CEPIS, 2004).

The fluid velocity through the passages or holes between adjacent compartments, v_2, was approximated by:

$$v_2 = \frac{Q}{bd_{ave}}$$

where Q is the volumetric flow rate of the fluid (ft^3/s; m^3/s), b is the width of the channels (ft; m), and d_{ave} is the average water depth around the baffles (ft; m).

The calculated velocity gradients were compared to a recommended range of values gathered from various source materials to determine the ideal conditions for treatment at this stage. The results, along with lines indicating the current operation values and the upper and lower limits of the recommended range of detention times, were graphed. These graphs, provided in the results section below, provided visual aids when analyzing the data.

4.1.3 Calculation of Velocity Gradient through Flocculation Basin

An Excel spreadsheet, similar to the one created for the rapid mixing chamber, was made for the flocculators and iterated the calculations over water temperatures of 77.0°F (25°C), 80.6°F (27°C), and 86.0°F (30°C). This set of data contained 33 points; three sets of ten falling within recommended ranges for velocity gradient, and three points correlating to the actual performance with the current flocculation motor.

Equations calculating the velocity gradient through a flocculation basin vary based on whether the unit is hydraulic or mechanical. Furthermore, they vary based on the specific design. Hydraulic flocculators can have vertical baffles that direct water over and under the obstructions, or they can have horizontal flow patterns around baffles offset side-to-side. Mechanical flocculators mix the water with either vertically- or horizontally-oriented rotational shafts. The three sets of flocculation basins at Mount Hope contain horizontal paddle-wheel flocculators. The equation used to calculate the velocity gradient through a basin with such a set-up was:

$$G = \sqrt{\frac{P_T}{\mu V}}$$

where G is the velocity gradient through the flocculation basin (s^{-1}), P_T is the total power expended by all of the paddle-wheels in a basin (W), μ is the dynamic viscosity of the fluid at a specific temperature ($lb_f/ft \cdot s$; $kg/m \cdot s$), and V is the volume of the flocculation basin (ft^3; m^3) (Department of the Army Corps of Engineers, 1984). Before the velocity gradient could be calculated, however, equations solving for the total power expended by the paddle-wheels and the Reynold's number of the flow needed to be carried out.

The total power, P_T, required in the equation above, was calculated by summing the power expended by each paddle-wheel, P_{wheel}. The power expended by one paddle-wheel was found using:

$$P_{wheel} = C_D \frac{\rho}{2} N_{arms} (1-k)^3 (2\pi\eta)^3 \sum_{1}^{n_{blades}} ({r_{bi}}^3 A_{bi})$$

where P_{wheel} is the power expended by one paddle-wheel flocculator (hp; W), C_D is the drag coefficient on the paddles (unitless), ρ is the fluid density at a specific temperature (lb/ft^3; kg/m^3), N_{arms} is the number of arms on each paddle-wheel (unitless), k is the slippage factor due to the difference in fluid and blade velocities (unitless), η is the rotational velocity of the paddle-wheel shaft (rev/s), n_{blades} is the number of blades per paddle-wheel arm (unitless), r_{bi} is the radial distance from the axis of rotation to the center of blade *i* (ft; m), and A_{bi} is the cross-sectional area of blade *i* normal to the direction of motion (ft^2; m^2) (Hendricks, 2011).

The drag coefficient, C_D, required in the power equation above, was determined based on the Reynold's number of the flow regime being examined. The Reynold's number (R_e) is the ratio of a fluid's inertial and viscous forces, producing a unitless measure that indicates whether the flow is laminar or turbulent. The equation used to calculate R_e for a horizontal paddle-wheel flocculator was:

$$R_e = \frac{{D_{pw}}^2 \eta \rho}{\mu}$$

where D_{pw} is the diameter of the paddle-wheel (ft; m), η is the rotational velocity of the paddle-wheel shaft (rev/s), ρ is the fluid density at a specific temperature (lb_f/ft^3; kg/m^3), and μ is the dynamic viscosity of the fluid at a specific temperature ($lb_f/ft\cdot s$; $kg/m\cdot s$). If $R_e \leq 1$, then $C_D = \frac{24}{R_e}$. If $1 < R_e < 10^3$, then experimental curves for C_D versus R_e should be consulted. If $R_e \geq 10^3$, then C_D should be determined based on the ratio between the length and width of the paddle-wheel's blade (Table 16) (Hendricks, 2011).

The calculated velocity gradients were compared to a recommended range of values gathered from various source materials to determine the ideal conditions for treatment at this stage. The results, along with lines indicating the current operation values and the upper and lower limits of the recommended range of detention times, were graphed. These graphs, provided in the results section below, provided visual aids when analyzing the data.

Table 16: Values of drag coefficient based on paddle-wheel dimensions, when $R_e \geq 10^3$ (Hendricks, 2011, p. 307)

$\frac{L}{w}$	C_D
1	1.16
5	1.2
20	1.5
>>20	1.9

4.1.4 Calculation of Detention Time in Sedimentation Basin

The process for calculating the detention time in the sedimentation basin involved fewer steps than the calculations for the previous two structures. For the horizontal flow, rectangular static settling tank in Mount Hope, the calculation required two properties of the water being examined. The equation used to solve for detention time was:

$$t = \frac{V}{Q}$$

where t is the detention time (s), V is the volume of the fluid in the sedimentation basin (ft^3; m^3), and Q is the volumetric flow rate of the fluid (ft^3/s; m^3/s) (Spellman, 2003).

The calculated detention times were compared to a recommended range of values gathered from various source materials to determine the ideal conditions for treatment at this stage. The results, along with lines indicating the current operation values and the upper and lower limits of the recommended range of detention times, were graphed. These graphs, provided in the results section below, provided visual aids when analyzing the data.

4.2 Results and Analysis

By performing calculations to analyze the flow patterns through the rapid mixing chamber, flocculation basin, and sedimentation basin, the effectiveness of the three structures in the purification process was determined and recommendations to further improve their efficacy could be made.

4.2.1 Calculation of Velocity Gradient through Rapid Mix Chamber

At the time of analysis, the Mount Hope Water Filtration Plant treated an average of 36 MGD (136 ML/day). Based on that value, the calculated velocity gradient in one pathway (of three) of the rapid mixer ranged between 146.69 and 154.81 s^{-1} for water temperatures between 77.0 and 86.0°F (25 and 30°C).

In order to estimate the velocity gradient over a range of discharges and temperatures, certain assumptions were made. The value for the Manning's coefficient was set to 0.014 because the interior of the mixing chamber is a relatively smooth concrete surface. The assumptions with the greatest effect on the values related to the depth of the water flowing over and under the baffles. The interior height of the rapid mixer is 5.31 ft (1.62 m), as measured during the second site visit (Figure 26). Accounting for some space occupied by air, and for numerical simplicity, a water depth of 1.55 m was assumed in each of the compartments in one pathway. The water volume within the structure was based off of this depth and was calculated as the sum of 12 rectangular prisms (Appendix D). The true depth of the water in each successive compartment is lower than that in the previous, following a hydraulic grade line due to head loss. Therefore, the true volume varies with flow rate, and the geometric evaluations of the volume are more complex. In addition to the volume, the turning velocity around the baffles was also

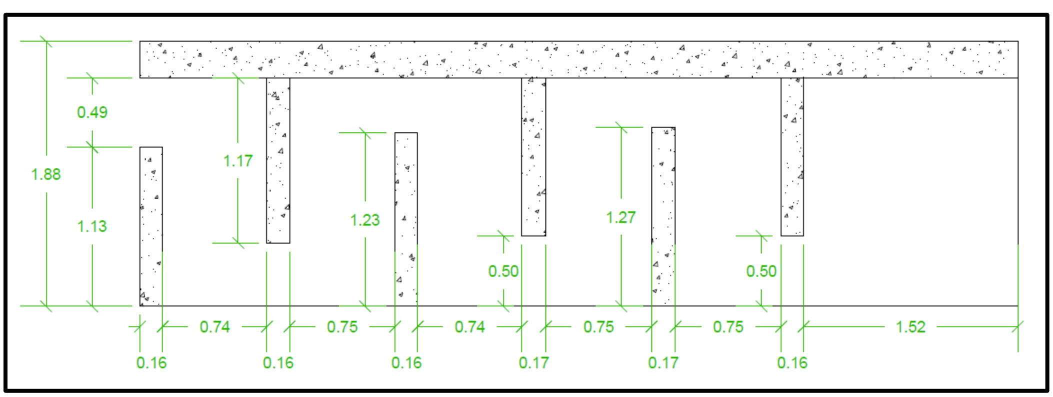


Figure 26: Elevation view of the vertically baffled rapid mixer at Mount Hope (Ring, 2016a)

affected by the water depth assumption. Because the baffle dimensions vary, so did the water depth above and below them. Rather than iterating the turning head loss equation six times for each flow rate and temperature, an average was taken for the water depth around each baffle. This reduced the number of iterations for turning head loss from 180 to 30. While these assumptions limited the results to a degree, they provided numbers that helped estimate the current velocity gradient within the time constraints of the project. The rest of the numbers used in the equations were either accepted values, such as the density of water and the acceleration due to gravity, or measurements taking during the trip to the plant.

Compared to recommended values between 300 and 1000 s^{-1}, the results for the structure's current performance, 146.69 – 154.81 s^{-1}, fell below the prescribed range (Table 17). As discussed in Section III.4.1.2, data points were created and graphed for three different water temperatures, under ten different plant discharges each (Figure 27). Four of the discharges were set to fall between 34 and 40 MGD (129 and 151 ML/day) to provide data for flows close to Mount Hope's current operation of 36 MGD (136 ML/day), as indicated by the vertical pink line on the graph. The other six discharges were chosen to provide velocity gradients that fell within the ranges found in the literature review portion of the project, as can be seen between the two horizontal lines on the graph. From the latter portion of the data, it was determined that discharges between 55.9 and 129.3 MGD (211.6 and 489.5 ML/day) would elevate the velocity gradient to a suitable level. While discharges in this range mathematically produced velocity gradients from 300 – 1000 s^{-1}, they were physically unrealistic. The lack of feasibility of such flows was deduced from field observations. When one of the pathways through the plant was drained so measurements of the structures could be taken, the transition region between the rapid mixer and sedimentation basin began to overflow. If the two remaining pathways could not

Table 17: Suggested velocity gradients through a rapid mixer, found in literature review sources

Purification Step	Velocity Gradient (s^{-1})	Detention Time	Source
Rapid Mix	500 – 1000	10 – 30 seconds	(Department of the Army Corps of Engineers, 1984)
Rapid Mix	400 – 1000	-	(Water Treatment Handbook, 2007)
Rapid Mix	300	30 seconds – 2 minutes	(Department of the Army Corps of Engineers, 2001)
Rapid Mix	300	10 – 30 seconds	(Edzwald, 2013)

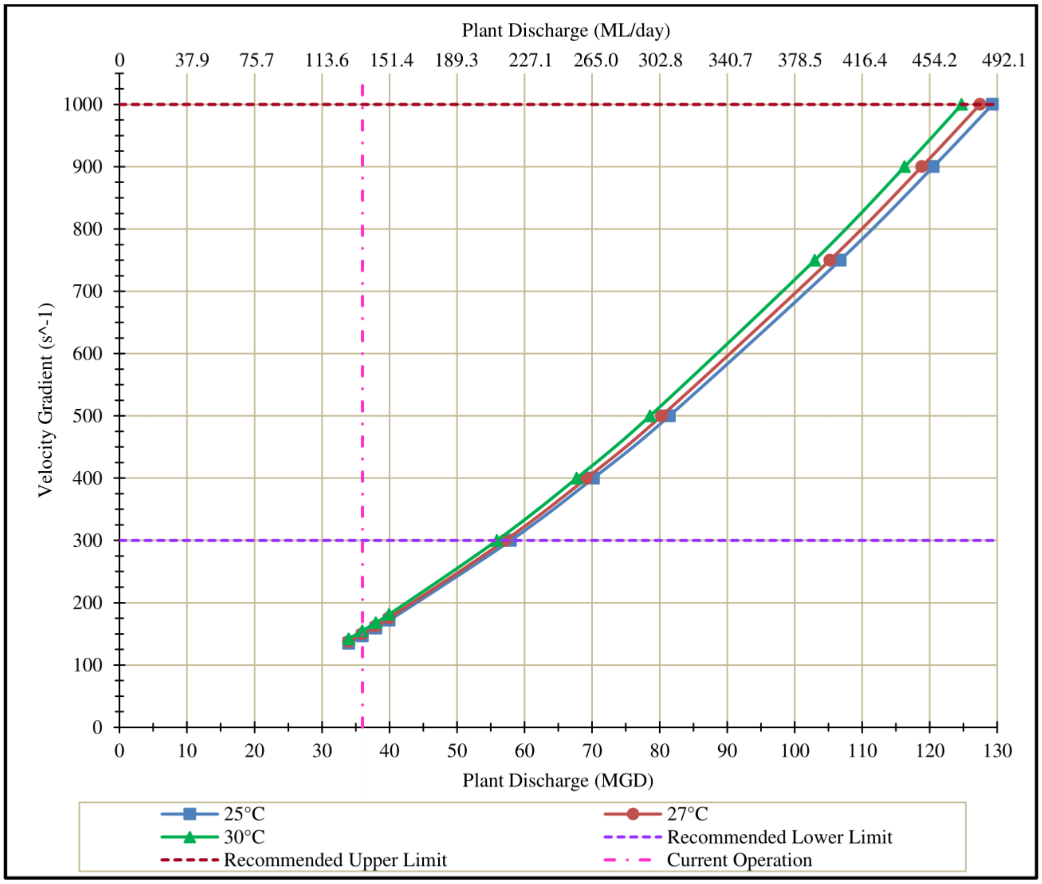


Figure 27: Velocity gradient vs. total plant discharge through a vertically baffled rapid mixer with varying water temperature

sustain the increase in flow from shutting down the third, then the structures would not be able to effectively respond to a more than tripled increase from 36 MGD (136 ML/day) to 129.3 MGD (489.5 ML/day).

4.2.2 Calculation of Velocity Gradient through Flocculation Basin

When in use, the flocculators of the Mount Hope Water Filtration Plant rotate at 1.49 rpm. At this rate, the velocity gradient in the flocculation basin was calculated to be between 6.75 and 7.12 s^{-1}, depending on the water temperature between 77.0 and 86.0°F (25 and 30°C).

The two largest assumptions in the calculations were made for the slippage factor and the water depth in the flocculation basin. The slippage factor, k, is used in the equation for the power expended by a paddle-wheel, mentioned in Section III.4.1.3. It accounts for the difference in velocities between the blades on the paddle-wheel and the water being mixed. The slippage factor is commonly taken between 0.24 and 0.32, and in this case, it was set to 0.30. In the literature review process, similar equations assumed a 70% relative velocity between the blades and water (Crittenden, Trussell, Hand, Howe, & Tchobanoglous, 2012). In the equation used, *k* is subtracted from 1, creating a 70% difference between velocities. The other significant assumption was made about the water depth in the flocculation basin. The calculations were done with a 12 ft (3.66 m) water depth, the height of the walls, derived from the measurements taken during the second field visit. Therefore, the flocculation basin was set to be treating its maximum capacity in the evaluation. The rest of the numbers used in the equations were either accepted values, such as the dynamic viscosity of water, or measurements taking during the trip to the plant (Figure 28).

A literature review process indicated that flocculators should create velocity gradients between 5 and 100 s^{-1} (Table 18). In order to achieve the suggested flow patterns, the paddle-wheel flocculators of Mount Hope would need to rotate between 1.17 and 8.97 rpm when the chamber is filled to capacity and the water temperature falls between 77.0 and 86.0°F (25 and 30°C) (Figure 29). The flocculators only rotate at one speed, as indicated by the intersections between the vertical pink line and the three curves in the graph, achieving values between 6.75 and 7.12 s^{-1}. While according to Crittenden et al. (2012) these values are sufficient for a horizontal shaft flocculator, as indicated by the purple horizontal line on the graph, they fall below the ideal range according to other sources. The next lowest velocity gradient accepted for a horizontal paddle-wheel flocculator is 20 s^{-1}. In order to meet this threshold, it was determined that the flocculators would need to exceed their operative range of 1.49 rpm to a higher range between 2.96 and 3.07 rpm.

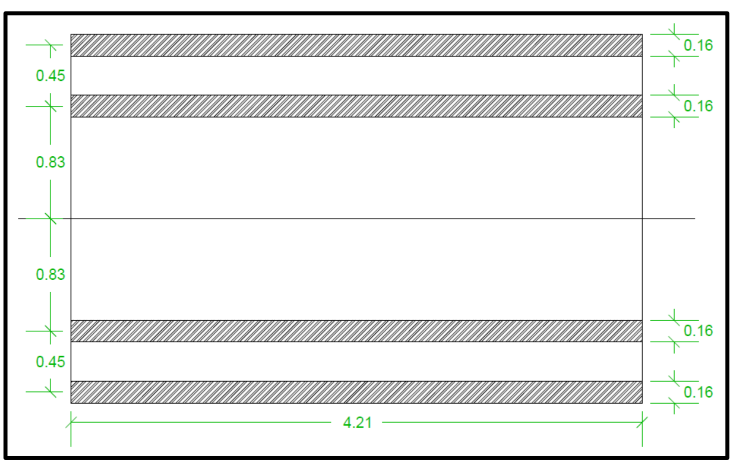


Figure 28: Elevation view of one horizontal paddle-wheel flocculator at Mount Hope (Ring, 2016a)

Table 18: Suggested velocity gradients through a flocculator, found in literature review sources

Purification Step	Velocity Gradient (s^{-1})	Detention Time	Source
Flocculation	20 – 100	30 – 60 minutes	(Department of the Army Corps of Engineers, 1984)
Flocculation	<100	-	(Water Treatment Handbook, 2007)
Flocculation	20 – 80	20 – 30 minutes	(Department of the Army Corps of Engineers, 2001)
Flocculation	5 – 40 (horizontal shaft) 20 – 50 (paddle wheels) 10 – 80 (vertical shaft)	10 – 30 minutes	(Crittenden, Trussell, Hand, Howe, & Tchobanoglous, 2012)

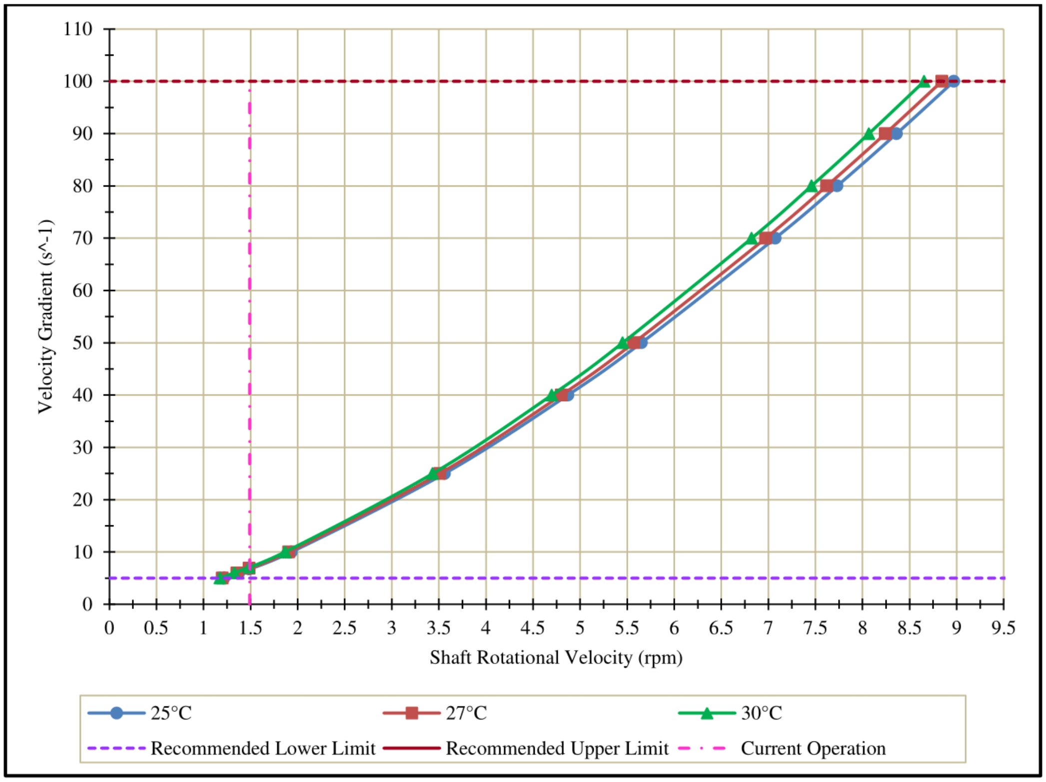


Figure 29: Velocity gradient vs. horizontal paddle-wheel flocculator shaft rotational velocity with varying water temperature

4.2.3 Calculation of Detention Time in Sedimentation Basin

Due to the current plant discharge of 36 MGD (136 ML/day), the detention time in the sedimentation basin at the time of analysis was between 83 and 100 min, depending on the water volume within the basin. The flocculators are located in the first two compartments of the sedimentation basin. Therefore, their activity affected the way that the volume in the sedimentation basin was considered. This led to two maximum volume calculations. In the event that the flocculators were in use, the volumes in the first two compartments were not considered as part of the sedimentation basin. In the event that the flocculators were off, which is the case for Mount Hope at all times except during severe storms, the first two compartments were also treated as sedimentation space. The volume calculations were made using measurements taken from a drained pathway during a field visit to the facility (Figure 30). The water depth used in the calculations was assumed to be equal to the maximum depth of the basin, 12 ft (3.66 m). Therefore, the volumes for the two scenarios were assumed to be maximums in the following discussion.

In comparison to the recommended lengths of time from 90 to 240 minutes, the detention times in the sedimentation basin were sufficient for certain water volumes (Table 19). When considering the structure with the flocculators turned off, and therefore a larger volume undergoing the settling process, all of the tested plant discharges fell within the prescribed time

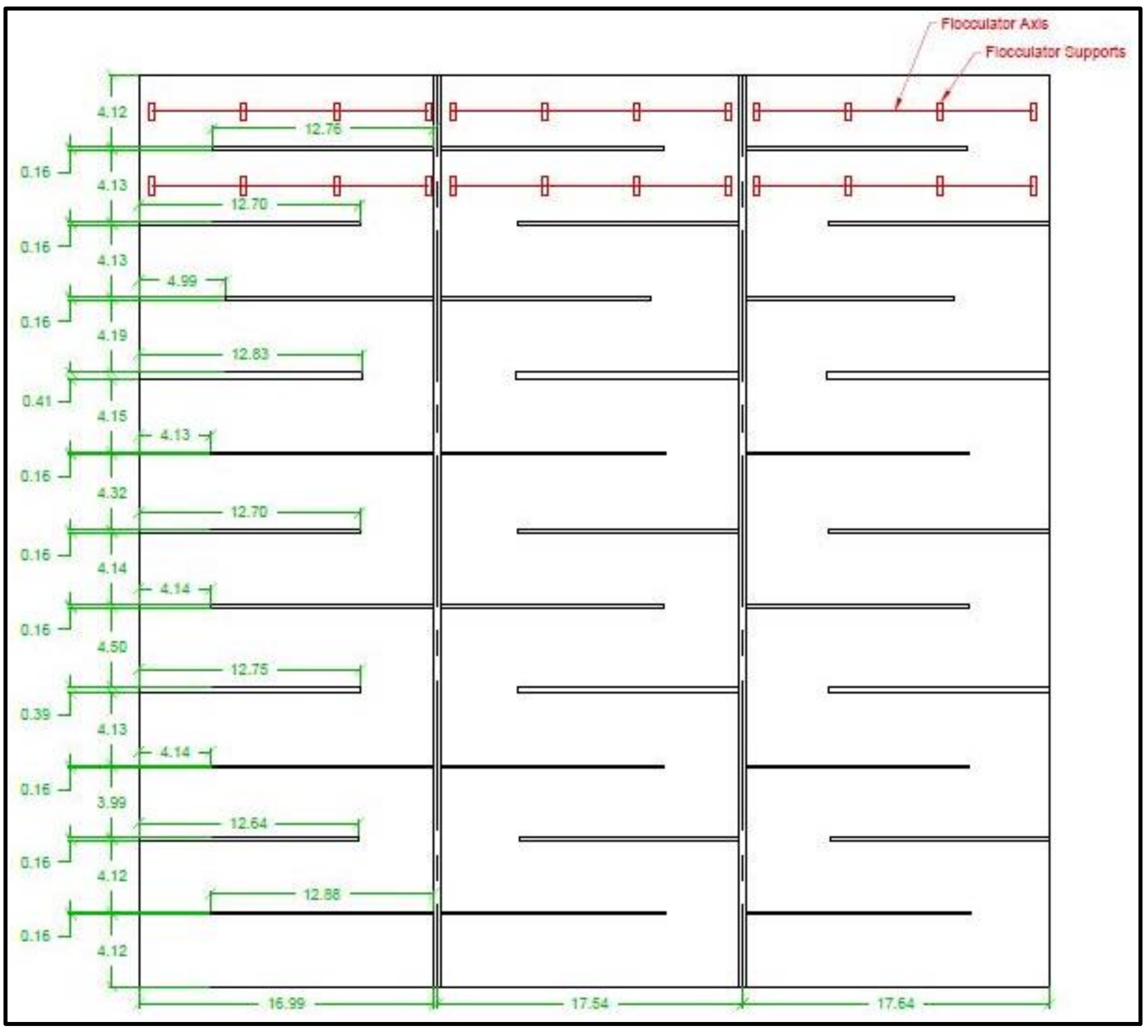


Figure 30: Plan view of the horizontally baffled sedimentation basin at Mount Hope (Ring, 2016a)

Table 19: Suggested detention times in a sedimentation basin, found in literature review sources

Purification Step	Detention Time	Source
Sedimentation	120 – 240 minutes	(Department of the Army Corps of Engineers, 1984)
Sedimentation	90 – 150 minutes	(Ghangrekar, 2012)
Sedimentation	>90 minutes	(King County Wastewater Treatment Division, 2016)

limits (Figure 31). This result showed that the water at this stage was being treated properly. A quantity of 40 MGD (151 ML/day) was the cutoff discharge at which the plant could produce potable water, while still maintaining a suitable sedimentation detention time, as indicated by the intersection of the blue curve with the purple horizontal line. Any higher flow rates would cause the water to flow too quickly through the structure, running the risk of reducing the quality of the effluent.

In the case that the flocculators were put to use, however, the current discharge of 36 MGD (136 ML/day) would not be detained in the basin long enough, as indicated by the intersection of the orange curve and the vertical pink line. While the lower limit for detention time was only 7 minutes longer than the existing performance of 83 minutes, the discharge would need to be reduced by 2.7 MGD (10 ML/day) to meet the limit. The discharge would need to be adjusted to a value between 12.5 and 33.3 MGD (47.3 and 126.1 ML/day) to maintain a detention time between 90 and 240 minutes. Because the plant needs to meet potable water demands set by the community, such a decrease in productivity was not feasible.

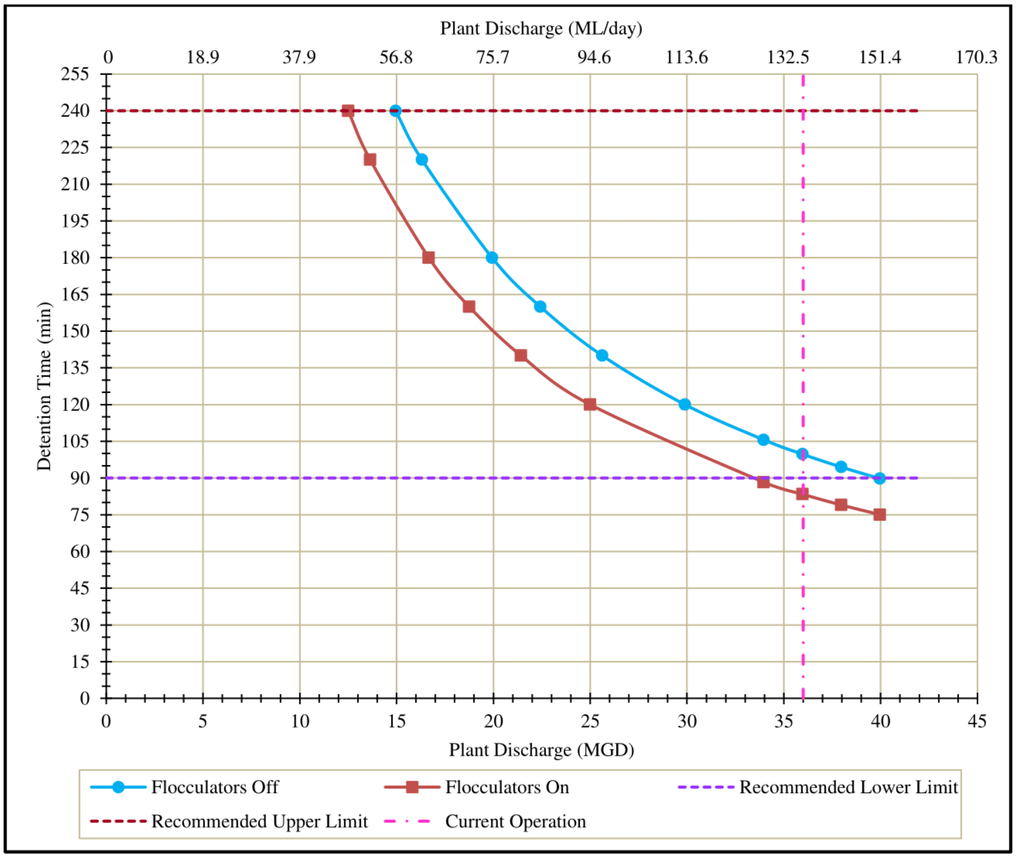


Figure 31: Detention time vs. plant discharge in a sedimentation basin with varying volume

4.3 Conclusions and Recommendations

At the time of calculation, velocity gradients through the rapid mixer ranged from 146.69 – 154.81 s^{-1}, and were lower than the recommended values of 300 – 1000 s^{-1}. When examining the equation used to calculate the velocity gradients, a possible solution was to increase the flow through the structure. In order to meet the minimum value of 300 s^{-1}, the plant's total daily discharge would need to be increased by at least 19.9 MGD (75.3 ML/day). The amount of stress that such an increase would place on the entirety of the plant, including the rapid mixer, would cause back-ups and overflow the structures. Therefore, this solution was deemed infeasible and ruled out. Instead, it is recommended that the dimensions of the structure be reviewed and potentially modified. Adjustments to the dimensions would alter the volume of water that the basin can sustain. Volumetric decreases would increase the velocity gradient of the water passing through the chamber, improving the purification at that step. When considering such modifications, however, the head height over each baffle should be checked, as failure to do so could overwhelm and interrupt operations.

When the flocculators were considered to be in use, the calculated velocity gradients through the flocculation basin, 6.75 – 7.12 s^{-1}, fell within the recommended range between 5 and 100 s^{-1}. While they met the 5 s^{-1} lower limit, they could be improved by being elevated further. Of the sources referenced, only one suggested acceptable values as low as 5 s^{-1}. A lower limit of 20 s^{-1} was more common. Therefore, stronger emphasis should be put on achieving velocity gradients closer to the median of the distribution, such as 50 s^{-1}. In order to attain greater rates, the flocculators would need to be able to rotate more quickly. Therefore, it is recommended that a motor be acquired that can operate at a higher rate and across a range of rotational velocities. This would allow operators to achieve a wider range of targeted velocity gradients, responding to the variations in water quality at any given time.

The sufficiency of the detention time in the sedimentation basin was determined depending on whether or not the flocculators were assumed to be in use. When the flocculators are turned off, they produce a greater effective volume that in turn lengthened the detention time to 100 min. In the less common scenario, occurring when the flocculators are turned on, the effective volume in the sedimentation basin is reduced by two compartments, and the resulting detention time of 83 min was not sufficient. In the event that the water quality derived from Gatún Lake deteriorates enough that operators deem it necessary to use the flocculators on a more regular basis, modifications to the structure would need to be considered. If this situation becomes a reality, it is recommended that modifications to the sedimentation basin be considered to increase its volume. Expansions to the basin would lengthen the detention time, elevating it into the target range. Additionally, other types of sedimentation basins, using newer technology, could be considered to improve the purification process.

These recommendations were made to the Hydraulics Engineering Unit of the ACP and to operators of the Mount Hope Water Filtration Plant to help make decisions regarding future updates and modifications to the plant to maintain its relevance in the water distribution market.

IV. Inspection and Maintenance of ACP Dams and Spillways

1.0 Design Statement

This chapter discusses two projects focused on the spillways of the Panama Canal. These projects fulfill the design capstone and Major Qualifying Project requirements at Worcester Polytechnic Institute. ABET requirements state that engineering design is open-ended, includes analysis and synthesis in an iterative cycle, and considers engineering standards and realistic constraints.

The first project, *Evaluation of the ACP's Formal Inspection Program of Dams and Spillways*, completed by Caitlin Burner, combined outside research with fieldwork and undergraduate coursework to provide suggestions to the ACP for improvement of their inspection processes. Through this work, an evaluation was completed and checklists and an inspection guideline to be followed by the team were designed.

Inspections of dams and spillways are essential to ensure their ability to meet capacity requirements and protect downstream communities. The dam and spillway structures owned by the ACP are responsible for maintaining proper operating levels for the Panama Canal, providing water to residents of Panama, and generating hydroelectric energy. Engineers and maintenance workers in the company were unsure of how well their program compared to global standards for formal inspection. This evaluation incorporated realistic constraints, such as time restrictions per spillway due to operation and weather, personnel limitations, and economics.

Scheduling constraints were considered, as they are the main difference between traditional formal inspections and those conducted by the ACP. Inspections on ACP components must be conducted while the structures are still operational, requiring additional safety considerations to protect the workers. Personnel limitations needed to be addressed during the project as well. During the first cycle of formal inspections in 2015, there was only one inspection team to examine all three dam and spillway structures. This project addressed the need for more staff in order to increase efficiency of inspections. Economic constraints were taken into account because the ACP is a for-profit company, they are unable to immediately provide funding for problems as they are encountered. This project had to address the importance of inspection as a way to find defects before failure occurred, allowing enough time for funds to be procured.

The second project, *Risk Analysis of Madden Dam and Spillway Drum Gates*, completed by Victoria Simpson, applied structural design and analysis knowledge from undergraduate coursework with information gained from field observation and document review to perform a risk analysis on the gates of Madden Spillway. A maintenance log and warning system for preventative maintenance were designed through the application of this knowledge.

This risk analysis was requested by the Engineering Division of the ACP to improve the efficiency of inspections and maintenance conducted on Madden Spillway. Risk analysis is a form of validation for economic funds and can be used to create preventative maintenance programs. Due to a different design and limited accessibility, Madden is considered to be the most high-risk spillway. This project was conducted under the constraints of safety, sustainability, and economics.

Safety, of both the ACP personnel as well as downstream communities, stood to be increased through this risk analysis. All repairs are made on site; therefore, knowledge of which items must be inspected gives teams the opportunity to arrange the proper safety measures. If any gate were to fail, downstream communities residing in the floodplain would be at risk. Preventative maintenance of the structure decreases the likelihood of failure. Sustainability was an important factor in the completion of this project, as the ACP would benefit from an extended usable lifespan of the gates. Due to the outdated design, new gates cannot be manufactured; therefore, their structural integrity must be preserved. Economics were taken into account because it is more cost-effective to make the repairs than to redesign the spillway gates after a critical failure.

These criteria, taken into account for both projects, allowed for improvements to be made to the Formal Inspection Protocol, as well as to the inspection and maintenance of Madden Spillway drum gates. This chapter provides suggestions for improving the efficiency and safety of Panama Canal spillway structures.

2.0 Background

The ACP's system of Dams and Spillways is essential to the operation of the Panama Canal. As the canal continues to age, the probability of failure for these structures increases. After successfully reaching 100 years of operation, the ACP is looking for improvements to their inspection and maintenance programs.

2.1 Spillways

A spillway is a structure that is built to allow an overflow of water from a dam to a downstream area (Kalantarnia, Chouinard, & Foltz, 2016). These structures protect dams from erosion and collapse, as well as safeguard downstream communities from uncontrolled flooding during heavy rains. While the crest of a dam must be above the maximum water level, the spillway crest must be at an equal elevation to the water level of a full reservoir (Spillway Definition - Design, Types and Classification of Spillway, 2014). Spillways can be either controlled or uncontrolled. A controlled spillway has gates that can be raised or lowered to release water, allowing the operators to maintain a specific water level. An uncontrolled spillway has no gates, allowing water to spill if the elevation exceeds the spillway crest. There are many different types of spillways depending on the geographic location of the area and the amount of rain that the area receives.

While there are many types, all spillways have the same essential components. To safely conduct water from a reservoir to the downstream area, a spillway needs an entrance channel, a control structure, a discharge channel, a terminal structure, and an exit channel (Figure 32) (Shiksha, 2013). The entrance channel is only required when the spillway does not draw water directly from the reservoir. When the spillway is located away from the reservoir, the entrance channel carries the water to the spillway. The control structure is the most important part of the spillway. This component is located at the upstream end of the spillway and controls the outflow of water from the reservoir. Usually, the control structure is an overflow crest designed to allow water over a certain elevation to spill. Once the water has passed over or through the control structure, it enters the discharge channel, also known as a conveyance structure. The discharge channel can be an enclosed pipe or an open channel and is responsible for safely carrying the water from the control structure to the downstream area (Beauchamp, 1984). Often, enclosed discharge channels travel directly through the dam structure itself, whereas open discharge channels travel on the surface of the dam or are separate from the dam. As the water

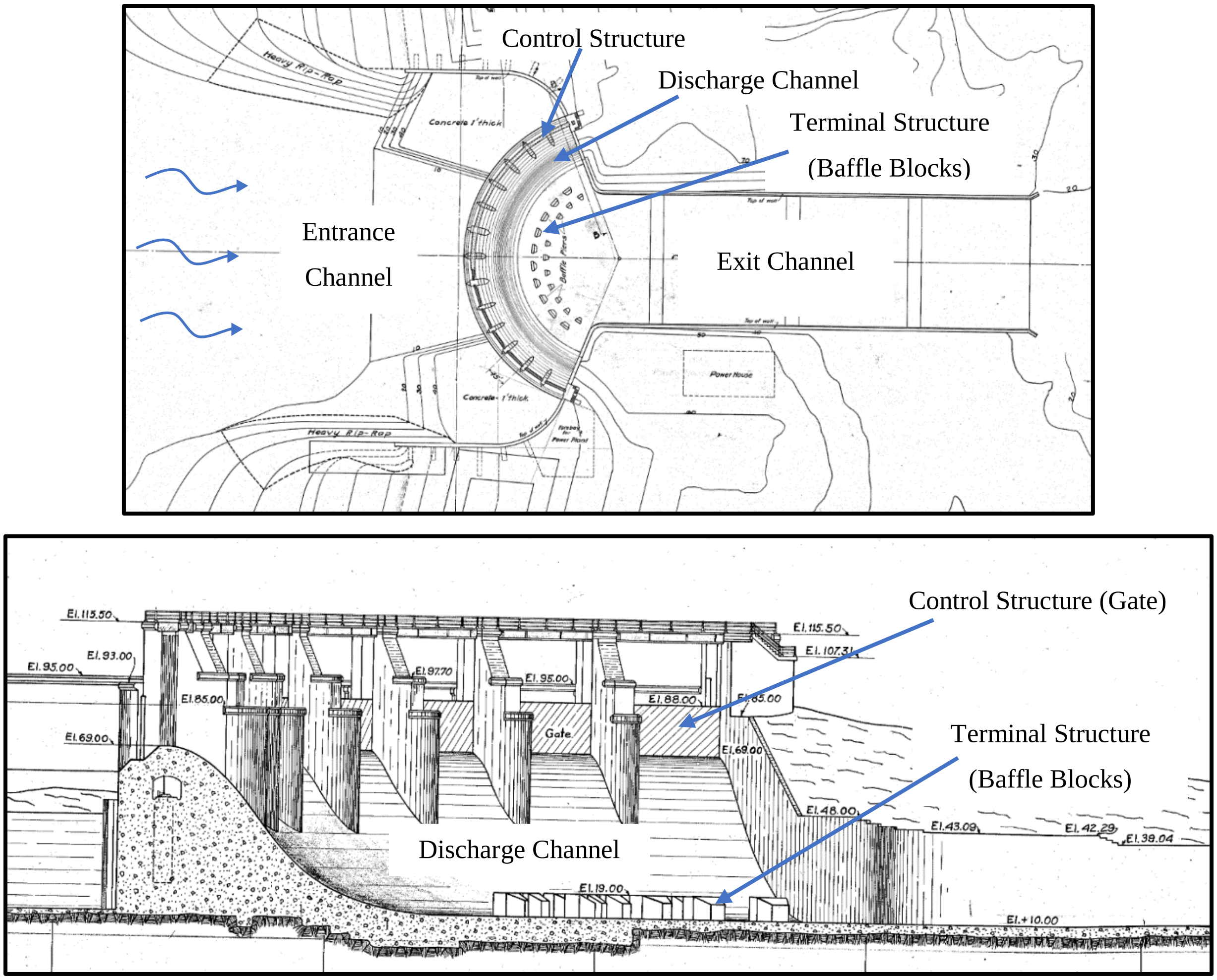


Figure 32: Components of Gatún Spillway (Panama Canal Flood Control Facilities, 1977a)

travels through the discharge channel, the potential energy it contained is converted to kinetic energy (Shiksha, 2013). The terminal structure is used to dissipate the kinetic energy. Many different designs are used for this purpose including hydraulic jump basins, roller buckets, baffle blocks, and ski-jump buckets. While these features differ in design, they all serve the purpose of disrupting the flow of water, causing a decrease in velocity. Following the terminal structure is the exit channel. This channel carries water from the terminal structure back to the river and is only necessary when the spillway does not discharge water directly downstream.

One of the most common types of spillways is an ogee spillway. If the main dam of a reservoir is long enough and has a high enough elevation, the ogee spillway will be integrated directly into the dam (Spillway Definition - Design, Types and Classification of Spillway, 2014). This design is characterized by its S-shaped profile (Figure 33). When water is discharged over

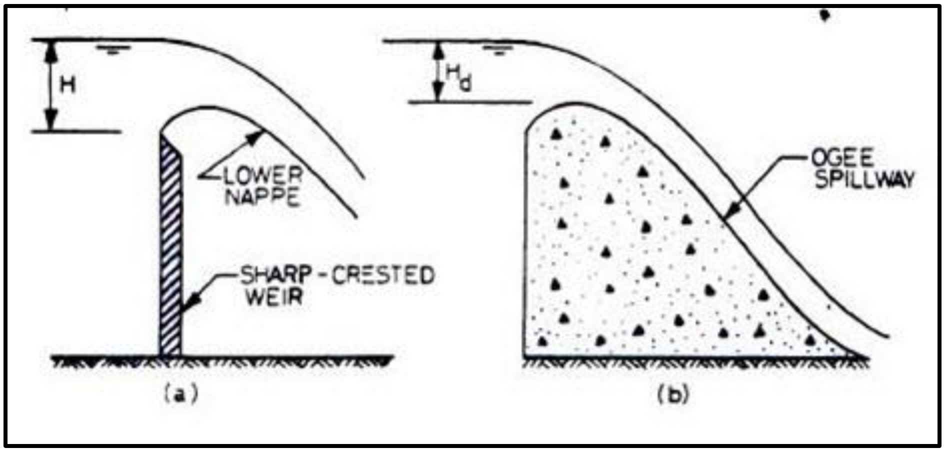


Figure 33: Ogee shaped spillway (Shiksha, 2013)

the spillway, the flow remains in contact with the concrete surface from the crest to the base, reducing the likelihood of damage to the concrete spilling basin (Shiksha, 2013).

2.2 Spillways of the Panama Canal

There are three spillways that aid in keeping the Panama Canal operational (Figure 34, yellow dots). Gatún Spillway is located on the Atlantic side of the canal, Miraflores Dam and Spillway is on the Pacific, and Madden Dam and Spillway is on the Chagres River (Alfaro, 2012). The three spillways use an ogee design and allow the ACP to maintain a safe water level for ships transiting the Panama Canal, while providing enough water for residents of the surrounding areas.

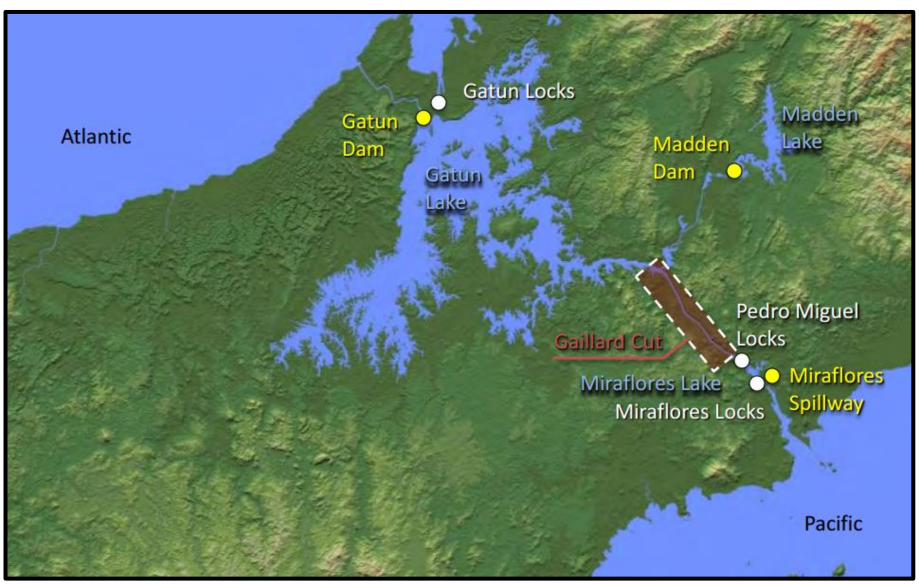


Figure 34: The Panama Canal principal components (Alfaro, 2012)

Gatún Spillway and earthen dams are responsible for maintaining the levels of Gatún Lake and the Culebra (Gaillard) Cut, which make up 21 mi (33 km) and 7.8 mi (12.6 km) of the Panama Canal, respectively (Panama Canal Flood Control Facilities, 1977a). Gatún Lake is also responsible for supplying water to residents of Panama. The lake, created during the construction of the original canal, was once the largest artificial lake in the world, with a surface area of 164 mi^2 (425 km^2) and a volume of 183 billion ft^3 (5.2 km^3) (Panama Canal Museum, 2014). The Gatún Spillway is located on the Atlantic side of Gatún Lake, adjacent to the original Gatún Locks (Figure 35).

The "Gatún Project," which included the planning and construction of the Gatún Spillway and two earthen dams, began in 1907 and was completed in 1913 (Panama Canal Flood Control Facilities, 1977a). Gatún Spillway is a semi-circular ogee spillway with 14 vertical lift gates. The semi-circular configuration of the spillway allows the spilling water to intersect as it reaches the discharge channel, dissipating its own energy. Because there is no standing pool in the spilling basin below the gates, concrete baffle blocks were also installed to dissipate the energy of the water (Figure 36).

Figure 35: Aerial view of Gatún Spillway and Locks (Panama Canal V.I.P. Slides, 1969)

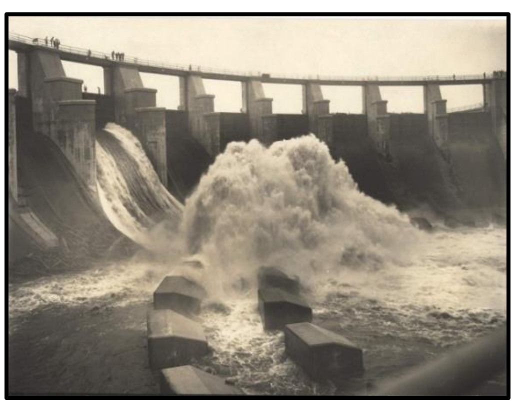


Figure 36: Gatún Spillway baffle blocks dissipating energy during a spill (Bradshaw, 2014)

The total length of the spillway is 808 ft (246.3 m) with a net length of 630 ft (192 m). After the original construction of the spillway, the crest was 69 ft (21 m) above sea level with 19 ft (5.8 m) high gates. The combined height of the crest and gates allowed the elevation of Gatún Lake to remain at 85 ft (26 m). The gates of Gatún Spillway are operated from a control board in the powerhouse located to the northwest of the spillway. During the initial construction of the spillway, engineers estimated that any one of the gates used were capable of discharging at least 10,000 ft^3/sec (283 m^3/sec) of water (Panama Canal Flood Control Facilities, 1977a). Assuming each gate is capable of this discharge, the spillway can release 140,000 ft^3/sec (3,964 m^3/sec) of water with all gates open. To maintain the operating level of Gatún Lake, spills occur approximately once per year, but may occur more frequently, depending on annual rainfall.

During the operational lifetime of the spillway, changes have been made in order to keep the structure in working condition. In 1927, after 13 years of operation, two of the baffle blocks were removed in order to direct water away from the powerhouse during spilling (circled in Figure 37) (US Army Corps of Engineers, 1996). The original gates are riveted, but over time, riveted construction has become obsolete. Therefore, as new gates have been constructed for replacements, they have been changed to a welded design. Although Gatún Spillway has 14 gates in the structure, there are two extra in storage for inspection and repair purposes. This flexibility allows the ACP to fully remove and replace gates when they are in need of significant repairs. Due to the expansion project and the raised operating water level of the lake to 89 ft (27.1 m) (Alarcón et al., 2011), the gates of Gatún Spillway were extended. Originally 45 ft (13.7 m) in width by 19 ft (5.7 m) in height, an extra 1.5 ft (0.5 m) was added to the height of each for a total of 20.5 ft (6.3 m) (Panama Canal Museum, 2016).

Figure 37: Panorama of Gatún Spillway (Wikipedia, 2016a)

Miraflores Dam and Spillway is adjacent to the Miraflores Locks, on the Pacific side of the Panama Canal. The structure created Miraflores Lake and is responsible for maintaining the water level at 52 ft (16 m) above sea level. The lake is located between the Miraflores and Pedro Miguel Locks and covers 1.2 mi (2 km) of the journey through the canal (Bray, 2016). The locks of the Panama Canal utilize gravity for their operation, as opposed to pumps. As a result, water travels with the ships through the lockages, causing the level of Miraflores Lake, which is relatively small, to raise considerably every day. During normal operation, Miraflores Spillway spills water once or twice a day to maintain the operating level of the lake (Figure 38).

The construction of the Miraflores Spillway was completed in 1914 (Panama Canal Flood Control Facilities, 1977b). It is an ogee spillway that is oriented linearly with a net length of 360 ft (109.7 m) (Figure 39). The crest is located at 38.6 ft (11.8 m) above sea level and provides a platform for eight 19 ft (5.7 m) tall vertical lift gates. The gates are identical in size and operation to the original gates at Gatún Spillway, which simplified replacement of any components.

Figure 38: Location of Miraflores Dam and Spillway in relation to the navigational channel (Wikipedia, 2016b)

Figure 39: Miraflores Dam (Mitch, 2007)

Although Miraflores Lake is relatively small, the engineers responsible for the design prepared for the worst-case scenario flow rate when planning the Miraflores Dam and Spillway. In the event that the Pedro Miguel Locks on the other side of Miraflores Lake failed and allowed the water from Gatún Lake to flow unrestricted, the engineers estimated that the inflow would be about 70,000 ft^3/sec (1,982 m^3/sec). Therefore, the spillway was designed with the ability to release that volume of water when the lake was at its highest allowable level.

Madden Dam and Spillway was constructed in 1935, forming Alhajuela (Madden) Lake (Panama Canal Flood Control Facilities, 1978). The structure is located to the east of Gatún Lake, upstream on the Chagres River. Depending on the season, the Chagres River could be very volatile and unpredictable, creating currents in Gatún Lake that disrupted the passage of vessels. Madden Dam and Spillway is responsible for maintaining the water level in the canal, providing a source of water to residents of Panama, and generating hydroelectric power.

Unlike Gatún and Miraflores Spillways, which use vertical lift gates, Madden Spillway utilizes drum gates. Drum gates can be longer than vertical lift gates, which reduces the number of gates needed in a spillway. The gates are hollow, metal, cylindrical sectors that are hinged at the centerline and controlled by a floatation chamber. The flotation chambers, or pools, are located beneath each drum gate and fill with water as the lake level rises. The drum gates float on top of the rising water in the pool, rotating upward to maintain the lake's elevation by continuing to block flow (Figure 40). By pumping water out of one or more of the pools, the gates are lowered, allowing lake water to flow over the top of the structure (Barker, Vivian, Matthews, & Oliver, 2003).

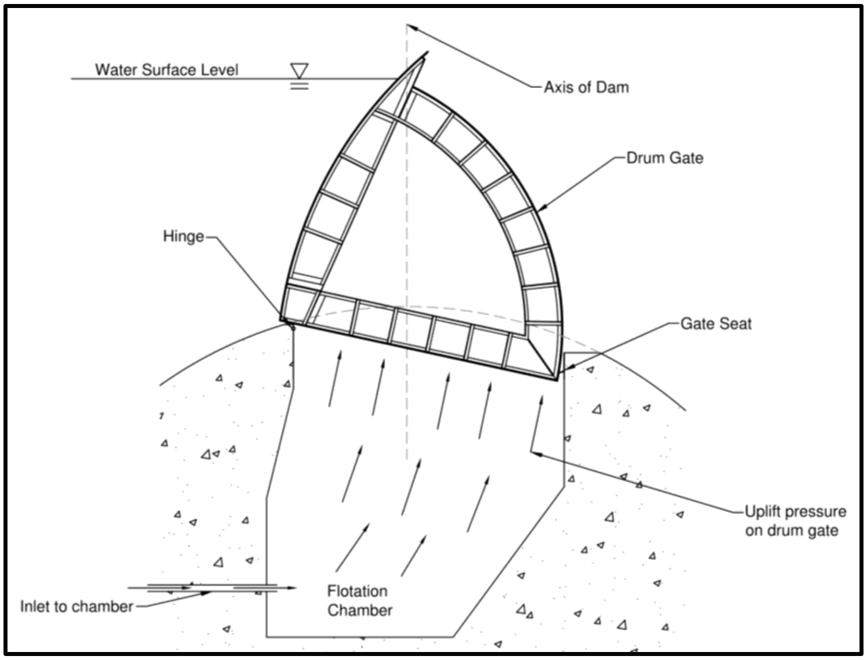


Figure 40: Section of Madden drum gate (Burner, 2016)

Madden Spillway has a concrete ogee design that is oriented linearly with a total length of 974 ft (297 m) and a height of 223 ft (68 m) (Panama Canal Flood Control Facilities, 1978). It has four drum gates, each with a length of 100 ft (30.5 m) and a height of 18 ft (5.5 m) (Figure 41). The structure also has six sluice gates, located at the base of the spillway, to flush sediment that accumulates in the lake. The spillway keeps Alhajuela Lake at an elevation of 260 ft (79 m) above sea level. To maintain this elevation and the elevation downstream, water is spilled once or twice a year, similar to Gatún Spillway.

Figure 41: Madden Dam and Spillway with Alhajuela Lake in the background and the Chagres River in the foreground (justin_n, 2007)

During construction, the spillway was assembled in 56 ft (17 m) long sections. The drum gates were fabricated in place and a vehicular bridge was built above them. Due to these construction techniques, there is no way to remove and replace any of the gates in Madden Spillway. Even if the bridge were to be removed to create access, the ACP currently has no plan of action for the removal of a gate. For many of the same reasons, and because drum gates are not a common design in modern engineering, the ACP does not have any replacement drum gates. As a result, Madden Spillway is considered to be the most high-risk spillway on the Panama Canal and the ACP is currently conducting a risk assessment of the structure.

2.3 Creation of Dam and Spillway Inspection Regulations

In the 1970s, a series of devastating dam failures occurred across the United States. On February 26, 1972, a dam in West Virginia failed, killing 125 people, injuring an additional 1,100, and destroying the homes of 6,000 residents. The Teton Dam in Idaho failed on June 5, 1976. This catastrophic failure caused $1 billion in damage, killed 11 people, and destroyed 8,000 residences and farm buildings. On November 6, 1977 the Kelly Barnes Dam in Georgia failed and killed 39 people (Federal Emergency Management Agency, 2013).

This series of dam failures sparked an initiative in the United States Federal Government to enact a law, allowing the U.S. Army Corps of Engineers (USACE) to inventory and inspect non-federal dams in the U.S. In particular, after the Kelly Barnes Dam failure, the USACE was instructed to inspect all non-federal dams that were classified as high-hazard due to their downstream populations. On July 20, 1979, President Carter signed Executive Order 12148, which created the Federal Emergency Management Agency (FEMA) and made them responsible for "the coordination of efforts to promote dam safety" (Baecher, Brubaker, Galloway, & Link, 2011).

After being established, FEMA published the Federal Guidelines for Dam Safety, which provided instructions for inspection and maintenance of dams (Federal Emergency Management Agency, 1979). The document took into account the fact that many dams in the United States had not been inspected since their construction and that much of the relevant data about a dam's site, design, construction techniques, and operation may be missing from its logs. FEMA also gave instructions pertaining to the inspection teams and equipment needed, as well as the types of inspections and what should be evaluated in each.

As dams age, they may become weaker due to a chemical reaction between alkalis in the cement and silica in the aggregate of the mix (U.S. Nuclear Regulatory Commission, 1978). Many other factors, such as erosion, seepage, settling, and cracking, can lead to the failure of a dam or spillway. As a result, inspection is very important in identifying and repairing any unsafe conditions that may develop in the structure.

2.4 Panama Canal Inspection Program

Due to American administration of the Panama Canal during the development of the dam safety initiatives, the canal became subject to the National Dam Inspection Act of 1972 and other subsequent dam safety programs (Panama Canal Flood Control Facilities, 1978). ACP employees began inspecting the dams and spillways responsible for the operation of the canal in July of 1974. After the United States transferred control of the canal back to the Panamanians, the ACP continued to hold the structures to the standards set by FEMA and the American Society of Civil Engineers (ASCE) for dam safety.

Depending on the risk classification of the dam, the frequency of inspection varies. For example, the Connecticut Department of Environmental Protection classifies dams from AA, negligible hazard potential and should be inspected at least once in its lifespan, to C, high hazard potential, which should be inspected every two years. There are also different types of inspections that should be conducted with different frequencies. The first type, informal inspections, are performed continuously and require that personnel monitoring the structure are making observations about changes in the dam or spillway. It is suggested that intermediate inspections be performed annually on high hazard dams and include a thorough field inspection of the structure. The other type of inspections, formal or special, should be performed approximately every 5 years, depending on the specific dam or spillway. Formal or special inspections should involve an in-depth review of all components and operations of the spillway (Fuss & O'Neill, Inc., 2001).

The dams and spillways of the Panama Canal are all classified as high-risk and are thus inspected regularly. The ACP has three types of routine dam and spillway inspections: visual, detailed, and formal. They also perform emergency inspections as necessary (Autoridad del Canal de Panamá, 2011). Visual inspections are completed annually and require operational tests and a simple walkthrough of the structure to identify any necessary repairs, maintenance, or replacements. Detailed inspections occur every three years, include the review of all critical elements, and may incorporate operational testing. Formal inspections are performed every 10-12 years and consist of detailed examinations of areas that are not usually evaluated. In formal inspections, the number of elements reviewed are reduced to the most critical components, but each of these elements are assessed in much greater detail. Mechanical testing is also carried out under maximum loading conditions at this time. Additionally, in the event of a natural disaster or sudden equipment failure, the ACP conducts emergency inspections.

2.5 Risk Assessment and Reliability Analysis

Many dam and spillway safety programs have well defined safety technical goals, but have poorly-defined pathways for achieving such goals. This leads to slow progress in achieving safety goals, inefficient use of available funds, a fragmented safety program, and poor understanding of the need for safety improvements. Risk estimates can be used to formulate and justify safety improvement programs and for strengthening ongoing safety management activities (Bowles, 2001).

Statistically, risk is defined as the product of the probability of failure and the loss associated with that failure. A structure fails when it is no longer able to perform as it was intended (Estes, Foltz, & McKay, 2005). Risk assessments are used to predict possible causes of failure and prevent them from occurring (Farkas, 2014). Assessments can be determined with several different methods, including block diagrams, fault tree analyses, failure mode and effect analyses (FMEA), decision trees, risk modeling, and risk tolerance charts.

Risk criteria are established to help develop a level above which risk would be considered unacceptable (Bowles, 2001). Reduction of risk can be achieved in one of two ways: by decreasing the probability of occurrence or by minimizing the loss associated with the failure. There are five categories to treat risk: avoidance of the risk, reduction or prevention of the probability of occurrence, mitigation of the consequences, transference of the risk, or acceptance of the risk (Bowles, 2001). Risk is considered tolerable if it is within a range that society can live with, while securing certain net benefits (ICOLD, 2000).

Reliability analysis is best for quantifying the acceptable amount of risk. It involves defining all random variables, predicting how loads will change and the structure will deteriorate over time, and quantifying the probability of failure of the structure at specific points in time. A structure is considered reliable if its capacity exceeds the demand placed on it. Because loads tend to increase over time and resistance tends to decrease as a structure deteriorates, the overall reliability of a structure can be expected to decrease over time. Reliability methods are used to optimize the life-cycle costs of a structure and to guide future maintenance and repair decisions. Maintenance budgets should be allocated to projects where doing nothing poses the greatest threat (Estes et al., 2005).

3.0 Evaluation of the ACP's Formal Inspection Program of Dams and Spillways

3.1 Methodology

The goal of this project was to evaluate the ACP's Formal Inspection Program of Dams and Spillways and provide suggestions to further improve their processes. Specifically, this project focused on the inspection of structural elements of the ACP's system of dams and spillways. To achieve this goal, the following objectives were identified:

1. Research the meaning of "formal inspection" in the context of other regions.
2. Review, both in the office and on-site, the processes currently followed by the ACP for inspection.
3. Compare U.S. standards to the ACP protocol for formal inspections and provide recommendations to improve efficiency and sustainability.

3.1.1 Investigation of Formal Inspection Programs

During American operation, the organization in control of the Panama Canal, the Panama Canal Commission, was required to follow United States standards for inspection. Therefore, special attention was paid to the protocol for formal inspections set by FEMA, as well as individual states. Specifically, this project reviewed FEMA's *Federal Guidelines for Dam Safety* (1979), the Texas Commission on Environmental Quality's *Inspection and Maintenance of Dams and Spillways* (2014), the Connecticut Department of Environmental Protection's *Guidelines for Inspection and Maintenance of Dams* (2001), and the Indiana Department of Natural Resources' *Indiana Dam Safety Inspection Manual* (2007) to gain an understanding of the scope of a formal inspection. Additionally, because the gates of a spillway are critical to the structure's function, further research was conducted on the inspection of riveted spillway gates. For formal inspection of spillway gates, two documents were reviewed: the Center for Advanced Technology for Large Structural Systems' *Structural Evaluation of Riveted Spillway Gates* (1992) and the United States Army Corps of Engineers' *Guidelines for Assessing Condition of Riveted Spillway Gates* (1994).

As these documents were reviewed, the inspection guidelines that each gave were recorded for future reference. Also listed were the essential personnel required for inspection teams, in addition to the documents necessary for preparation or review prior to inspection.

Furthermore, steps that appeared in multiple guidelines were given special notice, as there was sufficient evidence that they are integral parts of the inspection process. Any checklists that were mentioned by the documents were reviewed to gain an understanding of which components of the dam and spillway systems needed to be inspected in-depth, as opposed to visually.

3.1.2 Review of Current ACP Formal Inspection Protocol

Although the ACP has been conducting visual inspections of their dams and spillways since 1974, their formal inspection program did not begin until 2015. Because the program was newly implemented, there were not many previous inspection reports to review in order to gain an understanding of the scope of their formal inspections. Two inspections similar to formal inspections were conducted in the past, one in 1977 by the Mobile District Office of the South Atlantic Division and one in 1996 by the U.S. Army Corps of Engineers. Therefore, these two inspection reports were reviewed in order to understand how these inspections were previously conducted.

The ACP´s current Formal Inspection Protocol was reviewed to understand the preparation work that must be conducted, checklists of elements to inspect, instructions on what the main focus of each element is, and what level of detail the inspections should be conducted at. In 2015, the ACP developed a schedule outlining which spillway is to be inspected during which time of year. They also developed a future plan to determine which components of the structure would be inspected in the following years. These schedules were reviewed to verify that components were being inspected regularly and to provide any suggestions as to changes that could be made. Furthermore, observations were conducted during site visits to see if the protocols were being followed.

3.1.3 Evaluation of ACP Protocol and Creation of a Standard Document

After the review of the ACP Inspection Protocol, the guidelines pertaining to the Panama Canal were compared to the procedures for various locations in the United States. This process helped determine if the ACP was including the proper personnel on inspection teams and whether they were inspecting the spillways often enough. Moreover, this evaluation served to determine if the ACP documents were clear enough and included sufficient detail for the inspection team to follow. This step facilitated the creation of checklists of inspection elements and a guideline for writing inspection reports.

3.2 Results and Analysis

By researching U.S. standards for formal inspections and by reviewing similar documents from the ACP, a comparison between the two was made and recommendations for improvements to the ACP's protocol and efficiency related to inspection scheduling could be suggested.

3.2.1 Standards of Formal Inspections

From the review of FEMA's *Federal Guidelines for Dam Safety* (1979), the Texas Commission on Environmental Quality's *Inspection and Maintenance of Dams and Spillways* (2014), the Connecticut Department of Environmental Protection's *Guidelines for Inspection and Maintenance of Dams* (2001), and the Indiana Department of Natural Resources' *Indiana Dam Safety Inspection Manual* (2007), the important features and processes of a formal inspection were determined.

Inspection of older structures is extremely important, no matter the location, as companies and owners often lack the original documents from construction. Therefore, the design, capacity, and materials used may not be known. By routinely inspecting these structures, the structural integrity of the dam or spillway can be verified in order to ensure that the downstream population and development will not be affected. Dams can be classified into different categories based on their hazard. As the Panama Canal dams and spillways are all high hazard, the inspection procedure for high hazard dams was focused on.

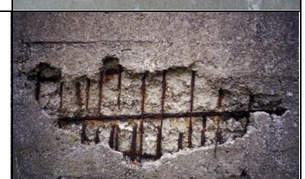
In relation to high hazard dams, all sources consulted dictated that formal inspections should occur every two years. It was also stated that for any new structures, a formal inspection should be completed after construction to give future teams a baseline to which to compare. Furthermore, if a spillway is required to spill an unusually large amount of water, it should be inspected soon after to confirm that no structural damage occurred in the process. A schedule of each formal inspection, past and future, should be maintained and include each feature that is inspected, how often inspections occur, the last inspection date, the last inspection report, the maintenance record and any repairs, and the next inspection date. If any major changes are made to the structure, those should also be recorded in the schedule.

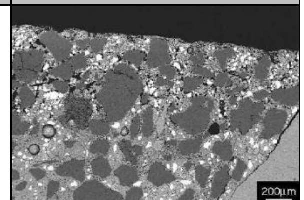
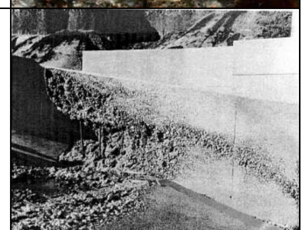
Personnel assigned to complete an inspection are critical in determining the quality of the inspection. Each member of the inspection team should be trained in their personal area of specialization and there should be a variety of specialists in order to ensure each function of the dam or spillway is properly tested. The inspection team should be instructed by experienced, licensed engineers. Inspection equipment is also vital to the success of the evaluation. General inspection equipment includes the inspection checklist, plans of the structure, binoculars, a tape measure, and a camera. Specialized equipment such as a probe, rock hammer, flow meter, and a water level indicator may be necessary depending on the element being inspected. Safety equipment such as hard hats, harnesses, steel-toed boots, safety glasses, gloves, safety vests, and life jackets are needed to ensure the security of the inspection team.

Before beginning the on-site inspection of a structure, plans must be reviewed. In older structures, the design criteria they were constructed to meet may not be the same as current safety standards. Therefore, a review of any original plans must be conducted in order to ensure that the dam or spillway still meets current design criteria. In particular, the hydraulic and geotechnical calculations should be examined to verify that the spillway is capable of spilling the proper amount of water and that the foundation is correct for current soil conditions. Any steel that was installed before 1939 should be highlighted during the review process because until the 1930s, there were no standards in place for chemical content in steel. Therefore, it is not guaranteed to have the expected material properties. After reviewing original construction documents, previous inspection reports and maintenance documents should be viewed. These documents allow the inspection team to identify any critical components of the dam or spillway and understand the history of problems in the structure. The team should also learn the current operational practices of the spillway and whether there are any new loads, problems, or unusual events. These steps ensure that the inspectors are well-informed before visiting the structure.

When conducting inspections, the team should know what types of damage to look for, depending on the material from which each element is made. Concrete should be examined for deterioration or any unfavorable change to the surface. Oxidation, wet and dry cycles, human activity, and forces of nature, such as erosive forces, are all common causes of concrete damage. While the umbrella term "deterioration" is commonly used, various types of damage to concrete can be observed as a result of different causes. Cracks, disintegration, scaling, spalling, popouts, pitting, efflorescence, drummy concete, faulty mixes, erosion, cavitation, and joint deterioration are all commonly seen during inspection (Table 20). The amount of deterioration should be compared to the original condition of the element and the type and location of damage should be recorded.

Table 20: Types of concrete damage (Indiana Department of Natural Resources, 2007)

Type of Damage	Description	Example
Cracks	Breakage without completely separating pieces of concrete	
Disintegration	Crumbling of concrete into small particles	
Scaling	Flaking or peeling of the concrete surface	
Spalling	Loss of large pieces of the concrete surface	
Popouts	Smaller version of spalling	
Pitting	Localized disintegration, development of small cavities in surface	
Efflorescence	Accumulation of the discharge of calcium compounds from the concrete	
Drummy concrete	Voids or separation of concrete beneath the surface	

Type of Damage	Description	Example
Faulty concrete mixes	Errors occurring in the aggregate, water ratio, amount of entrained air, mixing, placement, or curing procedures	
Erosion	Missing concrete caused by gravel or sand in fast-moving water	
Cavitation	Damage caused by turbulent flow, impact energy, or sub-atmospheric pressures on the surface of the concrete	
Joint deterioration	Missing sealant in joints	

These damages to concrete components should be understood by the inspection team before inspections begin. Each element inspected should be reviewed for any of these deteriorations. The concrete constituents to be observed in a typical formal inspection include: approach channel, inlets and control sections, discharge conduit, discharge channel, outlet structures and stilling basins, joints, control features, sidewalls, submerged areas, the upstream face, the downstream face, the left and right abutment walls, and the downstream channel. In addition to the specific damages to the concrete, inspection teams should also be aware of general concerns; such as alignment, obstructions, ruts, sedimentation, seepage, damaged seals, and displacements; which vary depending on the component being inspected (Appendix E).

Although most dams are constructed from concrete or soil and gravel, spillways with control structures also utilize metals, such as steel. Various defects can occur in metal, such as cracking and deformation, but the most commonly seen is corrosion. Cracking, the breakage of metal without splitting, is often seen in the form of fatigue cracks and can be located near rivets, corroded areas, and new welds. Deformation is the bending of a metal into a different arrangement than how it was originally designed and constructed. Corrosion is the formation of iron oxide resulting from exposure to water, which deteriorates a metal (Indiana Department of Natural Resources, 2007). This damage is most often found in metal elements such as spillway gates or steel reinforcing bars within the concrete. Corrosion damage arises in a variety of situations and locations. General atmospheric corrosion is expected to develop on spillway gates during their operational lifetime but is a slow, uniform thinning that does not cause substantial structural degradation. Localized corrosion, however, usually affects riveted gates and can cause more significant structural damage, as the corrosion is not spread over a large area (Table 21). Although some types of corrosion occur due to the environment, others are directly caused by the operation of the spillway, known as mechanically assisted corrosion. Once corrosion begins on metal surfaces, it will continue to progress, even if treated with preventative measures. However, the speed of progression is dependent on the repair procedures.

Steel inspections are particularly important in spillways because if the gates fail, the water level of the reservoir cannot be controlled. The operation of gates causes repeated loading and unloading cycles, leading to fatigue. Inspection teams should pay particular attention to signs of wind and wave action, gate lifting stresses on side seals, flow-induced vibration, rivet fatigue, and weld stresses. Elements of gates that should be inspected include skin plates, horizontal girders, end bearing assembly, seals, the lifting arrangement, the tracks and guides, and the sill. Additionally, drains providing pressure relief and trash racks for debris control should be inspected for typical metal damages (Appendix E: General Inspection Items for Dams and Spillways). For elements constructed before the 1930s,

Table 21: Types of corrosion and where they are found (Center for Advanced Technology for Large Structural Systems, 1992; United States Army Corps of Engineers, 1994)

Type of Corrosion	Description/Location
Crevice	Found in narrow openings between two elements
Pitting	Deep cavities with small surface area, can cause paint covering to blister and fail
Galvanic	Occurs between original construction and repairs when the metals have different electrochemical potentials
Stray-current	Occurs when a current does not follow its intended path
Filiform	Forms at cracks under the thin paint covering
Erosion Corrosion	Caused by the wear of the metal's protective coating by flowing water and the particles contained within it
Cavitation Corrosion	Caused by cavitation, which occurs due to extreme changes in pressure from large releases of water
Fretting	Caused by metal components rubbing together

welded repairs should be closely inspected for fatigue cracks, as steel produced during this time behaves unpredictably during the rapid heating and cooling caused by welding.

While more difficult to inspect, the underwater, upstream elements of dams and spillways must also be examined. These inspections focus on the submerged upstream face, looking for the same damages and deterioration as the concrete above the water level. Any submerged metal components, such as sluice gates, should be inspected for typical metal damages. In particular, submerged sections should be inspected closely for any debris, erosion, underwater structural damage, and undermining on the upstream face.

During the entire inspection process, the team should record all of the components evaluated and the condition that they were found in. The notes should be detailed enough for maintenance workers to easily locate the areas in need of repair. After the inspection has been completed, a detailed report should be prepared by the team. It should include the background information reviewed; any design, construction, or operational issues found; results of the field investigation; and any conclusions and recommendations made by the team. Pictures should be contained where necessary and any claims should be backed up with calculations and field measurements. Any damages found should have a detailed description of each damaged component, what type of damage was found, condition of surrounding elements, any possible causes of problem, and the possible effects of the problem on the function of the structure. The conclusions and recommendations section should contain an assessment of the structure's condition, any repairs necessary, and a schedule of when the repairs should be completed. The next time an inspection is conducted on the same structure, the team should include the state of these repairs in their report.

3.2.2 ACP Formal Inspection Protocol

The Panama Canal faces a unique situation for formal inspection because the evaluations cannot be carried out in a traditional manner. The waterway is operational 24 hours per day, 365 days per year; therefore, the spillways of the canal must always be functioning. This dictates that no spillway can be completely shut down for inspection, requiring that different elements must be inspected at different times. Every year, one of the three spillways is formally inspected. The remaining two must be visually inspected. Due to these constraints, the ACP has a modified procedure in comparison to other dam and spillway locations.

The Comité de Seguridad de Represas y Vertederos (CSRV – Dams and Spillways Safety Committee), established in 2009, is the ACP department responsible for developing safety and maintenance manuals for the system of dams and spillways. The CSRV is also accountable for inspections, maintaining all related information, and preparing a risk mitigation plan. It works with the Comité de Coordinación de Represas y Vertederos (CCRV – Dams and Spillways Coordination Committee), established in 2010, in order to ensure the inspections are complying with the safety and maintenance manuals and to coordinate inspection and maintenance efforts. These committees are multidisciplinary and contain employees from Civil Engineering, Mechanical Engineering, Electrical Engineering, Geotechnical Engineering, the Water Resources Division, and the Topography and Cartography Section.

For each inspection planned by the CCRV, a member from the Engineering Division is designated as inspector. This inspector must set an inspection date, ensure it is in compliance with the Annual Inspection Program, review the approved checklists, ensure each component is inspected, and propose improvements to the process. Other members of the inspection team are as follows: Civil Engineer, Mechanical Engineer, Geologist, Geotechnical Engineer, Structural Engineer, Hydraulic Engineer, Instrumentation Specialist, Corrosion Specialist, and Operation and Maintenance Representatives. The Operation and Maintenance Representatives, who work at the dam and spillway on a regular basis, assist the inspection team by providing additional information about the structure, operating equipment, and providing access to inspection areas.

The ACP inspection process is most unique in its inspection timeline. This is due to Panama's seasonal patterns, as well as the aforementioned scheduling difficulty. Miraflores Spillway is operated multiple times every day, whereas Gatún and Madden Spillways are operated approximately once a year, during the rainy season. The ACP made the decision to inspect Miraflores Spillway during the rainy season, because it would be spilling regardless of inspection time. Gatún Spillway must be inspected during the dry season when there is less of a chance that water will be spilled. Regardless of the season, the water level of Gatún Lake is above the spillway crest, located on the height of the gates (Figure 42). To inspect the gates, caissons must be temporarily placed so the gate can operate without losing the lake level. Madden Spillway must also be inspected during the dry season. Depending on rainfall, the water level varies. At its lowest point, the water is below the spillway crest, but at its highest, the water rises above the crest, located on the raised drum gate. The ACP currently has no caisson or

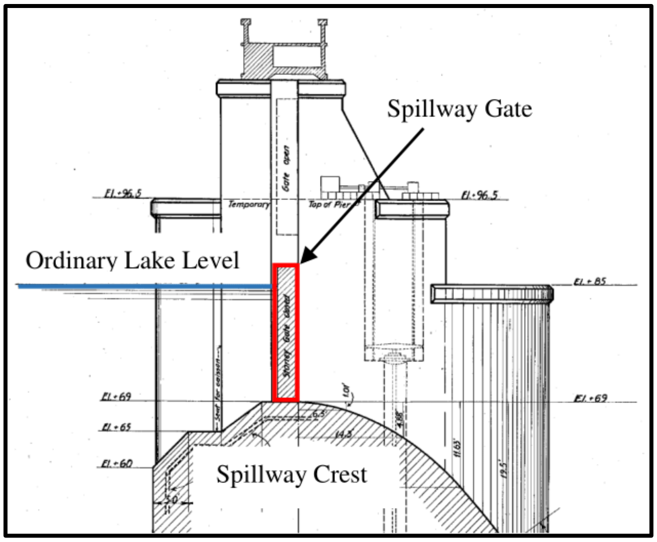


Figure 42: Level of Gatún Lake in relation to the spillway crest (Panama Canal Flood Control Facilities, 1977a)

device for Madden Spillway, requiring that it be inspected during the peak of dry season, when the water level is below the crest of the spillway and the drum gates are in the lowered position. Based on these factors, the ACP determined set dates when each spillway should be inspected (Table 22). Gatún is inspected at multiple times during the year because it utilizes more gates than the other spillways and contains more concrete surface area.

Not every element of the spillway is inspected annually. Due to the restricted time that the inspection team spends at each spillway and the size of the structures, another schedule dictates which spillway gate is inspected in certain years. For example, in fiscal year 2016, gates 5 and 6 of Miraflores Spillway, drum gate 3 of Madden Spillway, and gates 5 and 6 of Gatún Spillway were formally inspected. This causes Miraflores and Gatún to have a 10-year inspection cycle and Madden to have a 13-year cycle. However, visual inspections are conducted on the spillways each year, and if a particular element has significant deterioration, it will be scheduled for an earlier date than originally planned.

Table 22: Inspection periods for ACP spillways (Autoridad del Canal de Panamá, 2011)

2016 Fiscal Year Periods	Spillways
October 1 – January 31	Miraflores
February 1 – March 31	Gatún
April 1 – July 31	Madden
August 1 – September 30	Gatún

Before the inspection begins, the ACP has a similar process to those found in other formal inspection protocols. All historic information, designs and "as built" plans, past completed inspection reports, and monitoring instrumentation data must be reviewed. The inspection team will also use the assistance of outside sources, such as other ACP departments, construction firms that have experience with the ACP's dams and spillways, global dam and safety organizations, ACP operations and maintenance personnel, and nearby residents, to gain all relevant information. After the initial review, a plan is prepared. This plan includes the approved checklist of items to be inspected, modifications that should be made based on the current operation, the type and location of destructive and non-destructive tests to be conducted, instructions for underwater inspection, and an identification of the damages that can occur in concrete and metals and why they occur.

Similar to the other inspection protocols researched, the ACP gives instructions about what types of damage to look for and what to record when defects are found. The ACP identifies two different types of concrete cracking; individual and general. The direction, width, and depth of individual cracks should be recorded, as certain characteristics indicate a serious problem. An individual crack that is diagonal with an abrupt change in direction, a wide crack increasing in size, cracks adjacent to concrete displacements, and narrow, diagonal cracks can all indicate larger problems that may compromise the safety of the dam. The focus for general cracking differs from individual cracks, as the nature and extent of cracking must be recorded, instead of specific dimensions. The ACP highlights three types of general cracking: pattern cracking, caused by shrinkage of the surface of the concrete; D-cracking, with fine parallel cracks closely spaced; and plastic cracking, caused by the expansion and contraction of the concrete during wet or dry periods. The inspection team is also instructed to examine the concrete for general deterioration, which is defined as any change to the concrete that causes separation, cracking, or loss of strength. Examples of this include: surface defects, disintegration, spalling, efflorescence, hollow concrete, splintering, pitting, and peeling.

A checklist of concrete areas that need to be inspected is provided in the ACP's instructions. Although specific instructions are given for each location, most need to be power washed with water to make the concrete surface visible. Temporary scaffolding must also be installed to allow inspectors and maintenance workers to closely inspect all elements. A different list of inspection components is provided for each dam and spillway (Table 23).

Table 23: Concrete items of each spillway to be inspected (Autoridad del Canal de Panamá, 2015a; Autoridad del Canal de Panamá, 2015b; Autoridad del Canal de Panamá, 2015c)

Gatún Spillway	**Miraflores Dam and Spillway**	**Madden Dam and Spillway**
Upstream face of spillway	Upstream face of spillway	Upstream face of spillway
Downstream face of spillway	Downstream face of spillway	Downstream face of spillway
Upstream face of pillars	Upstream face of pillars	Upstream face of pillars
Downstream face of pillars	Downstream face of pillars	Downstream face of pillars
Discharge channel lateral walls	Lateral walls	Lateral walls
Discharge channel concrete slab	Access bridge above spillway	Concrete abutments
Concrete abutments	Upstream gallery	Bridge over the spillway
Upstream gallery	Downstream gallery	Concrete dams at end of spillway
Downstream gallery	Machinery tunnel	Needle valve slab discharge area
Machinery tunnel	Counterweight pits	Drum gate gallery and operating chambers
Counterweight pits		Sluice gate gallery and operating chambers
Baffle blocks		Needle valve gallery and operating chambers
Draft tube deck area		Cross cut galleries (tunnels)
		Cable tunnel
		Float well
		Freight shaft
		Drum gate chamber
		Pits

In their protocol, the ACP identifies corrosion, cracks, and deformation as the main concerns in steel components. Two categories of corrosion are recognized; generalized and highly localized. Generalized corrosion occurs over the surface of the material, whereas highly localized corrosion occurs in one specific location and can penetrate the material. Different types of corrosion, such as galvanic attack, confined space corrosion, pitting corrosion, intergranular corrosion, selective corrosion, erosion or cavitation corrosion, and stress corrosion, are mentioned in the protocol. Stress or corrosion cracks, fatigue, and overloading are other types of failure recognized by the ACP.

Before identifying individual elements to be inspected, the protocol provides common conditions for the types of deterioration. Corrosion is commonly found in areas where the metal has been distorted or welded; between contact of dissimilar metals; locations with high humidity, limited oxygen exposure, and high velocity flows; saline environments, and underground pipes.

Cracks develop in areas of high stress or existing corrosion, as well as areas overloaded beyond their intended capacity. Fatigue occurs in areas that are repeatedly exposed to the same type of loading. The steel components to be inspected at each spillway are provided in a checklist (Table 24). These items should have their protective coatings removed and have all corrosion cleaned from them. If required, thickness measurements will be taken. The inspection team also requires scaffolding to be temporarily installed so items can be inspected in detail.

Underwater inspections are conducted on the submerged upstream face of each of the ACP spillways. These inspections require divers to check the condition of the concrete surfaces. The protocol instructs the inspection team to work with the divers to establish a system by which the divers can locate both the depth and length of any defects that are found along the spillway. The current depth of the water at the time of inspection must be verified by the team before inspection begins. The defects for which the divers must examine the structure are: spalling or flaking of the concrete, concrete cracking, deterioration of the concrete surface, thickness

Table 24: Steel items of each spillway to be inspected (Autoridad del Canal de Panamá, 2015a; Autoridad del Canal de Panamá, 2015b; Autoridad del Canal de Panamá, 2015c)

Gatún Spillway	**Miraflores Dam and Spillway**	**Madden Dam and Spillway**
Upstream faces of gates	Upstream faces of gates	Drum gates interior faces
Downstream faces of gates	Downstream faces of gates	Drum gates exterior faces
Castings in the gate pillars	Castings in the gate pillars	Drum gate hinges
Trash racks	Transmission tower foundation	Drum gate hinge coverings
Deck grating above trash racks	Transmission tower castings	Upstream faces of service sluice gates
Deck grating supporting structure	Transmission tower structure	Downstream face of service sluice gates
Footbridge steel floor plates	Footbridge steel floor plates	Upstream face of emergency sluice gates
Footbridge beam bracing	Footbridge beam bracing	Downstream face of emergency sluice gates
		Sluice gate framework
		Stairs
		Generation building roof
		Transformer deck
		Sluice gate outlet trash rack structure
		Power and outlet trash rack structure

changes, bulges, undercuts, and cavitation damage. The area where the spillway meets the earth backfill or existing rock beneath it must be inspected for erosion. Additionally, the divers are requested to wear a camera that will record the diving inspection for review if any repairs or replacements are required.

Although the ACP requires a report for each inspection conducted, their formal protocol does not contain instructions on how this report should be written. However, there are detailed instructions on adding information to the *Cracking Records*. This document is used to observe the structure and relate the cracks to possible signs of weakness. The inspection team must record the characteristics of the crack, often under different loading conditions; the description of the crack type; the description of any other types of damages occurring simultaneously; and if the crack is in the same location as a previous repair. This record is intended to be compared to those of earlier years in order to determine if any location is particularly prone to cracking. If this is the case, a crack monitoring system can be put in place to measure movement, as well as the leakage source and flow.

3.2.3 Analysis of ACP Formal Inspection Protocol

Through a comparison of relevant U.S. formal inspection standards to the ACP Formal Inspection Protocol, an evaluation of the ACP's process was made. Overall, the majority of the required information for a protocol was addressed in the ACP's documents. However, these documents are not combined into one set of instructions. They were gathered from different sources over the course of a month, which indicates that the inspection team may not be able to easily review the process before conducting a formal inspection.

While most of the necessary information was included in the ACP documents, some was not compiled in a reader-friendly format. The damages that occur in concrete and steel were listed in different documents than the checklists of the concrete and steel elements to be inspected. A reader would need all documents on hand in order to know which problems to look for, instead of having one comprehensive checklist to use for inspections. Additionally, the checklists of items to inspect are broken up by structure, but they do not use a consistent format, leading to the possibility of items being missed. Using the existing checklists, a new one was created that lists each item to be inspected and what to look for during its examination (Table 25). Notes can be made in each column regarding the general condition it was found in and where a more detailed explanation of the damages can be found later in the report. The concrete checklist for each spillway includes items such as the upstream face and lateral walls, as well as each counterweight pit, spillway pier, and gate bay (Appendices F, G, and H).

In the ACP documents, the inspection checklists for metal objects were listed by larger components, as opposed to listing specific pieces of the larger components. A checklist similar to the one for concrete, with different tables for each dam and spillway, was created using materials from the ACP, the Indiana Department of Natural Resources' *Indiana Dam Safety Inspection Manual* (2007), and the Center for Advanced Technology for Large Structural Systems' *Structural Evaluation of Riveted Spillway Gates* (1992) (Table 26, Appendices F, G, and H).

From discussions with ACP engineers, it was determined that the spillway gates are operated at different frequencies. For example, in Gatún Spillway, gates on the same side of the spillway as the power generation building are opened first and closed last, in order to prevent the flow causing damage to the building's concrete outlet slab. Therefore, these gates experience more use and vibration during spilling than gates opposite to the generation building. However, there is no mention in the inspection protocol to pay special attention to the more frequently used gates. Instructions also stated that thickness measurements are taken "if required." The protocol does not give detail as to if this is a requirement scheduled at certain intervals or if it is determined based on conditions found in the field.

Table 25: Partial concrete checklist for Gatún Spillway with black areas for unneeded tests

	Concrete Condition	**Cracks**	**Seepage**	**Erosion**	**Settlement**	**Relative Movement**	**Drains and Drainage**	**Instrumentation**
Upstream Face								
Downstream Face								
Downstream Toe								
Left Lateral Wall								
Right Lateral Wall								
Bridge Deck and Framing (Concrete)								
Machinery Tunnel								
Upstream Gallery								
Downstream Gallery								

Table 26: Steel checklist for Madden Spillway

	Steel Condition	Cracks	Corrosion	Deformation	Skin Plate	Reinforcing Beams	End Bearing Assembly	Seals
Interior Face of Gate 1								
Interior Face of Gate 2								
Interior Face of Gate 3								
Interior Face of Gate 4								
Exterior Face of Gate 1								
Exterior Face of Gate 2								
Exterior Face of Gate 3								
Exterior Face of Gate 4								

Further conversations with the engineers indicated some room for improvement. They mentioned a need for ways to clean the concrete other than pressure washing. The current technique requires extensive setup and risks damaging the concrete. They also mentioned interest in different types of scaffolding that could be assembled and maneuvered more easily than the current structures (Figure 43).

Finally, through a review of past inspection reports, both formal and visual, it was determined that the American administration of the canal had a standardized format for reports, but after the transfer in 1999, the format was no longer used. An inspection writing guide would make writing the reports easier for the engineers and would enable others reading the report to quickly find specific information. A suggested outline for inspection reports was adapted from Indiana Department of Natural Resources' *Indiana Dam Safety Inspection Manual* (2007) and

Figure 43: Existing floating (left) and mobile (right) scaffolding used by the ACP

the Center for Advanced Technology for Large Structural Systems' *Structural Evaluation of Riveted Spillway Gates* (1992) for the Autoridad del Canal de Panamá (Appendix I).

Overall, the ACP has a comprehensive formal inspection protocol that would benefit from more research and organization, but much of the improvement will happen as the program becomes more established in the company.

3.3 Conclusions and Recommendations

Through the comparison of ACP inspection protocol and accepted standards of formal inspections, it was determined that the ACP meets most requirements. However, as 2015 was the first year that formal inspections were conducted, the inspection team still has challenges to overcome. Specifically, the processes can be improved in the areas of efficiency and sustainability.

During the review of the ACP documents, it was found that many of the important procedures and instructions were not compiled in the same location. To ensure that the inspection team has easy access to all important documents, all relevant instructions should be combined into a central document that is easily accessible by all involved parties. This central inspection protocol should include the checklists created over the course of this project (Appendices F, G, and H). These suggested steel and concrete checklists provide a preliminary foundation and can be modified by the engineers and inspection team. Additionally, it is suggested that the CSRV reviews the instructions and checklists routinely in order to continue improving the inspection process.

After viewing multiple inspection reports from both before and after the 1999 transfer of the canal, it was determined that the ACP could benefit from a structured inspection outline. It is recommended that the inspection team review the proposed inspection outline, and adapt it to best suit their needs (Appendix I). Future inspections should be written following the same format in order to allow persons reviewing reports to be able to quickly and easily find the necessary information. This guideline should be reviewed every five years to ensure that the material discussed in the report is still relevant and covers all necessary information.

The ideal situation for improving the efficiency of the ACP's Formal Inspections would be to hire more personnel. Although this is challenging due to the difficulty of obtaining funds to increase inspection teams, it would allow more elements of each structure to be reviewed during one fiscal year. If enough additional workers were hired, each dam and spillway could be assigned an inspection team to work year-round at the same structure. Although the crest and gates of Gatún and Madden spillways are not accessible during the peak of rainy season, equipment and concrete in the galleries could be inspected. With workers at each structure at all times, there would be fewer time restrictions and a shorter inspection cycle for each element.

To further increase the efficiency of inspection, engineers at the ACP indicated that they are in need of different scaffolding options. While research was conducted into different types of scaffolding, ACP personnel will need to further investigate what is available in Panama. However, it was determined that many companies exist that will provide both pre-manufactured or made-to-specification floating scaffolding to allow inspection teams to closely inspect areas of the spillways that are located close to the water. Additionally, scaffolding that is manufactured in standardized pieces and is made for easy assembly should be considered, as this can decrease the pre- and post- inspection assembly and disassembly periods (Figure 44).

Improvements can also be made in order to increase the sustainability and longevity of the spillway structures and their components. During the operation of the spillways, a log should be kept of which gates are opened during spilling and for how long. This log can be analyzed by the inspection team to understand if one of the gates is used more often or for longer than others. If there is a difference in usage, the more frequently used gates should be inspected more often, as they are more likely to sustain damage.

Thickness measurements should also be taken in accordance with an established schedule. This schedule can be added into the formal inspection protocol and will indicate the years that that measurements should be taken for which gates. Its establishment will allow future inspection teams access to more data regarding the condition of the gates. Therefore, it will help the team complete the inspection more efficiently.

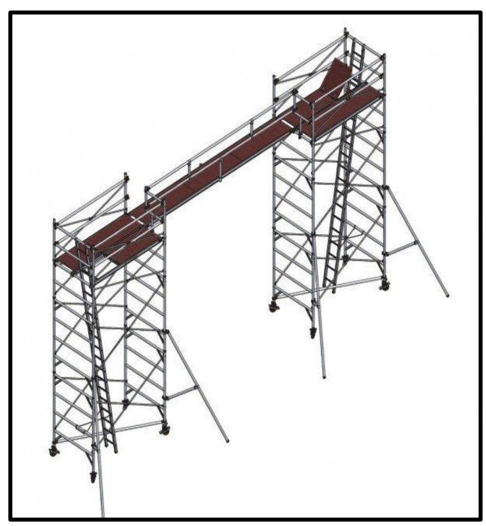


Figure 44: Proposed floating platform (left) (The Pontoon & Dock Company Ltd, 2016) and long-span scaffolding (right) (R&S Trade Center, 2016)

To help maintain the quality of the structure for a longer period of time, it is suggested that the ACP require low-pressure power washing to be used to clean the spillway surfaces before formal inspection. Although this may take longer to clean residue off of the concrete faces, high pressure power washing is known to erode surfaces and increase the damage that the structure has sustained. Using lower pressure still allows the concrete surfaces to be cleaned, but will help avoid additional damages.

These recommendations can be used by the ACP to further improve the efficiency and sustainability of their formal inspection program of dams and spillways, in order to extend the usable lifespan of their structures.

4.0 Risk Analysis of Madden Dam and Spillway Drum Gates

4.1 Methodology

The goal of this project was to improve the current maintenance program for the drum gates of Madden Spillway founded on a risk-based analysis methodology. To achieve this goal, four main objectives were identified:

1. Analyze the evolution of the structural condition of the Madden Spillway drum gates.
2. Research maintenance programs aimed at preserving adequate reliability of spillway gates.
3. Calculate and compare the demand and capacity of the drum gate's structural components.
4. Contribute to the improvement of the maintenance program based on risk analysis of the structural components.

4.1.1 Structural Condition of Drum Gates

Inspections of the spillways in the Panama Canal began in 1977. This project began with a review of the historical Madden Spillway maintenance reports from the years 1982 – 2015. These years were chosen because they are the reports the ACP recorded in their database. The review specifically focused on the structural aspects and maintenance work completed on each of the drum gates. Because the canal's operation was transferred to the Panamanians in 1999, reports dated after the year 2000 were written in Spanish. To be able to gain a clear understanding of the structural condition of the gates and their maintenance history, the reports from after the year 2000 were translated to English. The Comité de Seguridad de Represas y Vertederos (CSRV – Committee of Safety of Dams and Spillways) at the ACP was consulted to gain a better understanding of the parts of the Madden Dam and Spillway. Two visits were also made to the spillway, where access was available to enter the pool of one of the drum gates and walk on top of the upstream plate of gates. This provided an understanding of the scale of the structure and how complex the components are.

After reviewing the historical reports and consulting with the CSRV, a maintenance log was created to record the history of the drum gates. The log was organized according to the four separate drum gates, as well as what was found during each inspection, and what the recommendations or immediate actions that were taken each year between 1982 and 2015. This spreadsheet created a historical database recording all of the maintenance that has occurred for the structural components of each individual drum gate. The log was then analyzed for patterns that occurred for the different structural elements.

4.1.2 Reliability Maintenance Programs

Madden Dam and Spillway is considered the highest risk water retention structure in the Panama Canal system because there is no way to replace or remove any of its drum gates. This necessitates that the ACP maintain the structural integrity of all four gates. In order to perform a risk analysis of the drum gates, and to analyze the maintenance data gathered from the inspection reports, different reliability and risk assessment methods were researched. Specifically, this project reviewed *Spillway Gate Reliability and Handling of Risk for Radial and Drum Gates* from the NZSOLD/ANCOLD 2003 Conference on Dams (Barker et al., 2003) and the U.S. Army Corps of Engineers' *Estimating Risk from Spillway Gate Systems on Dams Using Condition Assessment Data* (Estes et al., 2005). The first report provided an understanding of fault tree analyses. A fault tree is "a systems engineering method for representing the logical combinations of various system states and possible causes which can contribute to a specified event (called the top event)" (Barker et al., 2003, p. 7). This analysis breaks the structure of the drum gate into its major components that could cause the failure of the whole system. The U.S. Army Corps of Engineers report explained the reliability of a structure in terms of capacity, the amount of stress it can resist, and demand, the amount of stress put on the structure. A structure is considered reliable if the capacity, C, of any given parameter the structure can withstand exceeds the demand, D, placed on it (Estes et al., 2005). The Madden Dam and Spillway is operated as a series system, which means that if any single component fails, the entire structure will fail. Therefore, it is important that each component of the drum gates has a capacity that exceeds its demand.

The ACP has already begun to develop a mitigation plan for the failure of Madden Dam and Spillway. The ACP's *Plan de Mitigación de Daños de las Compuertas del Vertedero de Madden*, identified the structural components of the drum gates that are of concern or high risk. With the identification of the critical structural components of the drum gates a block diagram, a type of fault tree analysis, was created to illustrate the different modes of failure that could occur.

4.1.3 Demand and Capacity of Structural Components

Some of the most critical structural components of the drum gates are the skin plates, which make up the outside structure of the gates. The three types of skin plates are the bottom skin plate, upstream skin plate, and downstream skin plate. The two most critical skin plates are the bottom and upstream plates because they are under direct water pressure (Figure 45). To determine the demand acting on the bottom and upstream skin plates, the stress caused by the water pressure on each plate was calculated. Since the downstream plate is not affected by direct water pressure, a risk analysis calculation was deemed unnecessary. The capacity, or allowable stress, was calculated for the type of steel used for the drum gates.

The stress acting on the bottom and upstream skin plates comes from the water pressure in the drum gate pools and Alhajuela Lake. To determine the demand on the plates, the stress due to the water pressure was calculated using the following equation:

$$\sigma = \frac{M}{Z}$$

where σ is the stress acting on the plate (psi; kPa), M is the bending moment acting in the y direction on the plate (lbs-in; kN-m), and Z is the section modulus of the plate (in^3; m^3) (Timoshenko, 1940).

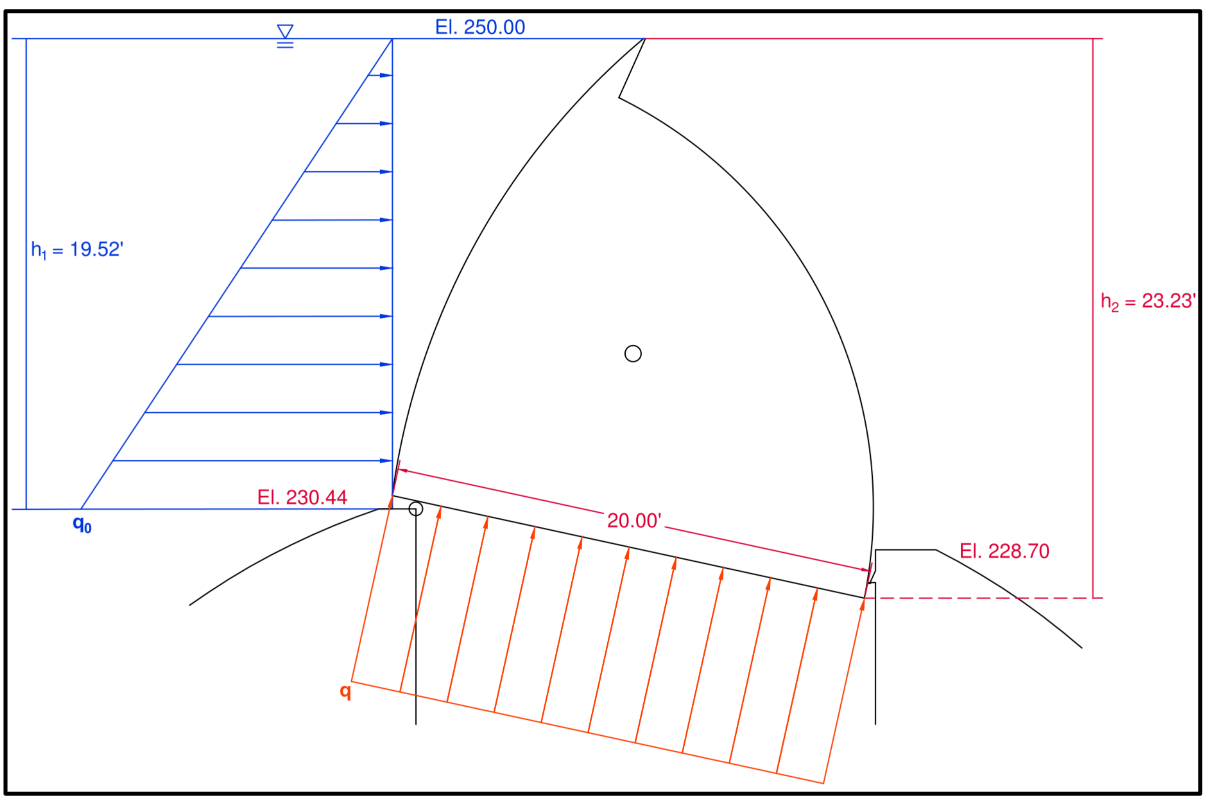


Figure 45: Water pressure acting on the skin plates of the drum gate (Burner, 2016)

The section modulus of the plate, Z, required in the equation above, was computed with the equation:

$$Z = \frac{at^2}{6}$$

where a is the length of the plate along the x-axis (in; m) and t is the thickness of the plate (in; m) (Timoshenko, 1940).

The bending moment for the bottom skin plate, M_b, was calculated by

$$M_b = \delta qab^2$$

where δ is a unitless coefficient for the maximum bending moments in the y-direction for uniformly loaded plates, and can be found using *Table 56: Bending Moments for Uniformly Loaded Plates in Case 6* from the *Theory of Plates and Shells*; q is the uniformly distributed load on the plate (psi; kPa); a is the length of the plate along the x-axis (in; m); and b is the width of the plate span along the y-axis (in; m) (Timoshenko & Woinowsky-Krieger, 1959).

The bending moment acting on the upstream skin plate, M_u, was computed with the subsequent equation:

$$M_u = \beta_1 qab^2$$

where β_1 is the unitless coefficient for bending under hydrostatic pressure, and can be found using *Table 14: Numerical Factors β and β_1 for Bending Moments in Simply Supported Rectangular Plates under Hydrostatic Pressure* from the *Theory of Plates and Shells*; q is the triangular distributed hydrostatic force acting on the plate; a is the length of the plate along the x-axis (in; m); and b is the width of the plate span along the y-axis (in; m) (Timoshenko & Woinowsky-Krieger, 1959).

Both the uniformly and triangular distributed loads on the plates, q, were determined by

$$q = \gamma_w h$$

where γ_w is the specific weight of water (pcf; kN/m^3) and h is the maximum height of the gate to the water elevation 250.00 ft (76.2 m) where the load is acting on the plate (ft; m) (Timoshenko & Woinowsky-Krieger, 1959).

The capacity of the steel used for these plates was calculated by the following equation:

$$\sigma_{allow} = 0.6F_y$$

where σ_{allow} is the allowable stress (ksi; MPa) and F_y is the yield strength of the steel used for the drum gates (ksi; MPa) (Timoshenko, 1940).

4.1.4 Improvement of Maintenance Program

After evaluating the demand and capacity of the bottom and upstream skin plates, the point of failure for each plate was determined. To find this point, two graphs were created to obtain the plates' critical thicknesses. The demand curve, capacity curve, original thickness point, critical thickness point, warning indication point, and 20% section loss of the original thickness point were graphed for each skin plate. The 20% section loss of the original thickness point was graphed because this is the standard amount of deterioration the ACP deems necessary for replacement or repair of the skin plates. These graphs were used to help validate or disprove the ACP's standard for section loss.

4.2 Results and Analysis

By creating a historical maintenance log and performing a risk analysis on the critical structural components, recommendations could be suggested to the ACP for preventative maintenance.

4.2.1 Historical Maintenance Log

After reviewing the Madden Dam and Spillway historical inspection and maintenance reports from 1982 – 2015, a maintenance history log was created to record the structural condition of the drum gates. The structural components were identified as the seals, hinges, interior framing members, cylinder heads, and skin plates (Figure 46). The condition of each of these components and the maintenance performed on them was recorded in the log for each drum gate (Appendix J).

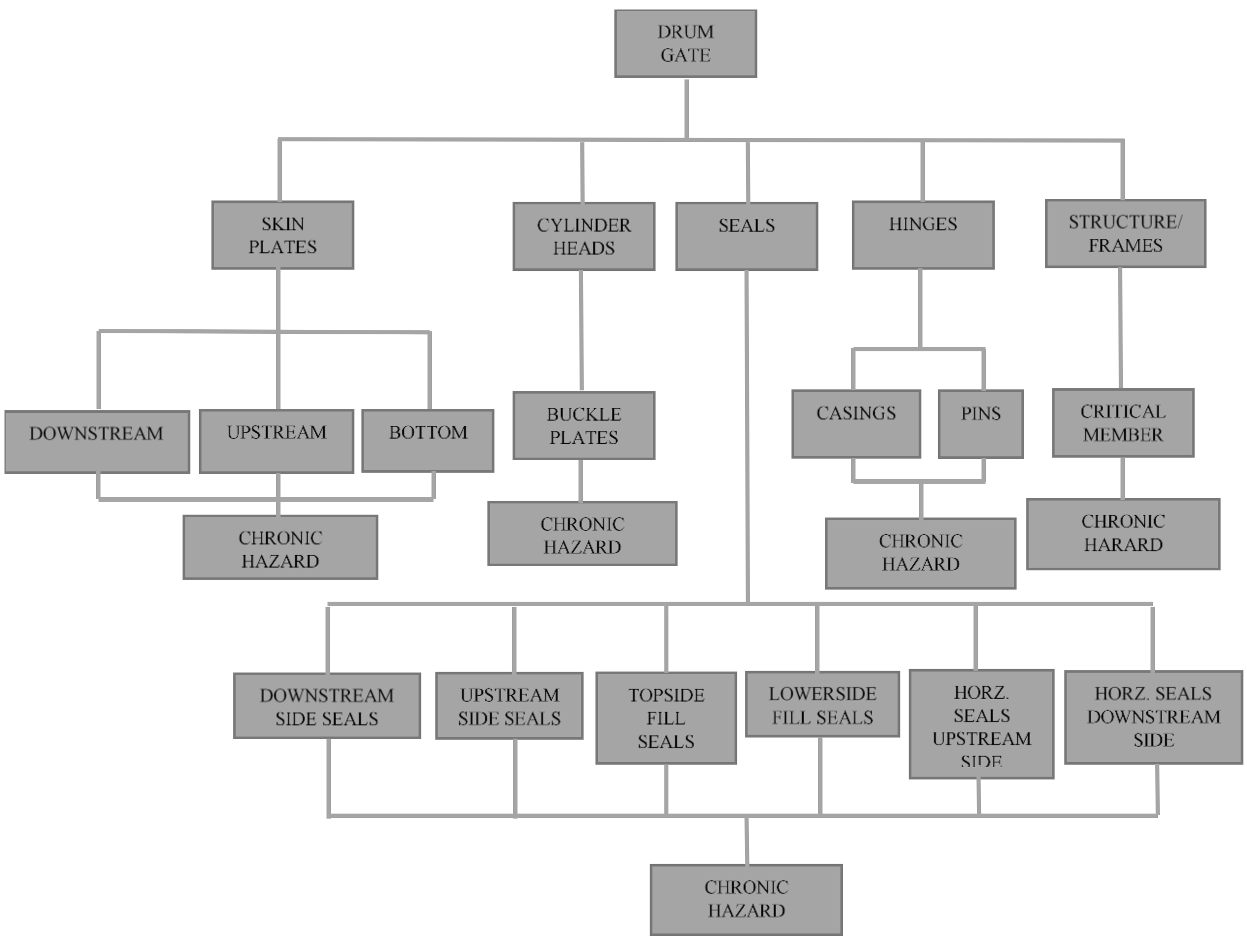


Figure 46: Structural components block diagram

There are six different types of seals utilized in each drum gate: the downstream side seals (left and right), the upstream side seals (left and right), the topside fill or transition seals (left and right), the horizontal seals of the upstream side foundries of the hinges, the horizontal seal of the downstream side seat foundries, and the lower side fill or transition seals (left and right) (Moreno, Lyew, & Miró, 2016). The failure of any of these sets of seals, through corrosion, cracks, and deformations, can affect the operator's ability to fill the floatation chambers, jeopardizing the control of the level and operation of the gates. Through the review of the inspection reports, it was found that there were often leaks in the seals of the drum gates, but to varying degrees. These seals are closely monitored to prevent serious damage that could result in the failure of the gates. Because the seals tend to wear at a faster rate than other structural members, they are inspected more frequently and replaced more often, meaning a risk analysis of these structures was not necessary.

The hinges of the gates consist of two key components: the pins and the casings. Each gate contains two end hinges, four contraction joint hinges, and 33 intermediate hinges. Failure of the hinges can cause the gates to lose their ability to rotate, preventing them from raising or lowering to control the water spillage. Damage to these structures can be caused by loss of thickness resulting from corrosion, vibration impacts from the drum gates during operation, loss of ductility, material weakening by chemical or environmental pollution, or wear due to friction. In 2003, severe corrosion was observed on all the hinges of all four drum gates. The repairs of the casings and replacement of some of the pins could only be completed on two of the gates at a time. Therefore, drum gates 3 and 4 were completed in 2004 and 1 and 2 were repaired in 2005 (Figure 47). Only the middle and contraction joint hinges were replaced because removing the end pins could affect the alignment of the drum gates. After the large tropical storm that occurred in 2010, a lot of sandy sedimentation had accumulated on all of the drum gates' hinges. To minimize damage to the casings and pins, the hinges were cleaned with a water pressure jet to remove the sedimentation. Based on the inspection and maintenance reports reviewed for this project, the hinges lasted for at least 68 years before needing replacement. Therefore, they do not deteriorate very quickly, leading to the conclusion that a risk analysis was unnecessary.

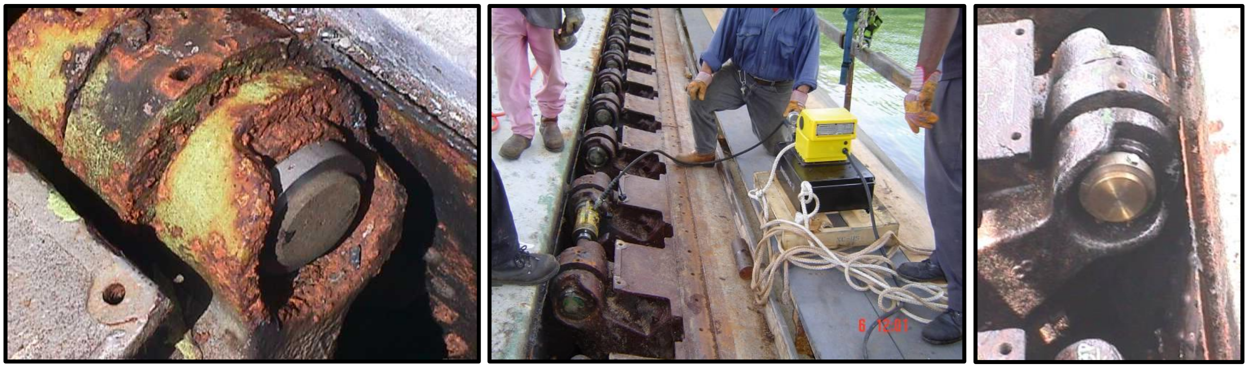


Figure 47: Corrosion on the hinges and the pin replacements (Chen & Cano, 2003; Autoridad del Canal Panamá, 2004)

The interior framing members are responsible for maintaining the structural shape of the drum gates. Failure of these members could cause the gates to fall apart. Deterioration of the steel frames is caused by section loss resulting from corrosion, fatigue, stress concentrations, metallurgical changes to the steel due to major welding repairs, increased operating loads, vibrations during the operation of the gates, or lack of maintenance or timely rehabilitation. Lack of continuous periodic inspections would allow deterioration to continue without knowledge of its occurrence. The interior of drum gate 1 was inspected between 1995 and 1996. Rust was detected on the corners of the bottom and downstream plates, as well as on the south end plate stiffeners. These areas were cleaned and painted to prevent further deterioration. Drum gate 2 had been scheduled to be inspected the same year, but because little deterioration was found in drum gate 1, the condition of gate 2 was assumed to be the same. In 2015, the interior of drum gates 3 and 4 were inspected. Light corrosion was found at the bottom of the structural frames in the bottom corners of the gate and interior side of the downstream plate. There was also substantial waste material found inside the gates that was removed. Because the drum gates are hollow structures, only small amounts of water and other environmental conditions affect the insides of them. This creates an environment that is less susceptible to corrosion. Therefore, the steel framing deteriorates at a slower rate.

The cylinder heads close off the ends of the drum gates and are made up of a series of buckle plates. Failure of these components would cause the gates to fill with water, preventing them from operating as intended. The causes for failure of the cylinder heads are similar to the interior framing members. It was observed that the buckle plates of the cylinder heads are deteriorating mostly due to corrosion, resulting in section loss. In 2009, the loss of thickness in the plates was about ⅛ in (0.32 cm) on drum gate 3. The plates were cleaned and painted to help prevent further deterioration. Thickness measurements taken in 2010 indicated that those buckle plates should have been replaced in 2012. Due to the difficulty in access and additional frictional forces acting on the cylinder heads, the analysis of this component was not included within the scope of this project.

The last main structural components of the drum gates are the skin plates. There are three skin plates that make up the exterior of the gates: the downstream skin plate, the upstream skin plate, and the bottom skin plate. All of the skin plates deteriorate by the same causes as the interior structure members and the cylinder heads. The only difference between the deterioration causes is that the skin plates also experience pressures from water acting directly on and perpendicular to the surfaces of the plates. The downstream skin plate is not considered to be a critical element because it is not in direct contact with water. It is also observed in the maintenance log that the downstream face is frequently monitored for corrosion and that thickness measurements are often conducted. The upstream and bottom skin plates experience direct water pressure from Alhajuela Lake and the flotation chamber, respectively, and are thus considered the most critical structural components and were analyzed further.

4.2.2 Bottom and Upstream Skin Plate Analyses

The bottom skin plate is a critical element because once the gate reaches its highest position, the water continues to flow into the pool, increasing the pressure acting upward on the plate, as well as the gate stop. The plate faces a greater risk of corrosion and deterioration, as it is almost always submerged underwater. The upstream skin plate is also critical because when water is flowing over the spillway, pressure from the flow can encourage cavitation, leading to cavitation erosion. Due to the changing lake levels throughout the year, the plate fluctuates between wet and dry conditions, which can cause an increase in corrosion, decreasing the strength of the plate. While the gates are spilling, both in the highest and lowest positions, vibrations occur, leading to cracking, loosening of bolts, and overall fatigue of the steel.

The skin plates were analyzed in 20 ft by 2 ⅓ ft (6.1 m by 0.71 m) sections based on Madden Spillway design plans. Because the 20 ft (6.1 m) length of the section along the x-axis is supported by rigid framing, it was assumed that the bending moment would occur along the 2 ⅓ ft (0.71 m) length, in the y direction (Figure 48).

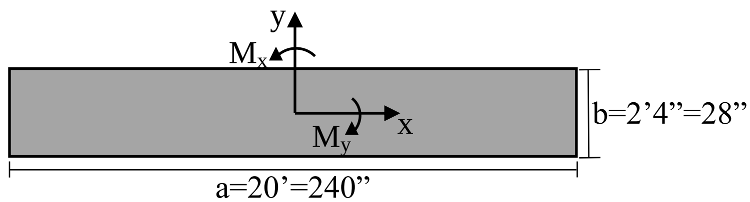


Figure 48: Bending moment acting on the skin plate section

The equation $\sigma = \frac{M}{Z}$ was used to calculate the demand on the bottom skin plate. In this case the bending moment, M_b, was computed using the equation $M_b = \delta qab^2$. The variable, δ, a coefficient that was determined using *Table 56* in the *Theory of Plates and Shells*, was found to be 0.0833 (Timoshenko & Woinowsky-Krieger, 1959). The loading, q, was assumed to be uniformly distributed to account for the worst case scenario force distribution and was calculated as 10.07 psi (69.40 kPa). The lengths for a and b were obtained from the plate section (Figure 48). Using these values, the bending moment was found to be 157.77 k-in (17.83 kN-m).

To calculate the section modulus, Z, the equation $Z = \frac{at^2}{6}$ was used. The original thickness of the plate, t, was ⅝ in (1.59 cm). With this plate thickness and the length a of 240 in (6.1 m), the section modulus was computed to be 15.625 in^3 (256.05 cm^3). These values produced a final stress, σ, of 10.10 ksi (69.64 MPa) acting on the bottom skin plate.

The demand acting on the upstream skin plate was solved similarly to the bottom skin plate, using the bending moment equation $M_u = \beta_1 qab^2$. The coefficient, β_1 = 0.0937, was obtained from *Table 14* in the *Theory of Plates and Shells* (Timoshenko & Woinowsky-Krieger, 1959). The loading, q, was assumed to be the greatest force acting at the maximum depth of the water due to hydrostatic principles, and was determined to be 8.46 psi (58.33 kPa). With this new coefficient and maximum loading, the bending moment was found to be 149.15 k-in (16.85 kN-m). Because the thickness, t, of the upstream skin plate was ½ in (1.27 cm), which was ⅛ in (0.32 cm) smaller than the bottom skin plate's thickness, the section modulus, Z, produced was smaller, totaling 10 in^3 (163.87 cm^3). The final stress acting on the plate was 14.9 ksi (102.73 MPa).

The capacity these plates can withstand is dependent on the strength of their steel. Madden Dam and Spillway was built between 1932 and 1935; therefore, A7 steel was used. A7 steel has a yield strength, F_y, of 33 ksi (227.53 MPa). To find the allowable stress of the plates, the yield strength was multiplied by the coefficient 0.6, which is a commonly accepted factor of safety. These values produced a stress limit of 19.8 ksi (136.52 MPa).

A structure is considered reliable when its capacity exceeds its demand. Assuming the skin plates maintained their original thicknesses, the capacity or allowable stress of the steel exceeds the demand on both plates. Therefore, the plates as originally designed are considered reliable. As structures age, they tend to deteriorate and, in the case of the skin plates of the drum gates, could result in a loss of thickness. To determine when this reduction in thickness should become a concern for the structural integrity of the skin plates, the demand equations were reverse solved to find the critical thickness. In the equation $\sigma = \frac{M}{Z}$, the stress limit, calculated above, was assumed to be 19.8 ksi (136.52 MPa). The critical thicknesses, the points at which the skin plates' demand would exceed their capacity, resulting in failure, were calculated to be 0.446 in (1.13 cm) for the bottom skin plate and 0.434 in (1.10 cm) for the upstream skin plate (See Appendix K for full calculations).

4.2.3 Maintenance Program Improvements

The critical thickness values, calculated using the yield strength of A7 steel, were verified by graphing the demand and capacity equations. The point of intersection of these two lines was where the demand was equal to the capacity, which represented the point of critical thickness for each skin plate. A factor of safety was then considered for each skin plate and compared to the ACP's recommendation for the acceptable amount of section loss.

The bottom skin plate's critical thickness occurs at approximately 0.45 in (1.14 cm). This corresponds to a section loss of 28.64%, or 0.18 in (0.46 cm) of thickness. According to the ACP guidelines, repairs or replacement of the plate should occur at 20% section loss from the original thickness. For the bottom skin plate, repairs would be considered at a thickness of approximately 0.5 in (1.27 cm). Using this standard, the plate would be repaired or replaced before reaching failure, but would only need to lose 0.05 in (0.13 cm) more of its thickness to become critical. Therefore, to maintain a greater factor of safety, a thickness 30% greater than the critical thickness was found. This number can be viewed as a warning indicator for maintenance workers to begin planning repairs or replacements of the existing plate. The warning indicator thickness occurs at approximately 0.58 in (1.47 cm) (Figure 49).

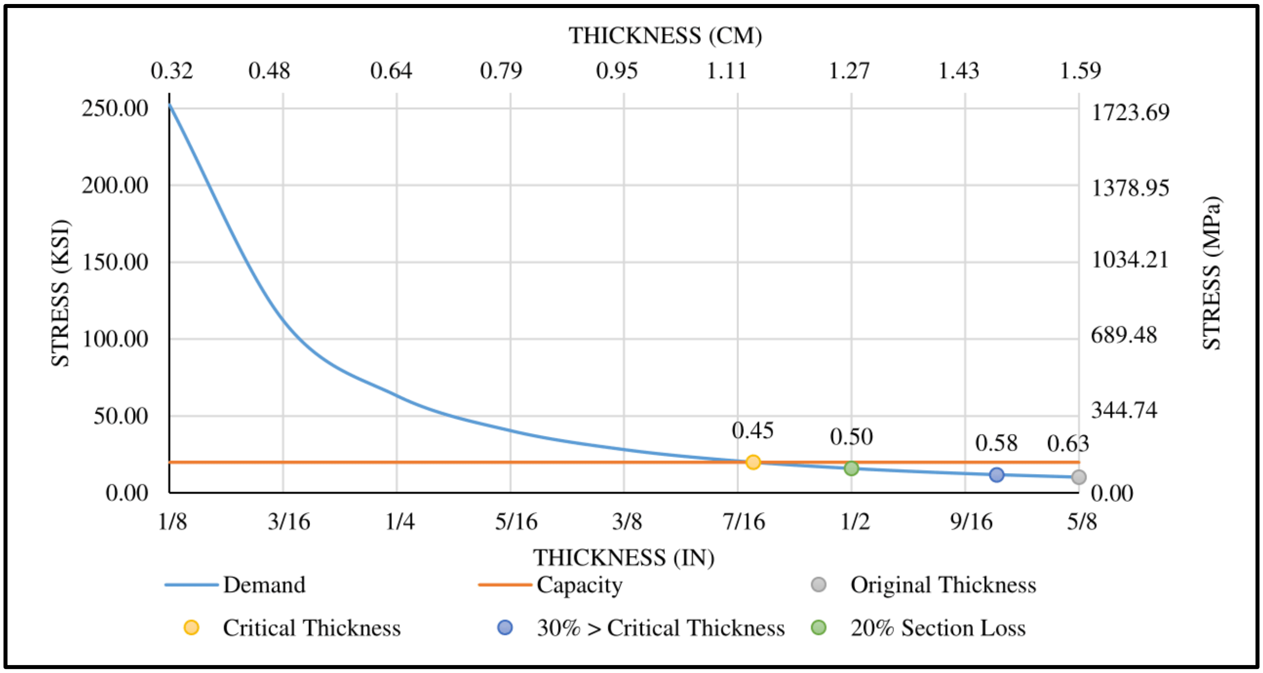


Figure 49: Demand and capacity stress equations for the bottom skin plate

The upstream skin plate's critical thickness occurs at approximately 0.43 in (1.09 cm). Because this plate began at a thickness of ½ in (1.27 cm), the critical section loss is 13.20%, corresponding to a loss of about 0.07 in (0.18 cm) of the original thickness. This section loss is less than the ACP standard, therefore the plate would fail before repairs or replacement would be considered. To prevent this failure and maintain a factor of safety, a warning indicator 30% greater than the critical thickness was calculated. However, because the thickness value was greater than the original thickness of the plate, this warning indicator was invalid. Therefore, a warning indicator 10% greater than the critical thickness was found. This indicator occurs at 0.48 in (1.22 cm) (Figure 50). The upstream skin plate cannot afford to lose a significant portion of its thickness before it becomes a structural concern.

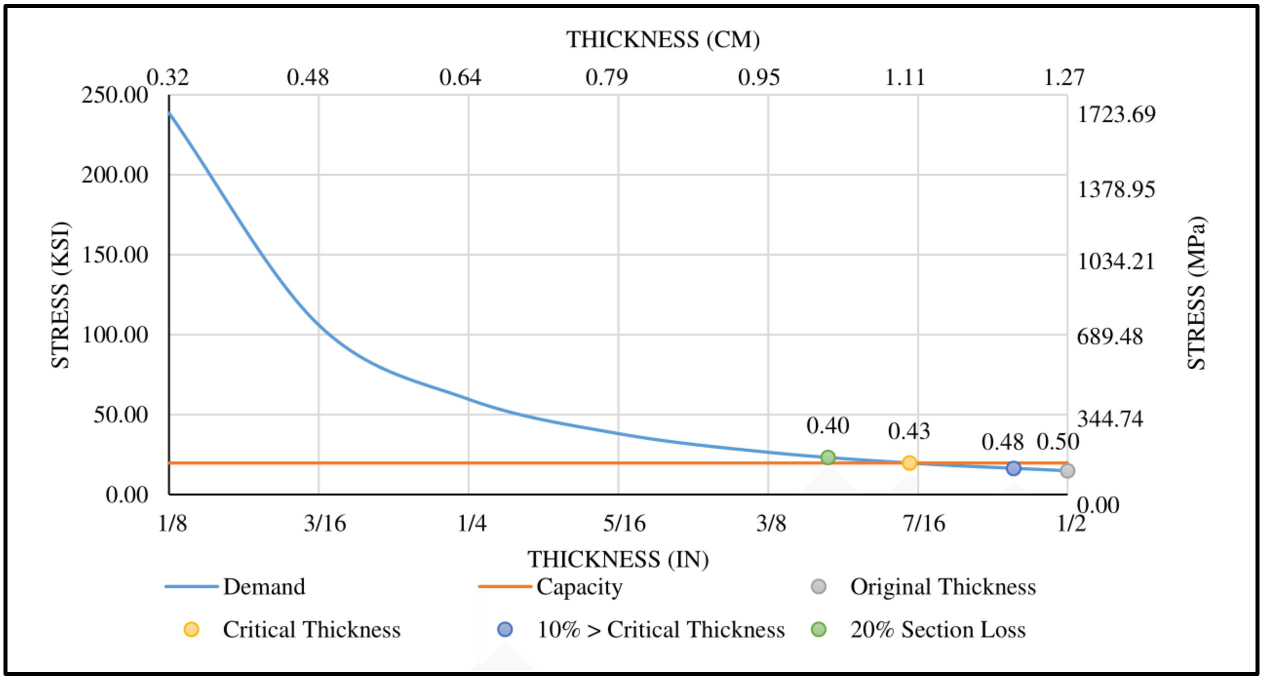


Figure 50: Demand and capacity stress equations for the upstream skin plate

4.3 Conclusions and Recommendations

After reviewing the inspection reports to make a historical maintenance log and performing a risk analysis for the stresses acting on the bottom and upstream skin plates, it was determined that the Madden Spillway drum gates are still in good structural condition. Drum gates typically last for approximately 100 years. It is important that the structural integrity of Madden Dam and Spillway is monitored and maintained, as it is currently 81 years old. This can be accomplished with improvements to the efficiency and effectiveness of the inspection and maintenance programs.

While creating the historical maintenance log, it was found that prior recommended repairs were not addressed in following reports, unless the same recommendation was made several years in a row (Appendix J). To ensure the inspection team and maintenance personnel are aware of the repairs being completed or still in progress, the inspection and maintenance reports should include an overview of the work done on each gate from the previous year. Additionally, it is suggested that the ACP continue to update the historical maintenance log for the structural components of the drum gates to ensure an easily accessible and coherent record of their condition be kept.

Work on the drum gates is usually completed on two gates at a time. Considering this, maintenance conducted on each gate should be reviewed to ensure that all four gates are in similar condition. Often, two of the gates were repaired for several years in a row, allowing the other two to fall into further disrepair. There were also times where components were inspected on two gates, but were not examined on the remaining gates until years later. For example, the interior of gate 1 was inspected in 1995, but the same areas of gates 3 and 4 were not inspected until 20 years later, in 2015. More periodic and consistent inspections should occur for the different components of each drum gate to prevent unnoticed deteriorations that can result in untimely maintenance or failure.

Based on the condition of the structural components found in the inspection reports, it is suggested that stress analyses for the cylinder heads and the gate stop be performed. The cylinder heads currently present high amounts of corrosion on their surfaces, and the friction created when the gates are operated contributes to an increase in section loss. A stress analysis of these elements would define their critical thickness points. Stress analyses should also be performed for the gate stop because once the gate reaches the stop, the water continues to put pressure on this component, producing a high concentration of stresses.

To further increase the efficiency of the drum gates' maintenance program, the risk analysis performed for the bottom and upstream skin plates should be continued by conducting thickness measurements for each. These measurements should be taken every few years to develop a deterioration timeline. This timeline would allow ACP personnel to produce a degradation curve for each plate. With this information, a model for the probability of failure of a drum gate due to the thinning of the skin plate could be made. If welding is required for these repairs or for other repairs of the steel, it is important to establish a slow heating and cooling process. The composition of the A7 steel used for the construction of the drum gates contains high levels of carbon, which results in poor weldability. Failing to slow down the heating and cooling processes could result in weakening of the surrounding steel and cracking in those areas. These recommendations can improve the efficiency and effectiveness of the ACP's maintenance of the Madden Dam and Spillway drum gates.

V. Conclusion

The work that went into accomplishing the four projects compiled in this report was completed in conjunction with several ACP employees across many departments. Background knowledge from previous coursework, experience from prior internships, information gathered from extensive research, lab work, and field visits all came together for these analyses. They organically led to recommendations that were given to the ACP in hopes of improving the projects' respective systems. The *Analysis of Chemical Consumption Patterns at Miraflores Filtration Plant* project examined how post-expansion operations affected chemical consumption during water treatment and made recommendations for the further investigation of water quality parameters in potable water. The *Process Analysis of Mount Hope Water Filtration Plant* project evaluated purification components and suggested modifications that could either be made to the water flow or plant structures to increase the quality of treatment. The *Evaluation of the ACP's Formal Inspection Program of Dams and Spillways* project compared various inspection protocols and proposed new guidelines and checklist materials to refine the ACP's procedures. The *Risk Analysis of Madden Dam and Spillway Drum Gates* project compiled a maintenance record and identified the critical members of a drum gate to determine the risk associated with each component. The project goals were successfully completed to address challenges faced by the ACP that arose as results of the recently completed expansion project and the overall age of the Panama Canal structures.

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Appendices

Appendix A: Map of Panama

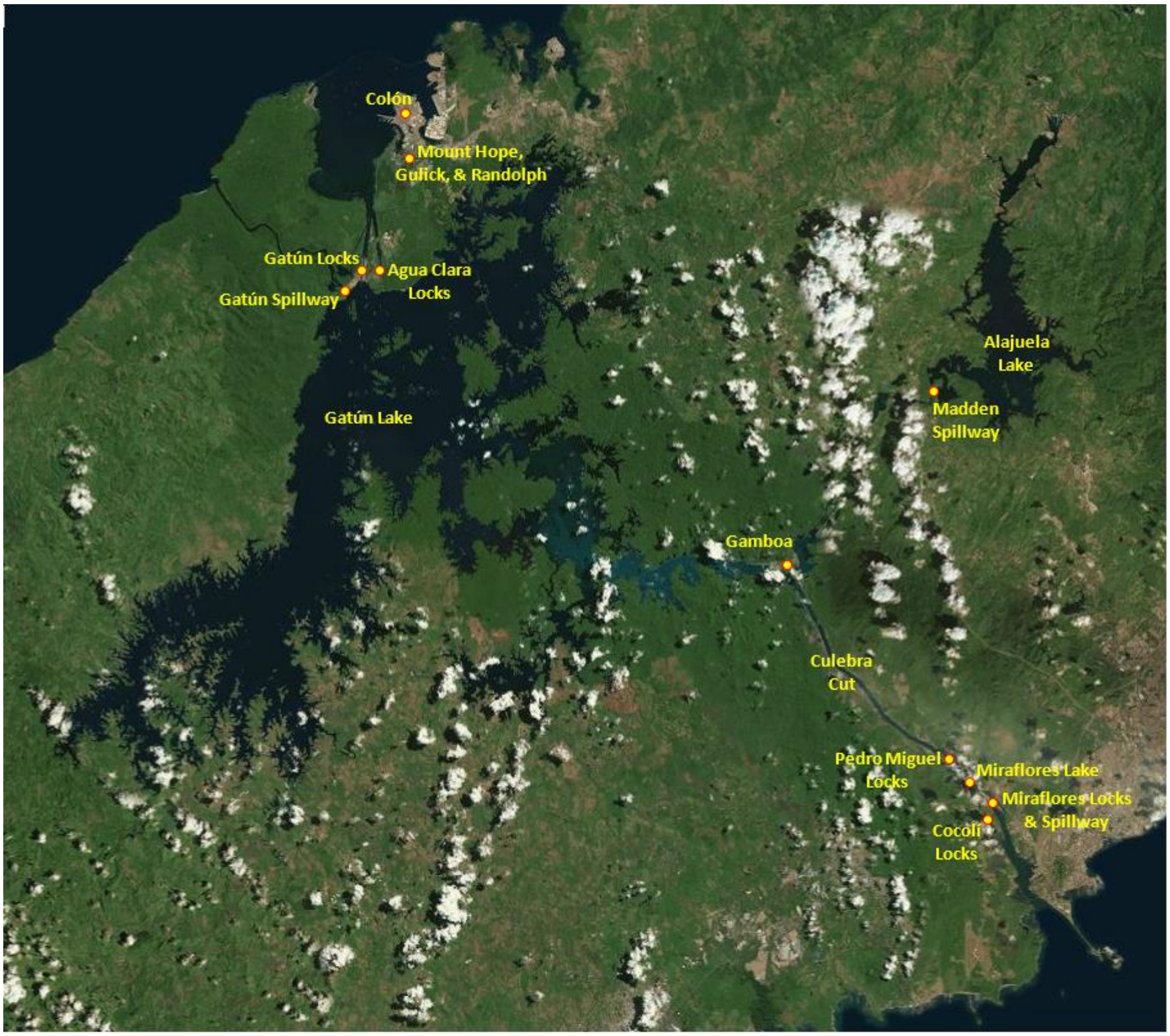


Figure 51: Map of Panama Canal region (Autoridad del Canal de Panamá, 2016e)

Appendix B: Components of Panama Canal Water Treatment Plants

Table 27: Components' size and quantity comparisons between the Mount Hope and Miraflores treatment plants

	Mount Hope	Miraflores
Aerator		
Type	Spray Nozzle Waterfall Aerator	Spray Nozzle Waterfall Aerator
Basin	60 ft by 66 ft (18m by 20m)	86 ft by 130 ft (26 m by 40 m)
Batteries	5	7
Nozzles	17 per battery (85 total)	15 per battery (105 total)
Rapid Mixer		
Type	Hydraulic, Vertically Baffled	Hydraulic, Vertically Baffled
Number of Baffles	6	8
Number of Pathways	3	3
Chemicals Added	Alum, Fluoride, Chlorine, & Carbon	Alum, Fluoride, Chlorine, Carbon, & Polymers
Flocculators and Sedimentation Basins		
Type of Sedimentation Basin	Horizontally Baffled	Horizontally Baffled
Basin	171 ft by 171 ft (52 m by 52 m)	300 ft by 125 ft (91 m by 38 m).
Pressure Baffle Walls	2	2
Light Baffle Walls	9	4
# of Pathways	3	3
# of Compartments per Pathway	12	7
# of Compartments Occupied by Flocculators	2	1
Type of Flocculators	Horizontal Paddle-wheels	Horizontal Paddle-wheels
# of Flocculators	6	3
Filters		
Type	Rapid Sand Gravity Filters	Rapid Sand Gravity Filters
# of Filters	10	20
# of Layers	3	3
Bottom Layer	Gravel	Gravel
Middle Layer	Sand	Sand
Top Layer	Anthracite Coal	Anthracite Coal
Pumps		
# of Pumps	11	29

Appendix C: Graphs of Chemical Consumption and Parameter Changes

Part 1: Comparisons of Chemical Consumption Patterns from Periods 1, 2, and 3 to Period 4

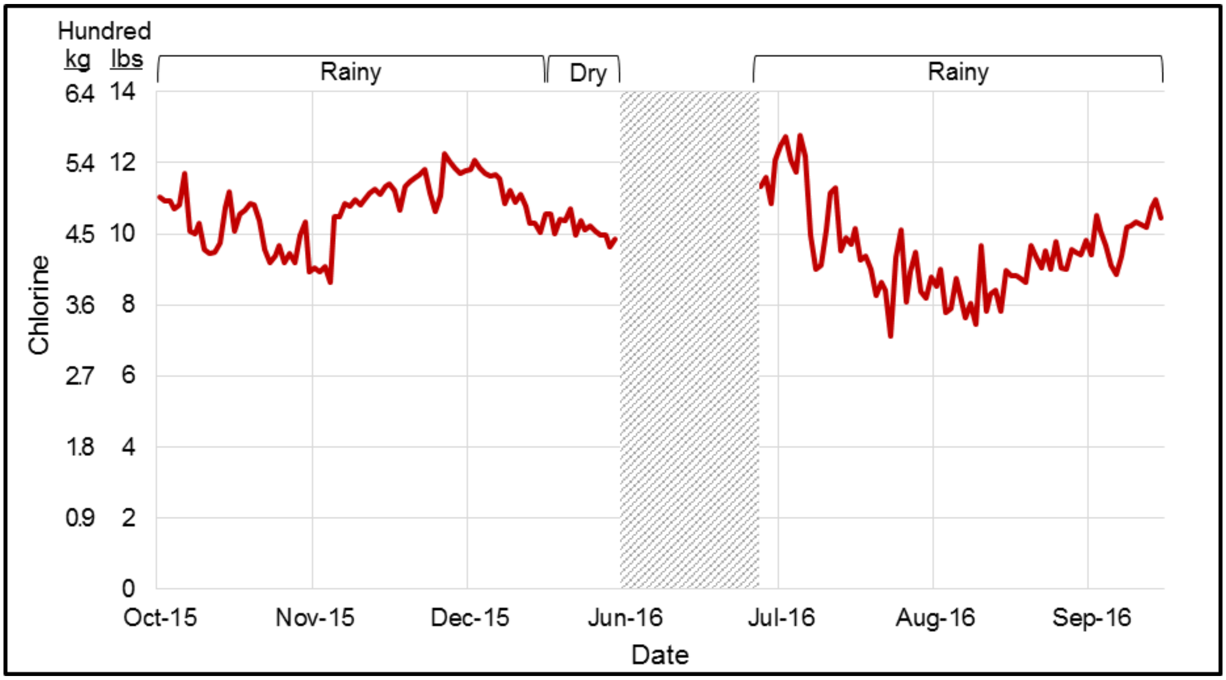


Figure 52: Consumption of chlorine between Period 1 and 4 (shaded area represents dates that do not fall within the periods of interest)

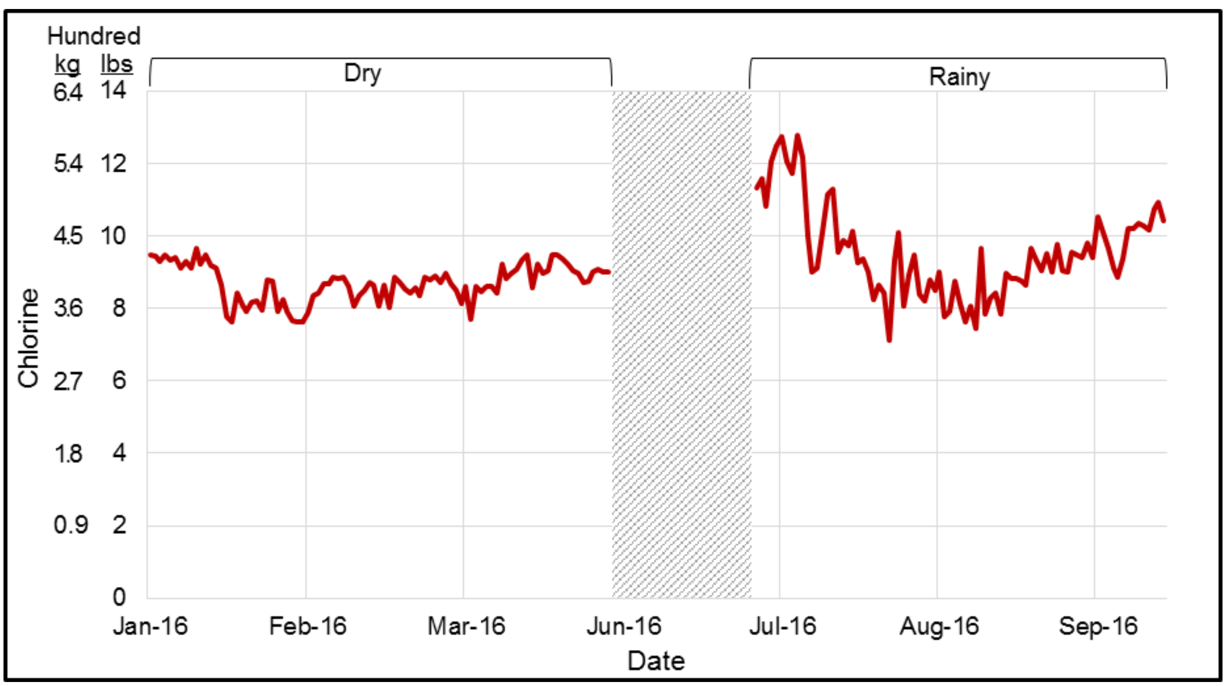


Figure 53: Consumption of chlorine between Period 2 and 4 (shaded area represents dates that do not fall within the periods of interest)

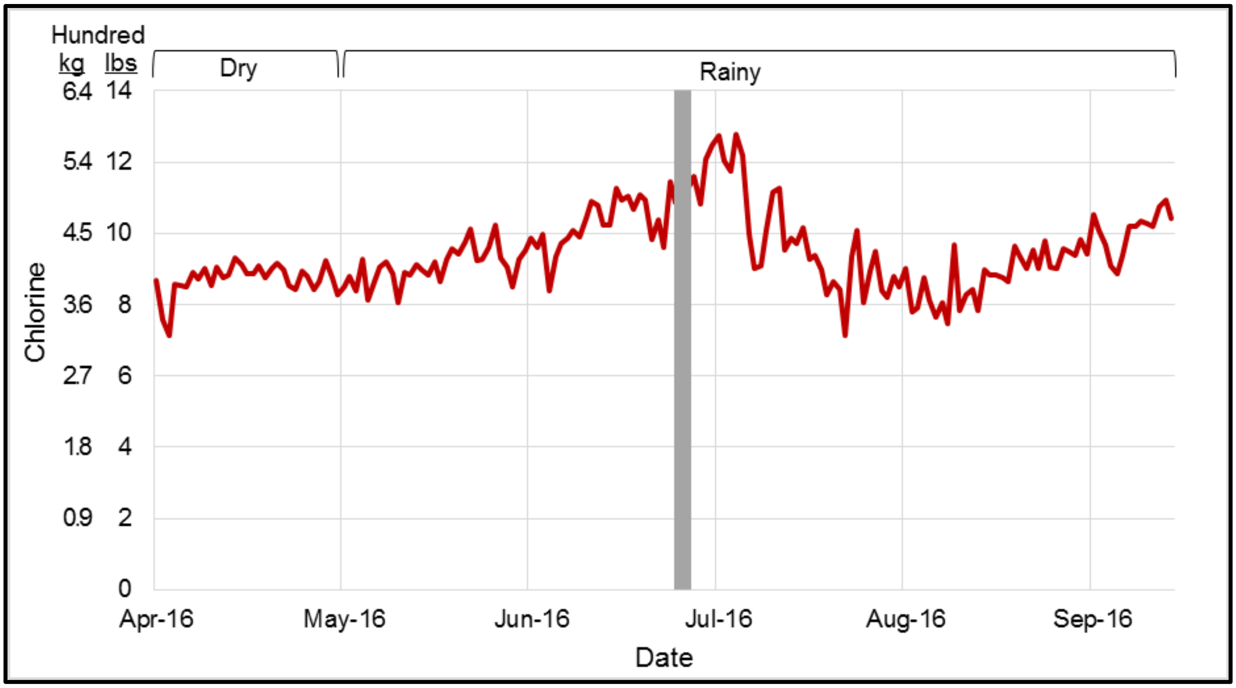


Figure 54: Consumption of chlorine between Period 3 and 4 (gray line represents expansion inauguration date)

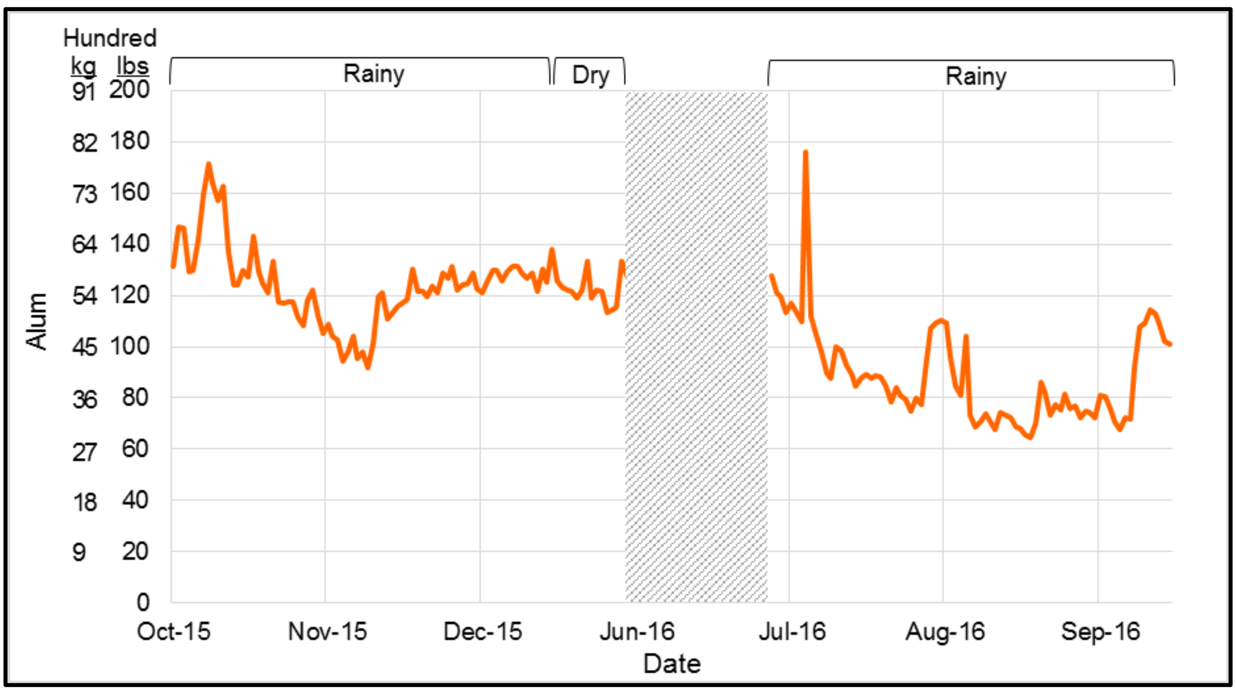


Figure 55: Consumption of alum between Period 1 and 4 (shaded area represents dates that do not fall within the periods of interest)

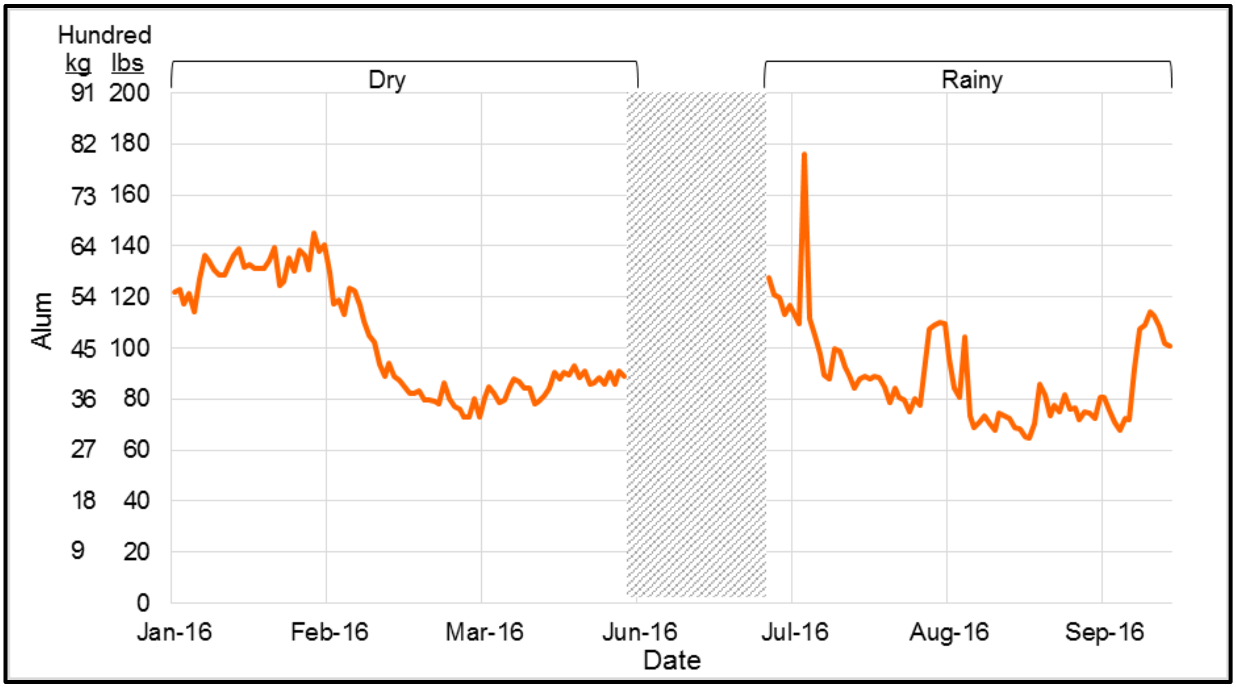


Figure 56: Consumption of alum between Period 2 and 4 (shaded area represents dates that do not fall within the periods of interest)

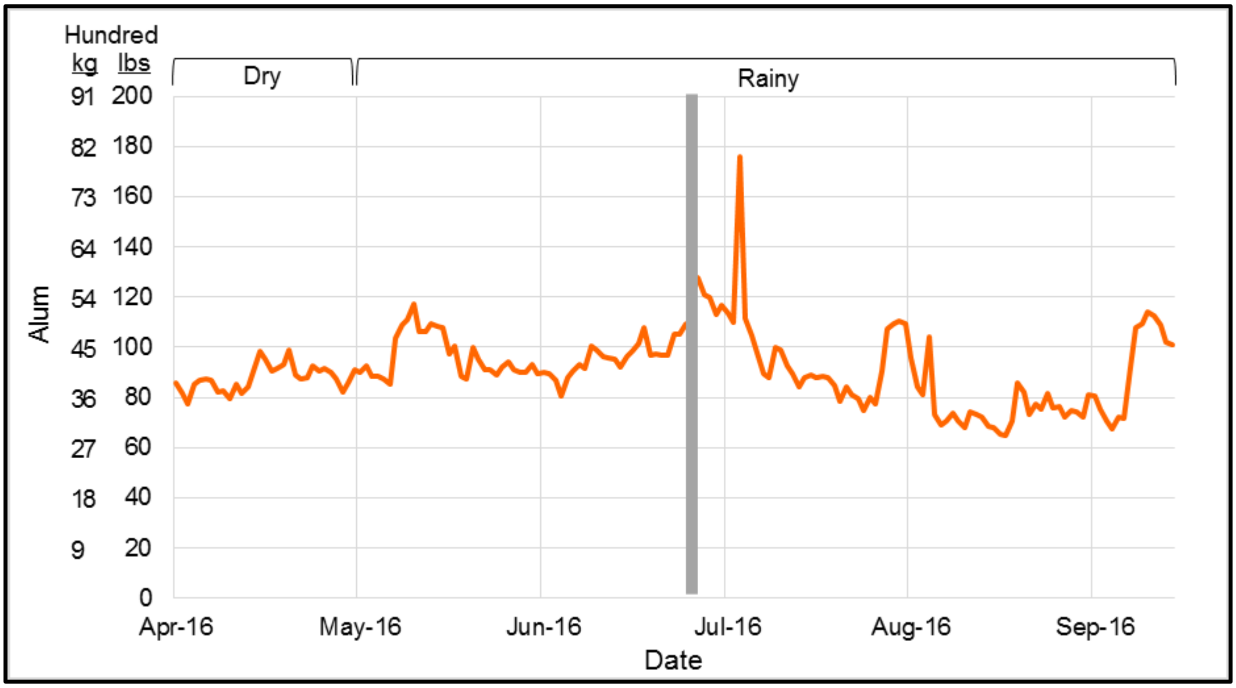


Figure 57: Consumption of alum between Period 3 and 4 (gray line represents expansion inauguration date)

Part 2: Relationships of Chemicals with Different Parameters between Periods 1, 2, and 3 and Period 4.

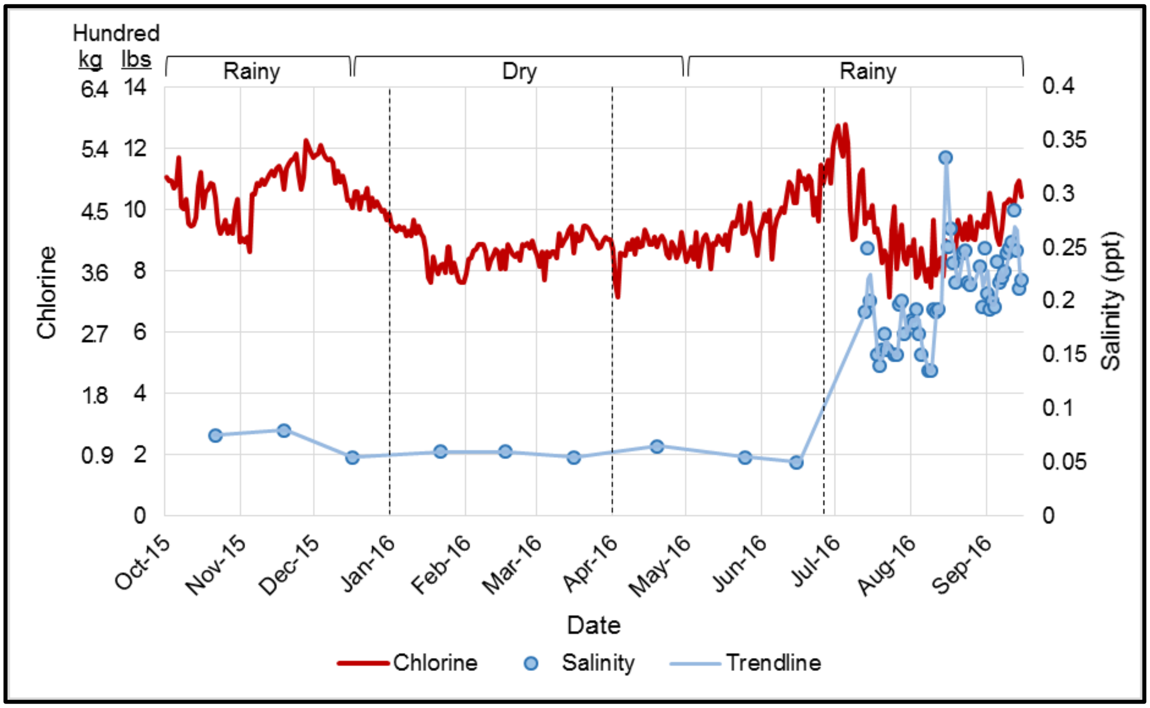


Figure 58: Chlorine consumption in relation to salinity levels at Miraflores

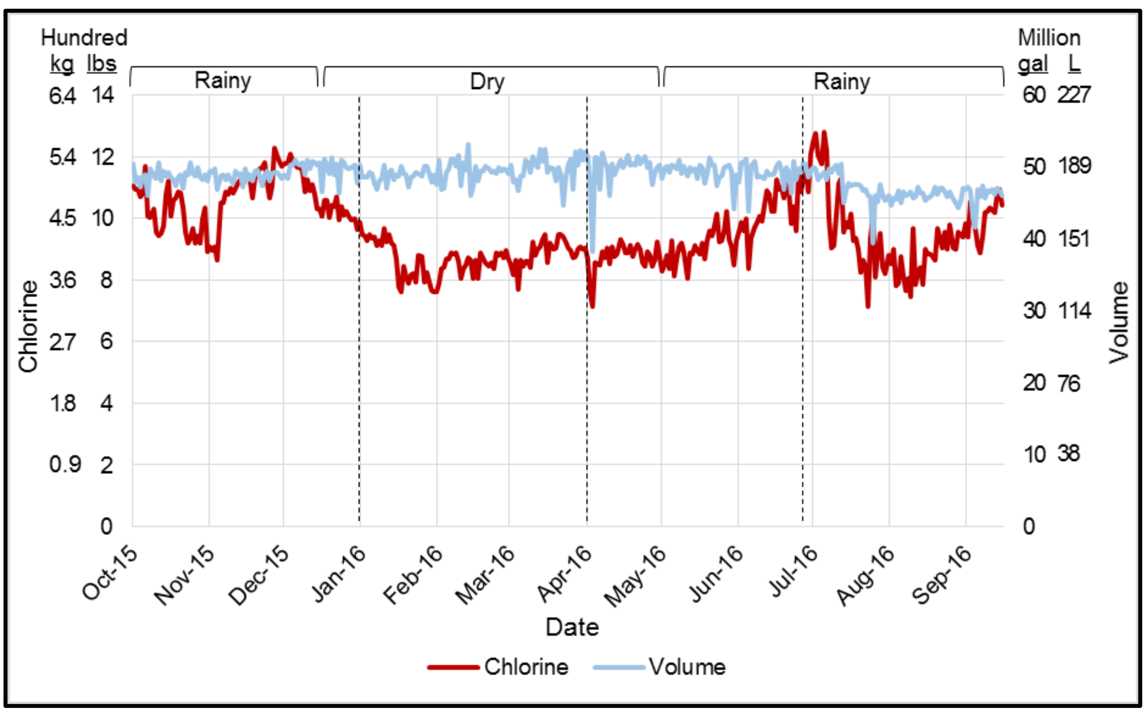


Figure 59: Chlorine consumption in relation to volume of influent

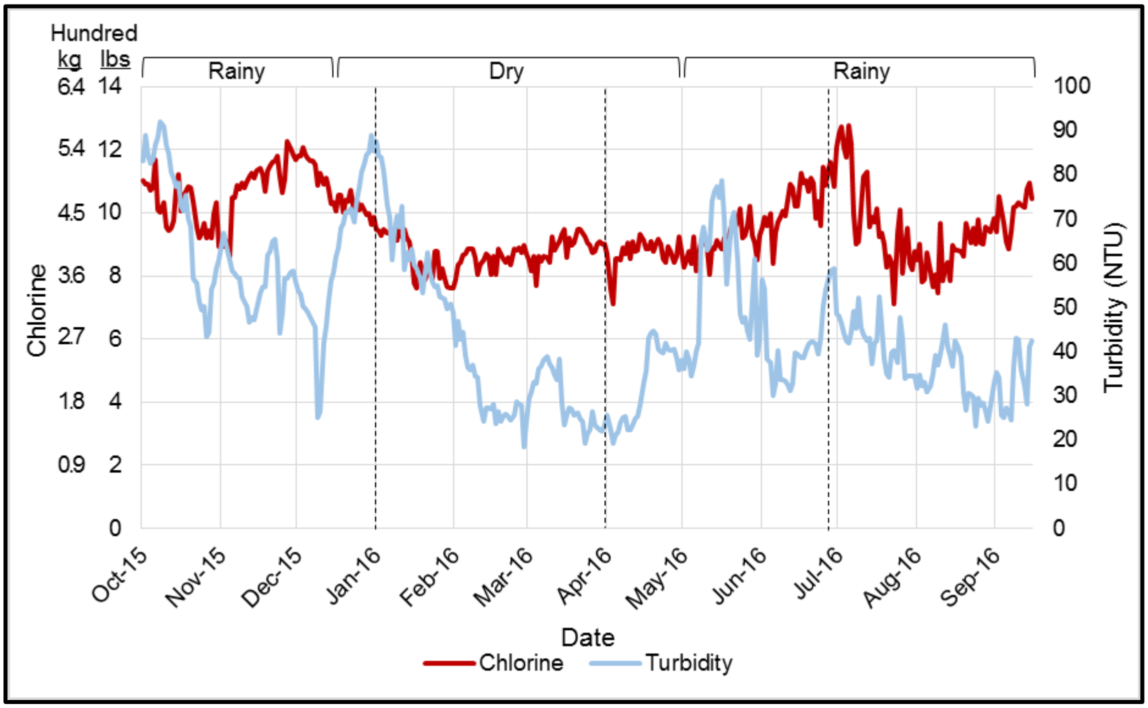


Figure 60: Chlorine consumption in relation to turbidity levels

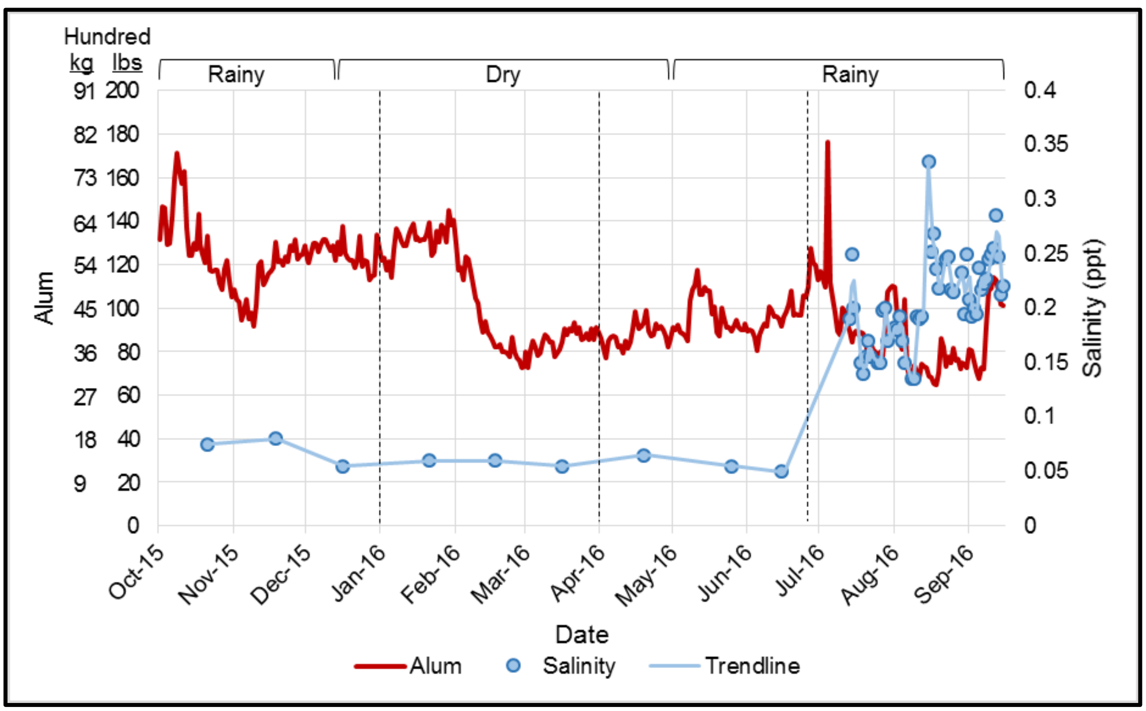


Figure 61: Alum consumption in relation to salinity levels

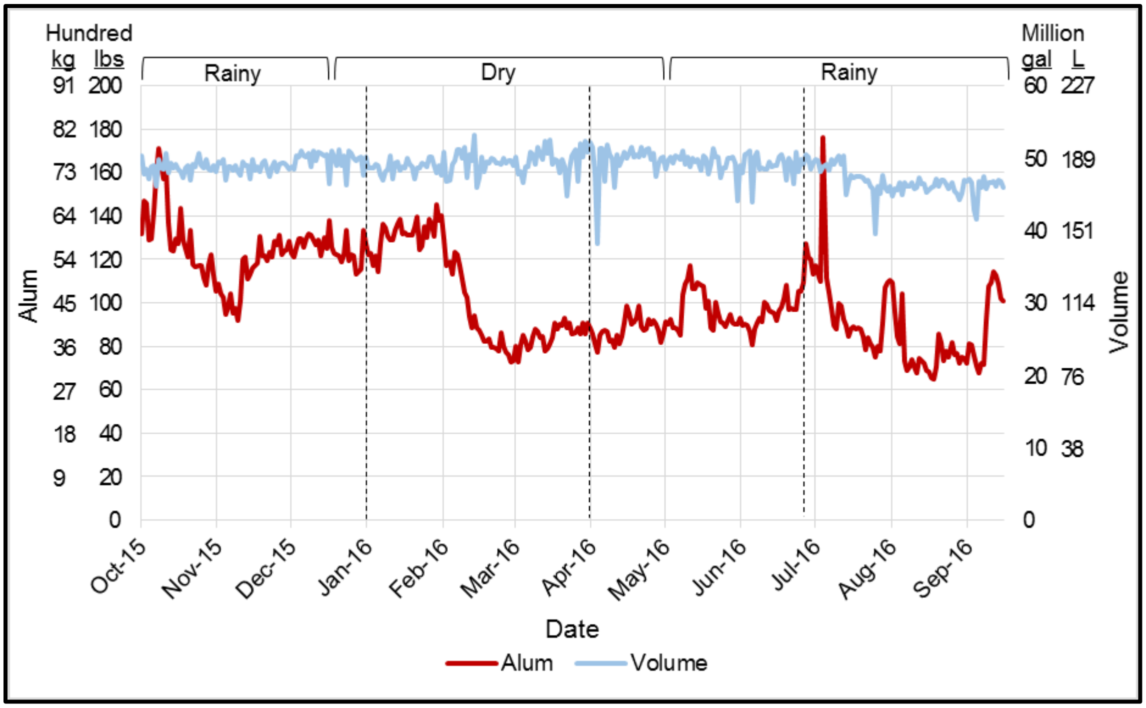


Figure 62: Alum consumption in relation to volume of influent

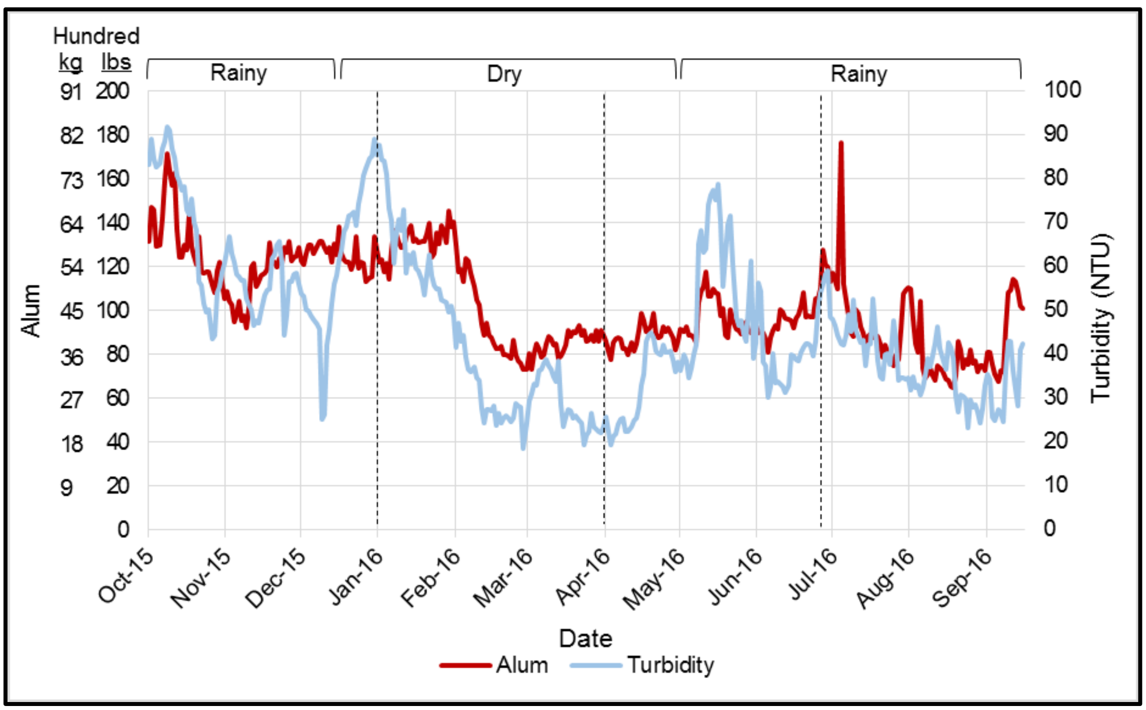


Figure 63: Alum consumption in relation to turbidity levels

Appendix D: Materials Used for Mount Hope Water Filtration Plant Analysis

Rapid Mixing Chamber

Table 28: Values used in the rapid mixing calculations

Parameter	Variable	Value	Source
Acceleration due to Gravity	g	9.81 m/s^2	Accepted Value
Water Density at 25°C	ρ	997.13 kg/m^3	Accepted Value
Water Density at 27°C	ρ	996.59 kg/m^3	Accepted Value
Water Density at 30°C	ρ	995.71 kg/m^3	Accepted Value
Water Dynamic Viscosity at 25°C	µ	0.00089 kg/m·s	Accepted Value
Water Dynamic Viscosity at 27°C	µ	0.000852 kg/m·s	Accepted Value
Water Dynamic Viscosity at 30°C	µ	0.000798 kg/m·s	Accepted Value
Baffle Spacing	a	0.75 m	Measured (Figure 65)
Channel Width	b	2.74 m	Measured (Figure 65)
Number of Compartments	m	6	Measured (Figure 67)
Manning's Coefficient	n	0.014	Assumed (concrete walls)
Water Depth	d	1.55 m	Assumed
Water Volume	V	23.45 m^3	Calculated
Length through Channel	ℓ	4.68 m	Calculated
Average Water Depth around Baffles	d_{ave}	0.42 m	Calculated

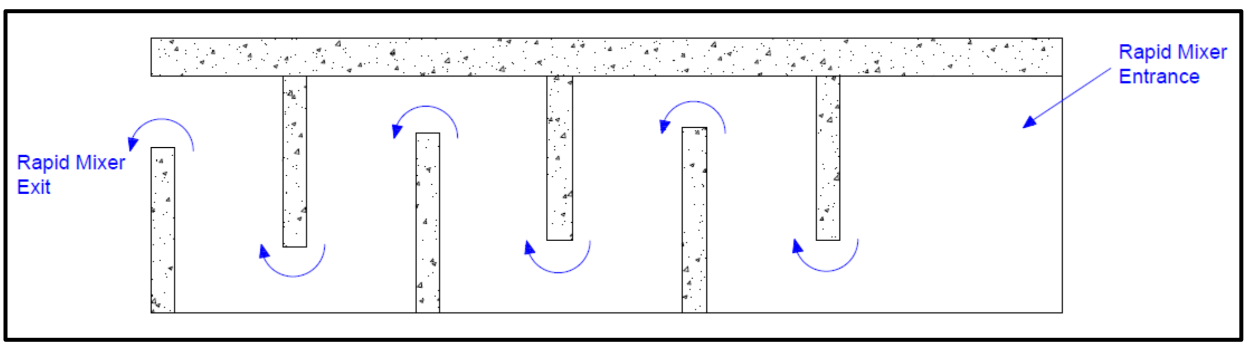


Figure 64: Flow pattern through the hydraulic, vertically baffled rapid mixer, entrance from aeration basin, exit to sedimentation basin (elevation view) (Ring, 2016a)

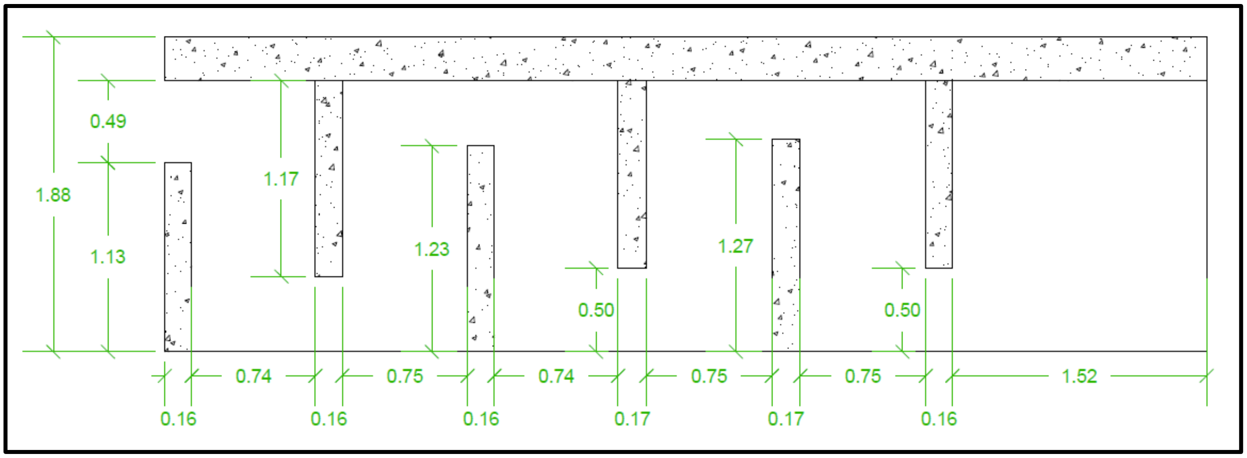


Figure 65: Measurements taken for the rapid mixing chamber during the second site visit (dimension normal to the view equal to 2.74 m) (elevation view) (Ring, 2016a)

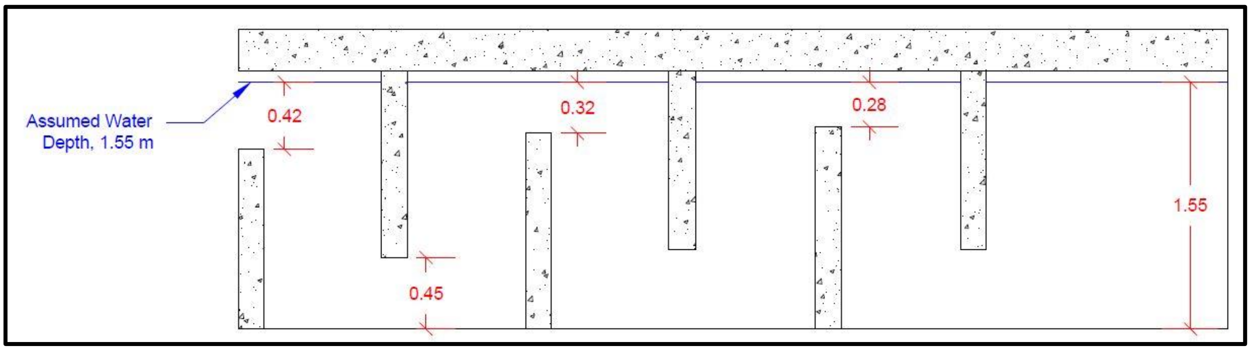


Figure 66: Water depth assumed for calculations of the rapid mixing chamber (elevation view) (Ring, 2016a)

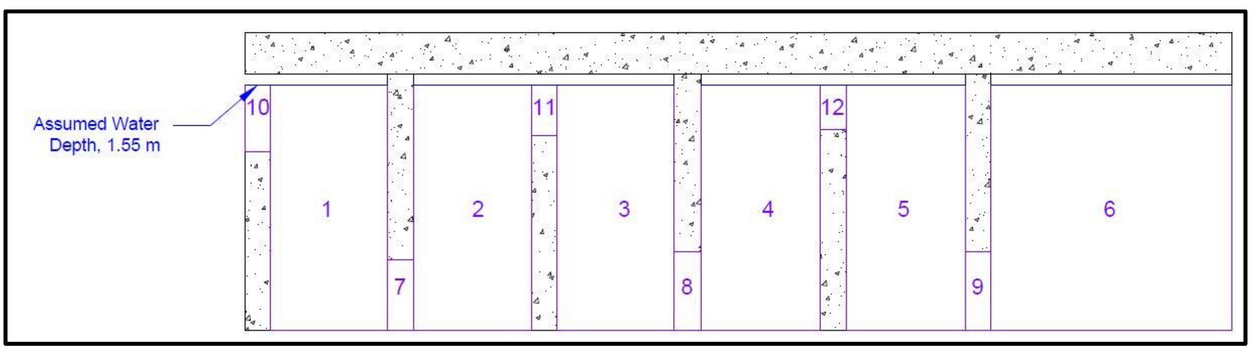


Figure 67: Simple geometry used to calculate the water volume in the rapid mixer, based on the assumed water depth (elevation view) (Ring, 2016a)

Estimation of Volume of One Rapid Mixing Pathway

$V = xyz$

1. $V = (0.74\ m)(1.55\ m)(2.7432\ m) = 3.1465\ m^3$
2. $V = (0.75\ m)(1.55\ m)(2.7432\ m) = 3.1890\ m^3$
3. $V = (0.74\ m)(1.55\ m)(2.7432\ m) = 3.1465\ m^3$
4. $V = (0.75\ m)(1.55\ m)(2.7432\ m) = 3.1890\ m^3$
5. $V = (0.75\ m)(1.55\ m)(2.7432\ m) = 3.1890\ m^3$
6. $V = (1.5240\ m)(1.55\ m)(2.7432\ m) = 6.4800\ m^3$
7. $V = (0.16\ m)(0.45\ m)(2.7432\ m) = 0.1975\ m^3$
8. $V = (0.17\ m)(0.5\ m)(2.7432\ m) = 0.2332\ m^3$
9. $V = (0.16\ m)(0.5\ m)(2.7432\ m) = 0.2195\ m^3$
10. $V = (0.16\ m)(0.42\ m)(2.7432\ m) = 0.1843\ m^3$
11. $V = (0.16\ m)(0.32\ m)(2.7432\ m) = 0.1405\ m^3$
12. $V = (0.17\ m)(0.28\ m)(2.7432\ m) = 0.1306\ m^3$

$$V_{tot} = \sum_{i=1}^{12} V_i$$

- $V_{tot} = 3.1465\ m^3 + 3.1890\ m^3 + 3.1465\ m^3 + 3.1890\ m^3 + 3.1890\ m^3 + 6.4800\ m^3 + .1975\ m^3 + 0.2332\ m^3 + 0.2195\ m^3 + 0.1843\ m^3 + 0.1405\ m^3 + 0.1306\ m^3 = \mathbf{23.4456\ m^3}$

Estimation of Straight Length through One Rapid Mixing Pathway

$$l = [(water\ depth)(number\ of\ compartments)] - \left[\sum height\ of\ water\ around\ baffle\ turns\right]$$

- $l = [(1.55\ m)(6\ m)] - [0.5\ m + 0.5\ m + 0.28\ m + 0.28\ m + 0.5\ m + 0.5\ m + 0.32\ m + 0.32\ m + 0.5\ m + 0.5\ m + 0.42\ m] = \mathbf{4.68\ m}$

Calculation of Average Height of Water around Baffle Turns

$$d_{ave} = \frac{\sum height\ of\ water\ around\ baffle\ turns}{number\ of\ turns}$$

- $d_{ave} = \frac{0.5\ m + 0.28\ m + 0.5\ m + 0.32\ m + 0.45\ m + 0.42\ m}{6} = \mathbf{0.42\ m}$

Table 29: Excel calculations solving for head loss due to friction in one rapid mixing pathway (25°C)

$$h_1 = \left(\frac{nv_1}{R_h^{\frac{2}{3}}}\right)^2 l \qquad v_1 = \frac{Q}{ab} \qquad A = ab \qquad P = 2a + 2b \qquad R_h = \frac{A}{P}$$

	Variable	Measurement									
water temperature	T	25°C									
Manning's coefficient	n	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014
spacing between baffles	a (m)	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
channel width	b (m)	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432
velocity in the channels	v_1 (m/s)	0.241324	0.2555653	0.2697579	0.28395062	0.4117639	0.4988165	0.5788253	0.7584757	0.8565042	0.91882855
cross-sectional area	A (m^2)	2.0574	2.0574	2.0574	2.0574	2.0574	2.0574	2.0574	2.0574	2.0574	2.0574
wetted perimeter	P (m)	6.9864	6.9864	6.9864	6.9864	6.9864	6.9864	6.9864	6.9864	6.9864	6.9864
hydraulic radius	R_h (m)	0.2944864	0.2944864	0.2944864	0.29448643	0.2944864	0.2944864	0.2944864	0.2944864	0.2944864	0.29448643
length of the last section	l (m)	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68
head loss due to friction	h_1 (m)	0.0002727	0.0003058	0.0003407	0.00037749	0.0007938	0.0011649	0.0015686	0.0026934	0.0034346	0.00395261

Table 30: Excel calculations solving for head loss around baffle turns in one rapid mixing pathway (25°C)

$$h_2 = \frac{(m+1){v_1}^2 + m{v_2}^2}{2g} \qquad v_2 = \frac{Q}{bd_{ave}}$$

water temperature	T	25°C									
# of compartments	m	6	6	6	6	6	6	6	6	6	6
velocity in the channels	v_1 (m/s)	0.2413	0.2556	0.2698	0.2840	0.4118	0.4988	0.5788	0.7585	0.8565	0.9188
channel width	b (m)	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432
average water depth around baffle	d_{ave} (m)	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
velocity in the passages or holes from one compartment to another	v_2 (m/s)	0.43094	0.45637	0.48171	0.50705	0.73529	0.89074	1.03362	1.35442	1.52947	1.64077
gravity	g (m/s^2)	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81
head loss from turns	h_2 (m)	0.07757	0.08699	0.09692	0.10739	0.22583	0.33141	0.44625	0.76625	0.97711	1.12448

Table 31: Excel calculations solving for velocity gradient in one rapid mixing pathway (25°C)

$$G = \sqrt{\frac{\rho g Q h_L}{\mu V}}$$

	Variable	Measurement									
water temperature	T	25°C									
density of water	ρ (kg/m³)	997.13	997.13	997.13	997.13	997.13	997.13	997.13	997.13	997.13	997.13
gravity	g (m/s²)	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81
flow rate	Q (m³/s)	0.4965	0.5258	0.555	0.5842	0.84716315	1.0262651	1.1908751	1.5604879	1.7621717	1.89039787
head loss	h_L (m)	0.07784118	0.08729956	0.09726506	0.10776904	0.22662354	0.3325753	0.4478199	0.7689387	0.9805446	1.12843709
dynamic viscosity	μ (kg/ms)	0.00089	0.00089	0.00089	0.00089	0.00089	0.00089	0.00089	0.00089	0.00089	0.00089
volume of mixing basin	V (m³)	23.4456	23.4456	23.4456	23.4456	23.4456	23.4456	23.4456	23.4456	23.4456	23.4456
velocity gradient	G (s⁻¹)	134.601238	146.690182	159.077826	171.795784	299.999656	399.99954	499.99943	749.99914	900	1000

Table 32: Excel calculations solving for head loss due to friction in one rapid mixing pathway (27°C)

	Variable	Measurement									
water temperature	T	27°C									
Manning's coefficient	n	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014
spacing between baffles	a (m)	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
channel width	b (m)	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432
velocity in the channels	v_1 (m/s)	0.241324	0.2555653	0.2697579	0.28395062	0.4058915	0.4917025	0.5705702	0.7476585	0.8442889	0.90572446
cross-sectional area	A (m²)	2.0574	2.0574	2.0574	2.0574	2.0574	2.0574	2.0574	2.0574	2.0574	2.0574
wetted perimeter	P (m)	6.9864	6.9864	6.9864	6.9864	6.9864	6.9864	6.9864	6.9864	6.9864	6.9864
hydraulic radius	R_h (m)	0.2944864	0.2944864	0.2944864	0.29448643	0.2944864	0.2944864	0.2944864	0.2944864	0.2944864	0.29448643
length of the last section	l (m)	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68
head loss due to friction	h_1 (m)	0.0002727	0.0003058	0.0003407	0.00037749	0.0007713	0.0011319	0.0015242	0.0026171	0.0033373	0.00384067

Table 33: Excel calculations solving for head loss around baffle turns in one rapid mixing pathway (27°C)

	Variable	Measurement									
water temperature	T	27°C									
# of compartments	m	6	6	6	6	6	6	6	6	6	6
velocity in the channels	v_1 (m/s)	0.241324	0.25556528	0.26975795	0.28395062	0.4058915	0.4917025	0.57057022	0.7476585	0.8442889	0.90572446
channel width	b (m)	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432
average water depth around baffle	d_{ave} (m)	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
velocity in the passages or holes from one compartment to another	v_2 (m/s)	0.4309357	0.45636657	0.48171062	0.50705467	0.7248062	0.8780402	1.0188754	1.33510447	1.5076588	1.61736511
gravity	g (m/s^2)	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81
head loss from turns	h_2 (m)	0.0775685	0.08699378	0.09692437	0.10739156	0.2194342	0.3220248	0.43361341	0.74454517	0.9494382	1.092639

Table 34: Excel calculations solving for velocity gradient in one rapid mixing pathway (27°C)

	Variable	Measurement									
water temperature	T	27°C									
density of water	ρ (kg/m^3)	996.59	996.59	996.59	996.59	996.59	996.59	996.59	996.59	996.59	996.59
gravity	g (m/s^2)	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81
flow rate	Q (m^3/s)	0.4965	0.5258	0.555	0.5842	0.83508113	1.0116288	1.1738912	1.5382326	1.7370401	1.86343751
head loss	h_L (m)	0.07784118	0.08729956	0.09726506	0.10776904	0.22020555	0.3231568	0.4351376	0.7471623	0.9527755	1.09647967
dynamic viscosity	μ (kg/ms)	0.000852	0.000852	0.000852	0.000852	0.000852	0.000852	0.000852	0.000852	0.000852	0.000852
volume of mixing basin	V (m^3)	23.4456	23.4456	23.4456	23.4456	23.4456	23.4456	23.4456	23.4456	23.4456	23.4456
velocity gradient	G (s^{-1})	137.532909	149.885156	162.542609	175.537569	299.999656	399.99954	499.99943	749.99914	900	1000

Table 35: Excel calculations solving for head loss due to friction in one rapid mixing pathway (30°C)

	Variable	Measurement									
water temperature	T	30°C									
Manning's coefficient	n	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014
spacing between baffles	a (m)	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
channel width	b (m)	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432
velocity in the channels	v_1 (m/s)	0.241324	0.2555653	0.2697579	0.28395062	0.3972454	0.4812286	0.5584163	0.7317324	0.8263044	0.8864313
cross-sectional area	A (m^2)	2.0574	2.0574	2.0574	2.0574	2.0574	2.0574	2.0574	2.0574	2.0574	2.0574
wetted perimeter	P (m)	6.9864	6.9864	6.9864	6.9864	6.9864	6.9864	6.9864	6.9864	6.9864	6.9864
hydraulic radius	R_h (m)	0.2944864	0.2944864	0.2944864	0.29448643	0.2944864	0.2944864	0.2944864	0.2944864	0.2944864	0.29448643
length of the last section	l (m)	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68
head loss due to friction	h_1 (m)	0.0002727	0.0003058	0.0003407	0.00037749	0.0007388	0.0010842	0.0014599	0.0025068	0.0031966	0.00367879

Table 36: Excel calculations solving for head loss around baffle turns in one rapid mixing pathway (30°C)

	Variable	Measurement									
water temperature	T	30°C									
# of compartments	m	6	6	6	6	6	6	6	6	6	6
velocity in the channels	v_1 (m/s)	0.241324	0.25556528	0.26975795	0.28395062	0.3972454	0.4812286	0.5584163	0.73173236	0.8263044	0.8864313
channel width	b (m)	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432	2.7432
average water depth around baffle	d_{ave} (m)	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
velocity in the passages or holes from one compartment to another	v_2 (m/s)	0.4309357	0.45636657	0.48171062	0.50705467	0.7093669	0.8593368	0.99717197	1.30666492	1.4755437	1.58291304
gravity	g (m/s^2)	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81
head loss from turns	h_2 (m)	0.0775685	0.08699378	0.09692437	0.10739156	0.2101853	0.3084518	0.41533705	0.71316336	0.9094204	1.04658538

Table 37: Excel calculations solving for velocity gradient in one rapid mixing pathway (30°C)

	Variable	Measurement									
water temperature	T	30°C									
density of water	ρ (kg/m^3)	995.71	995.71	995.71	995.71	995.71	995.71	995.71	995.71	995.71	995.71
gravity	g (m/s^2)	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81	9.81
flow rate	Q (m^3/s)	0.4965	0.5258	0.555	0.5842	0.81729277	0.9900797	1.1488857	1.5054662	1.7000388	1.82374376
head loss	h_L (m)	0.07784118	0.08729956	0.09726506	0.10776904	0.21092411	0.309536	0.416797	0.7156702	0.912617	1.05026417
dynamic viscosity	μ (kg/ms)	0.000798	0.000798	0.000798	0.000798	0.000798	0.000798	0.000798	0.000798	0.000798	0.000798
volume of mixing basin	V (m^3)	23.4456	23.4456	23.4456	23.4456	23.4456	23.4456	23.4456	23.4456	23.4456	23.4456
velocity gradient	G (s^{-1})	142.047356	154.805058	167.877985	181.299499	299.999656	399.99954	499.99943	749.99914	900	1000

Flocculation Basin

Table 38: Values used in the flocculation calculations

Parameter	Variable	Value	Source
Water Density at 25°C	ρ	997.13 kg/m^3	Accepted Value
Water Density at 27°C	ρ	996.59 kg/m^3	Accepted Value
Water Density at 30°C	ρ	995.71 kg/m^3	Accepted Value
Water Dynamic Viscosity at 25°C	μ	0.00089 kg/m·s	Accepted Value
Water Dynamic Viscosity at 27°C	μ	0.000852 kg/m·s	Accepted Value
Water Dynamic Viscosity at 30°C	μ	0.000798 kg/m·s	Accepted Value
Number of Arms on Paddle-wheel	N_{arms}	2	Measured (Figure 68)
Number of Paddle-wheels in One Pathway	N_{wheels}	6	Measured (Figure 70)
Blade Length	L	4.21 m	Measured (Figure 69)
Blade Width	w	0.16 m	Measured
Blade Radial Distance 1	r_{b1}	0.83 m	Measured (Figure 69)
Blade Radial Distance 2	r_{b2}	1.28 m	Measured (Figure 69)
Paddle-wheel Diameter	D	2.72 m	Measured (Figure 69)
Slippage Factor	k	0.3	Assumed
Average Shaft Rotational Velocity	η	1.49 rpm	Calculated
Water Depth	d	3.66 m	Assumed
Water Volume	V	515.49 m^3	Calculated
Blade Drag Coefficient	C_D	1.5	(Table 40)
Area of Blade	A_b	0.6736 m^2	Calculated

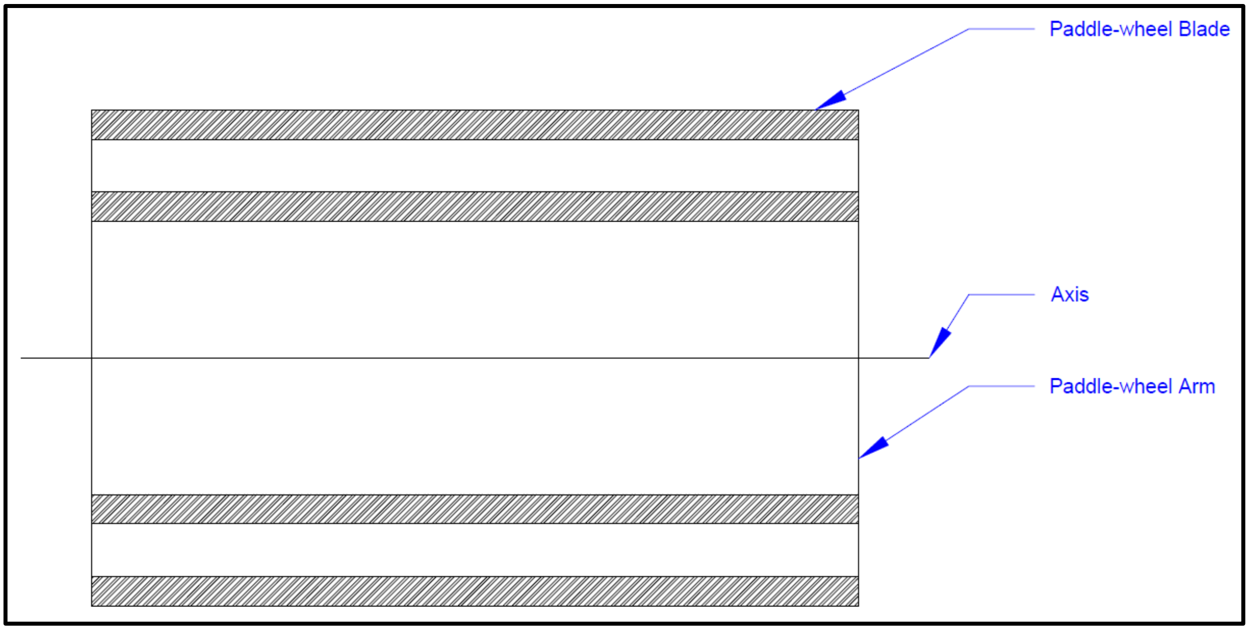


Figure 68: Elevation view of one horizontal paddle-wheel flocculator and its components (Ring, 2016a)

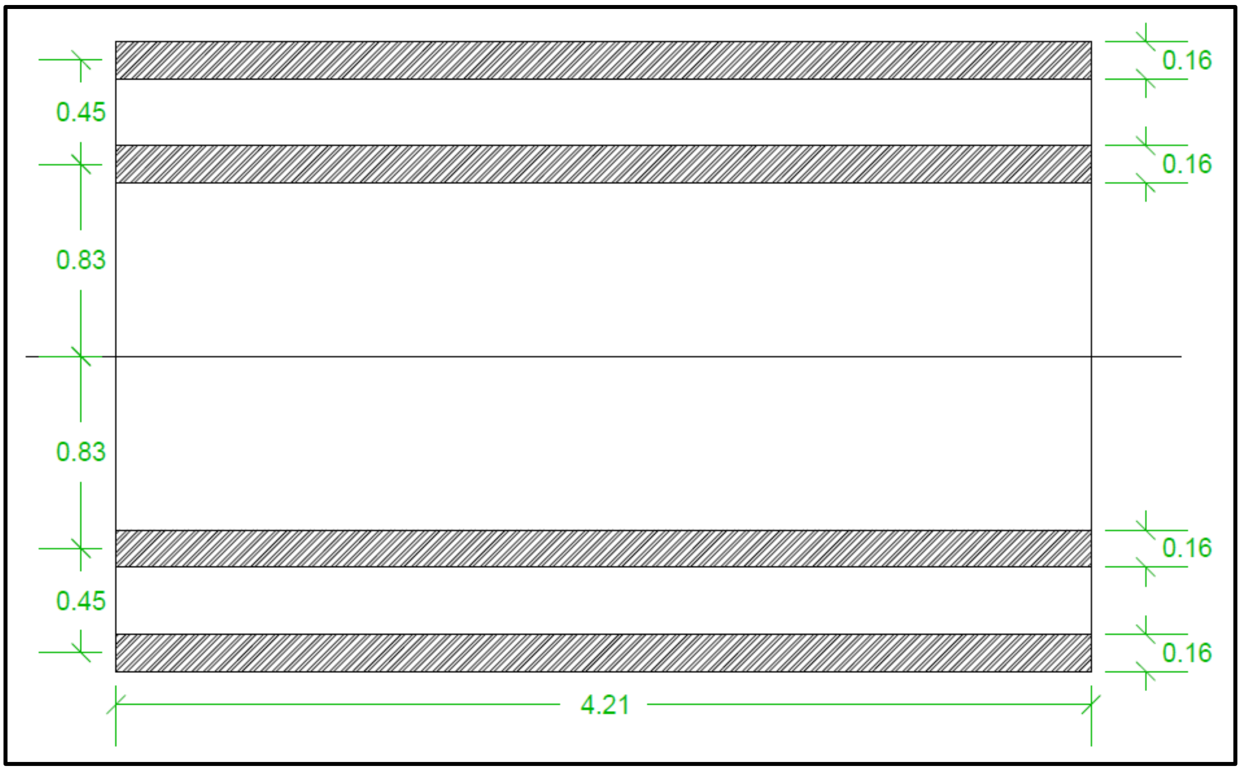


Figure 69: Measurements taken for the flocculators during the second site visit (elevation view) (Ring, 2016a)

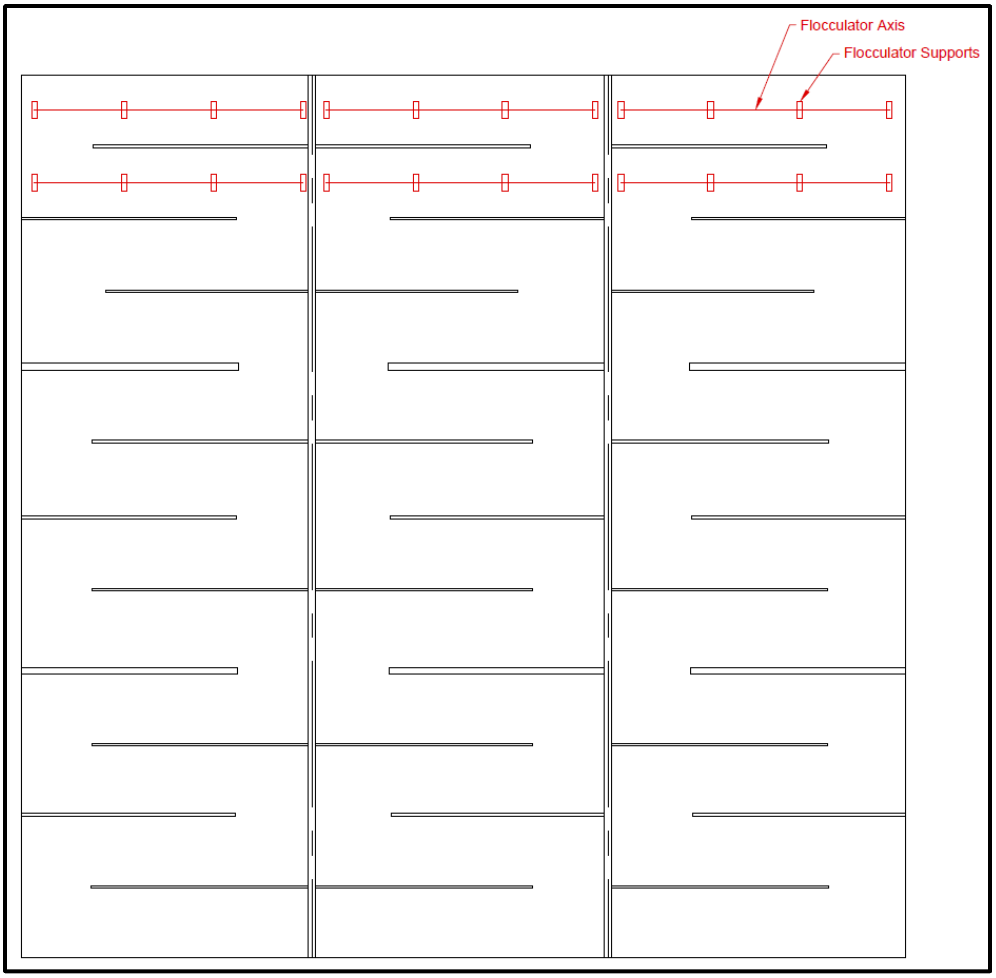


Figure 70: Location of the flocculators within the sedimentation basin (plan view) (Ring, 2016a)

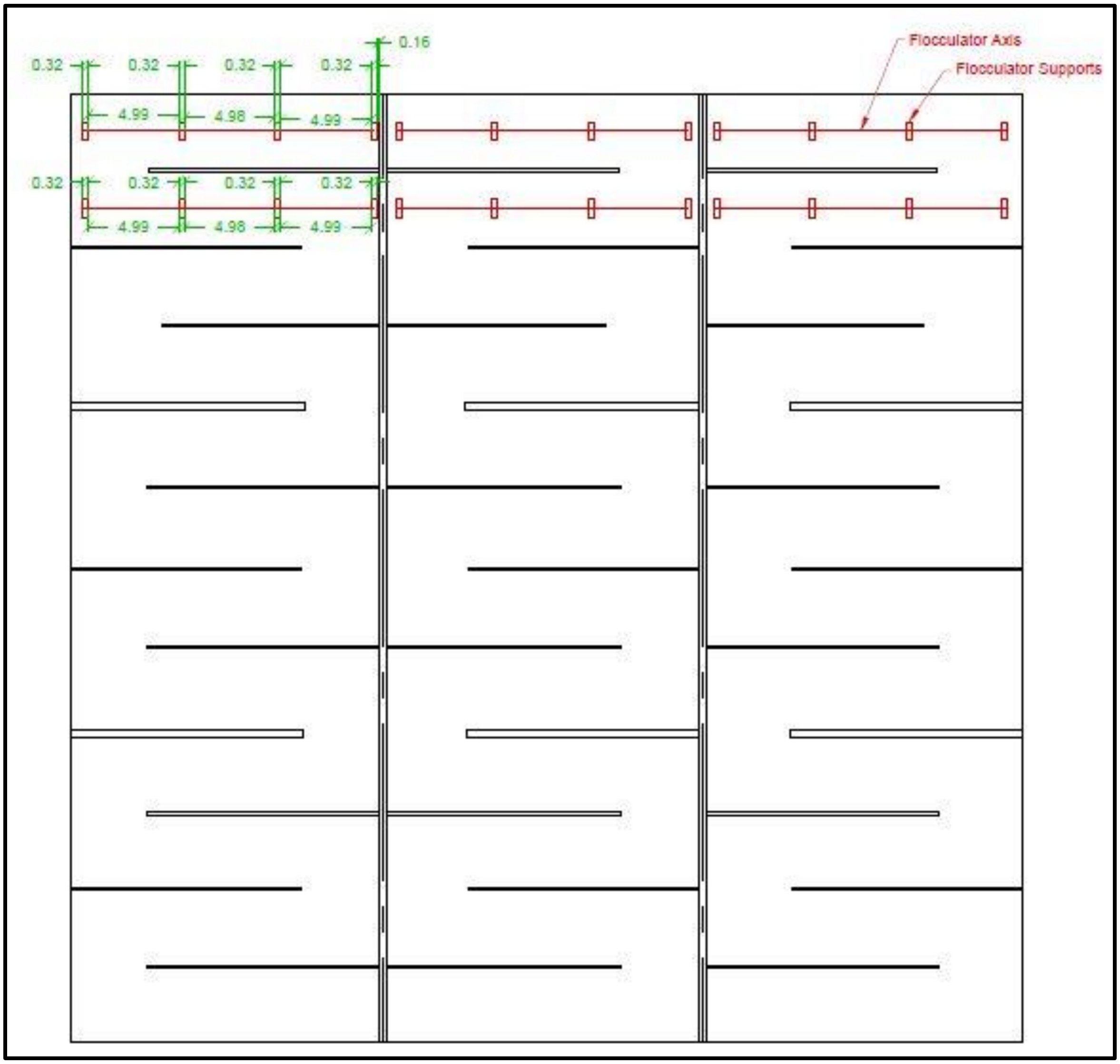


Figure 71: Dimensions locating the flocculators within the sedimentation basin (maximum basin depth equal to 3.66 m) (plan view) (Ring, 2016a)

Calculation of Average Shaft Rotational Velocity of Flocculators

Table 39: Results from two tests on the flocculators to determine the average shaft rotational velocity

Revolutions	Time	
5	3 min 18.6 s	198.6 s
5	3 min 25 s	205 s

$$t_{ave} = \frac{\sum time}{number\ of\ test}$$

- $t_{ave} = \frac{198.6\ s + 205\ s}{2} = 201.8\ s$

$$\eta_{ave} = \frac{number\ of\ rotations_{ave}}{t_{ave}}$$

- $\eta_{ave} = \frac{5\ rotations}{201.8\ s} = (0.024777\ rps)\left(\frac{60\ s}{1\ min}\right) = \mathbf{1.4866\ rpm}$

Estimation of Volume of One Flocculation Chamber

$V = xyz$

1. $V = (16.99\ m)(4.12\ m)(3.66\ m) = 256.1956\ m^3$
2. $V = (4.23\ m)(.16\ m)(3.66\ m) = 2.4771\ m^3$
3. $V = (16.99\ m)(4.13\ m)(3.66\ m) = 256.8175\ m^3$

$$V_{tot} = \sum_{i=1}^{3} V_i$$

- $V_{tot} = 256.1956 + 2.4771 + 256.8175 = \mathbf{515.4902\ m^3}$

Picking the Drag Coefficient of Flocculator Blades

$$\frac{L}{w} = \frac{length\ of\ blade}{width\ of\ blade}$$

- $\frac{L}{w} = \frac{4.21\ m}{.16\ m} = 26.3125$

Table 40: Selection of the blade drag coefficient for the flocculation calculations based on the blades' length to width ratios

$\frac{L}{w}$	C_D
1	1.16
5	1.2
20	***1.5***
>>20	1.9

Calculation of Area of Flocculator Blade

$A = Lw$

- $A = (4.21\ m)(0.16\ m) = \mathbf{0.6736\ m^2}$

Table 41: Excel calculations solving for the power expended by one paddle-wheel flocculator (25°C)

$$P_{wheel} = C_D \frac{\rho}{2} N_{arms} (1-k)^3 (2\pi\eta)^3 \sum_{1}^{n_{blades}} (r_{bi}{}^3 A_{bi})$$

	Variable	Measurement										
	T	25°C										
blade drag coeffiecient	C_D	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
desity of water	ρ (kg/m^3)	997.13	997.13	997.13	997.13	997.13	997.13	997.13	997.13	997.13	997.13	997.13
#of arms on the paddle wheel	N_{arms}	2	2	2	2	2	2	2	2	2	2	2
slippage factor due to difference in water & blade speeds	k	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
shaft rotational velocity	η (rev/s)	0.024777	0.020292	0.022915	0.032212	0.059334	0.081168	0.094187	0.117872	0.128846	0.139372	0.1495131
radial dist. from axis of rotation to center of blade	r_{bi} (m)	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
		1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28
area of paddle	A_{bi} (m^2)	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736
		0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736
	$r_{b1}{}^3 * A_{b1}$	0.385155723	0.385156	0.385156	0.385156	0.385156	0.385156	0.385156	0.385156	0.385156	0.385156	0.3851557
	$r_{b2}{}^3 * A_{b2}$	1.412641587	1.412642	1.412642	1.412642	1.412642	1.412642	1.412642	1.412642	1.412642	1.412642	1.4126416
summation	$\sum(r_{bi}{}^3 * A_{bi})$	1.79779731	1.797797	1.797797	1.797797	1.797797	1.797797	1.797797	1.797797	1.797797	1.797797	1.7977973
power expended by one paddle wheel flocculator	$P_{for\ one\ wheel}$ (kg*m^2/s^3)	3.479875095	1.91159	2.752691	7.646361	47.78976	122.3418	191.1591	374.6718	489.3673	619.3553	764.63627

Table 42: Excel calculations solving for the velocity gradient through the flocculation basin (25°C)

$$G = \sqrt{\frac{P_T}{\mu V}}$$

	Variable	Measurement										
water temperature	T	25°C										
total power dissipated by the flocculators	P_T (kg*m^2/s^3)	20.87925057	11.46954	16.51615	45.87817	286.7386	734.0507	1146.954	2248.031	2936.204	3716.132	4587.818
dynamic viscosity	μ (kg/ms)	0.00089	0.00089	0.00089	0.00089	0.00089	0.00089	0.00089	0.00089	0.00089	0.00089	0.00089
volume of flocculation basin	V (m^3)	515.4902	515.4902	515.4902	515.4902	515.4902	515.4902	515.4902	515.4902	515.4902	515.4902	515.4902
velocity gradient	G (s^{-1})	6.746091744	4.999975	5.999971	9.99995	24.99988	39.9998	49.99975	69.99966	79.99961	89.99955	99.99951

Table 43: Excel calculations solving for the Reynold's number through the flocculation basin, to verify the assumption for CD (25°C)

if R_e>1000, the assumption to use C_D from the table is correct and the calculations are valid

$$R_e = \frac{D_{pw}{}^2 \eta \rho}{\mu}$$

	Variable	Measurement										
	T	25°C										
diameter of paddle wheel	D (m)	2.72	2.72	2.72	2.72	2.72	2.72	2.72	2.72	2.72	2.72	2.72
shaft rotational velocity	η (rev/s)	0.024777	0.020292	0.022915	0.032212	0.059334	0.081168	0.094187	0.117872	0.128846	0.139372	0.149513
desity of water	ρ (kg/m^3)	997.13	997.13	997.13	997.13	997.13	997.13	997.13	997.13	997.13	997.13	997.13
dynamic viscosity	μ (kg/ms)	0.00089	0.00089	0.00089	0.00089	0.00089	0.00089	0.00089	0.00089	0.00089	0.00089	0.00089
Reynold's number	R_e	205375.3446	168199.8	189938.5	267000.5	491819.1	672799	780714.2	977036.4	1068002	1155244	1239306

Table 44: Excel calculations solving for the power expended by one paddle-wheel flocculator (27°C)

	Variable		Measurement									
	T		27°C									
blade drag coeffecient	C_D	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
desity of water	ρ (kg/m^3)	996.59	996.59	996.59	996.59	996.59	996.59	996.59	996.59	996.59	996.59	996.59
#of arms on the paddle wheel	N_{arms}	2	2	2	2	2	2	2	2	2	2	2
slippage factor due to difference in water & blade speeds	k	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
rotational velocity	η (rev/s)	0.024777	0.020003	0.022588	0.031753	0.058489	0.080012	0.092845	0.116192	0.127009	0.137384	0.1473812
radial dist. from axis of rotation to center of blade	r_{bi} (m)	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
		1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28
area of paddle	A_{bi} (m^2)	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736
		0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736
	$r_{b1}^3 * A_{b1}$	0.385155723	0.385156	0.385156	0.385156	0.385156	0.385156	0.385156	0.385156	0.385156	0.385156	0.3851557
	$r_{b2}^3 * A_{b2}$	1.412641587	1.412642	1.412642	1.412642	1.412642	1.412642	1.412642	1.412642	1.412642	1.412642	1.4126416
summation	$\sum(r_{bi}^3 * A_{bi})$	1.79779731	1.797797	1.797797	1.797797	1.797797	1.797797	1.797797	1.797797	1.797797	1.797797	1.7977973
power expended by one paddle wheel flocculator	$P_{for\ one\ wheel}$ (kg*m^2/s^3)	3.477990553	1.830038	2.635257	7.320151	45.75095	117.1224	183.0038	358.6876	468.4775	592.9168	731.9961

Table 45: Excel calculations solving for the velocity gradient through the flocculation basin (27°C)

	Variable		Measurement									
water temperature	T		27°C									
total power dissipated by the flocculators	P_T ($kg*m^2/s^3$)	20.86794332	10.98023	15.81154	43.9209	274.5057	702.7347	1098.023	2152.126	2810.865	3557.501	4391.977
dynamic viscosity	μ (kg/ms)	0.000852	0.000852	0.000852	0.000852	0.000852	0.000852	0.000852	0.000852	0.000852	0.000852	0.000852
volume of flocculation basin	V (m^3)	515.4902	515.4902	515.4902	515.4902	515.4902	515.4902	515.4902	515.4902	515.4902	515.4902	515.4902
velocity gradient	G (s^{-1})	6.89302447	5.000066	6.000081	10.00013	25.00033	40.00052	50.00066	70.00093	80	90	100

Table 46: Excel calculations solving for the Reynold's number through the flocculation basin, to verify the assumption for CD (27°C)

if R_e>1000, the assumption to use C_D from the table is correct and the calculations are valid

	Variable		Measurement									
	T		27°C									
diameter of paddle wheel	D (m)	1.72	2.72	2.72	2.72	2.72	2.72	2.72	2.72	2.72	2.72	2.72
shaft rotational velocity	η (rev/s)	0.024777	0.020003	0.022588	0.031753	0.058489	0.080012	0.092845	0.116192	0.127009	0.137384	0.147381
desity of water	ρ (kg/m^3)	996.59	996.59	996.59	996.59	996.59	996.59	996.59	996.59	996.59	996.59	996.59
dynamic viscosity	μ (kg/ms)	0.000852	0.000852	0.000852	0.000852	0.000852	0.000852	0.000852	0.000852	0.000852	0.000852	0.000852
Reynold's number	R_e	85739.81556	173104.1	195476.7	274785.6	506159.5	692416.4	803478.1	1005525	1099133	1188918	1275431

Table 47: Excel calculations solving for the power expended by one paddle-wheel flocculator (30°C)

	Variable		Measurement									
	T		30°C									
blade drag coeffiecient	C_D	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
desity of water	ρ (kg/m^3)	995.71	995.71	995.71	995.71	995.71	995.71	995.71	995.71	995.71	995.71	995.71
#of arms on the paddle wheel	N_{arms}	2	2	2	2	2	2	2	2	2	2	2
slippage factor due to difference in water & blade speeds	k	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
rotational velocity	η (rev/s)	0.024777	0.019577	0.022107	0.031076	0.057242	0.078307	0.090867	0.113717	0.124304	0.134458	0.144242
radial dist. from axis of rotation to center of blade	r_{bi} (m)	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
		1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28
area of paddle	A_{bi} (m^2)	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736
		0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736	0.6736
	$r_{b1}^3*A_{b1}$	0.385155723	0.385156	0.385156	0.385156	0.385156	0.385156	0.385156	0.385156	0.385156	0.385156	0.3851557
	$r_{b2}^3*A_{b2}$	1.412641587	1.412642	1.412642	1.412642	1.412642	1.412642	1.412642	1.412642	1.412642	1.412642	1.4126416
summation	$\sum(r_{bi}^3*A_{bi})$	1.79779731	1.797797	1.797797	1.797797	1.797797	1.797797	1.797797	1.797797	1.797797	1.797797	1.7977973
power expended by one paddle wheel flocculator	$P_{for\ one\ wheel}$ (kg*m^2/s^3)	3.474919449	1.714011	2.468177	6.856046	42.85029	109.6967	171.4011	335.9462	438.7869	555.3397	685.60459

Table 48: Excel calculations solving for the velocity gradient through the flocculation basin (30°C)

	Variable		Measurement									
water temperature	T		30°C									
total power dissipated by the flocculators	P_T ($kg*m^2/s^3$)	20.8495167	10.28407	14.80906	41.13627	257.1017	658.1804	1028.407	2015.677	2632.722	3332.038	4113.628
dynamic viscosity	μ (kg/ms)	0.000798	0.000798	0.000798	0.000798	0.000798	0.000798	0.000798	0.000798	0.000798	0.000798	0.000798
volume of flocculation basin	V (m^3)	515.4902	515.4902	515.4902	515.4902	515.4902	515.4902	515.4902	515.4902	515.4902	515.4902	515.4902
velocity gradient	G (s^{-1})	7.119284423	5.00001	6.000012	10.00002	25.00005	40.00008	50.0001	70.00013	80.00015	90.00017	100.0002

Table 49: Excel calculations solving for the Reynold's number through the flocculation basin, to verify the assumption for CD (30°C)

if R_e>1000, the assumption to use C_D from the table is correct and the calculations are valid

	Variable		Measurement									
	T		30°C									
diameter of paddle wheel	D (m)	1.72	2.72	2.72	2.72	2.72	2.72	2.72	2.72	2.72	2.72	2.72
shaft rotational velocity	η (rev/s)	0.024777	0.019577	0.022107	0.031076	0.057242	0.078307	0.090867	0.113717	0.124304	0.134458	0.144242
desity of water	ρ (kg/m^3)	995.71	995.71	995.71	995.71	995.71	995.71	995.71	995.71	995.71	995.71	995.71
dynamic viscosity	μ (kg/ms)	0.000798	0.000798	0.000798	0.000798	0.000798	0.000798	0.000798	0.000798	0.000798	0.000798	0.000798
Reynold's number	Re	91460.92558	180720	204076.8	286875.1	528428.4	722879.9	838827.8	1049764	1147500	1241236	1331556

Sedimentation Basin

Table 50: Values used in the sedimentation basin calculations

Parameter	Variable	Value	Source
Water Depth	d	3.66 m	Assumed
Volume, Flocculators On	V	2631.1070 m^3	Calculated
Volume, Flocculators Off	V	3146.5972 m^3	Calculated

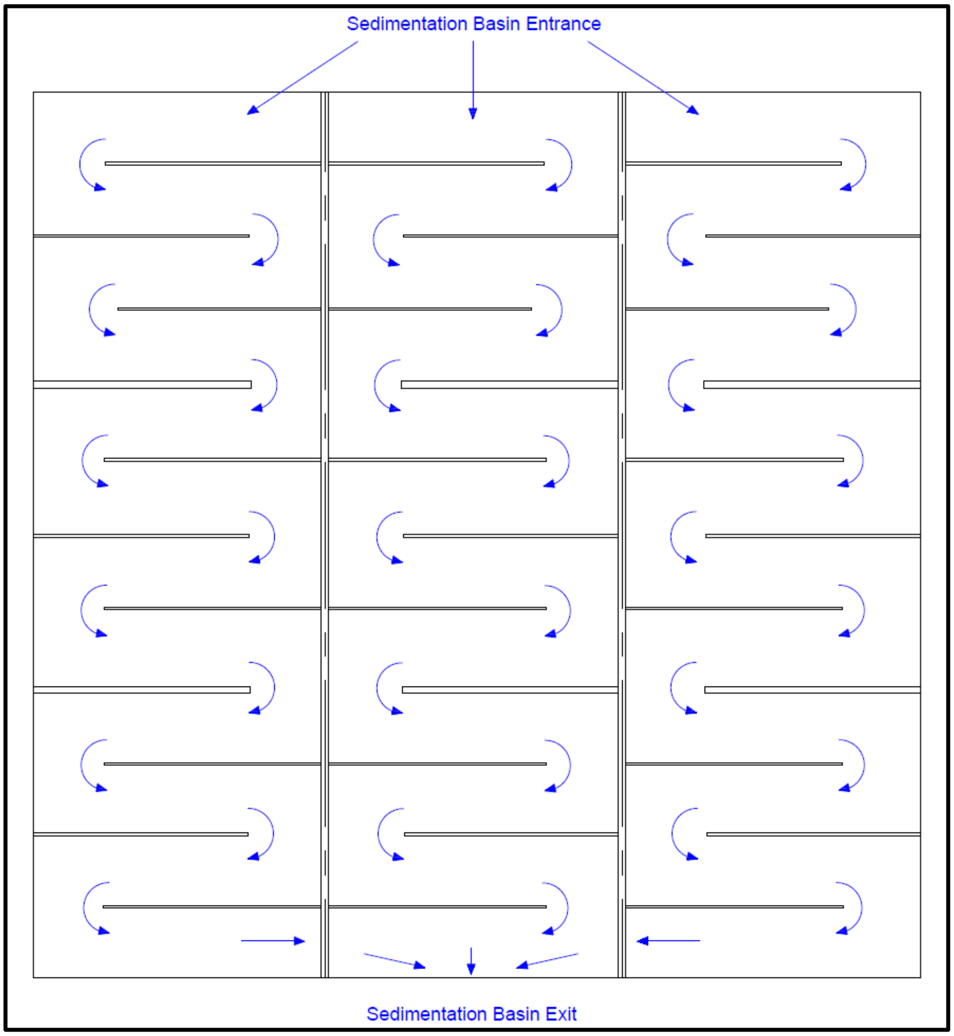


Figure 72: Flow pattern through the horizontally baffled sedimentation basin, entrance from rapid mixer, exit to filtration building (plan view) (Ring, 2016a)

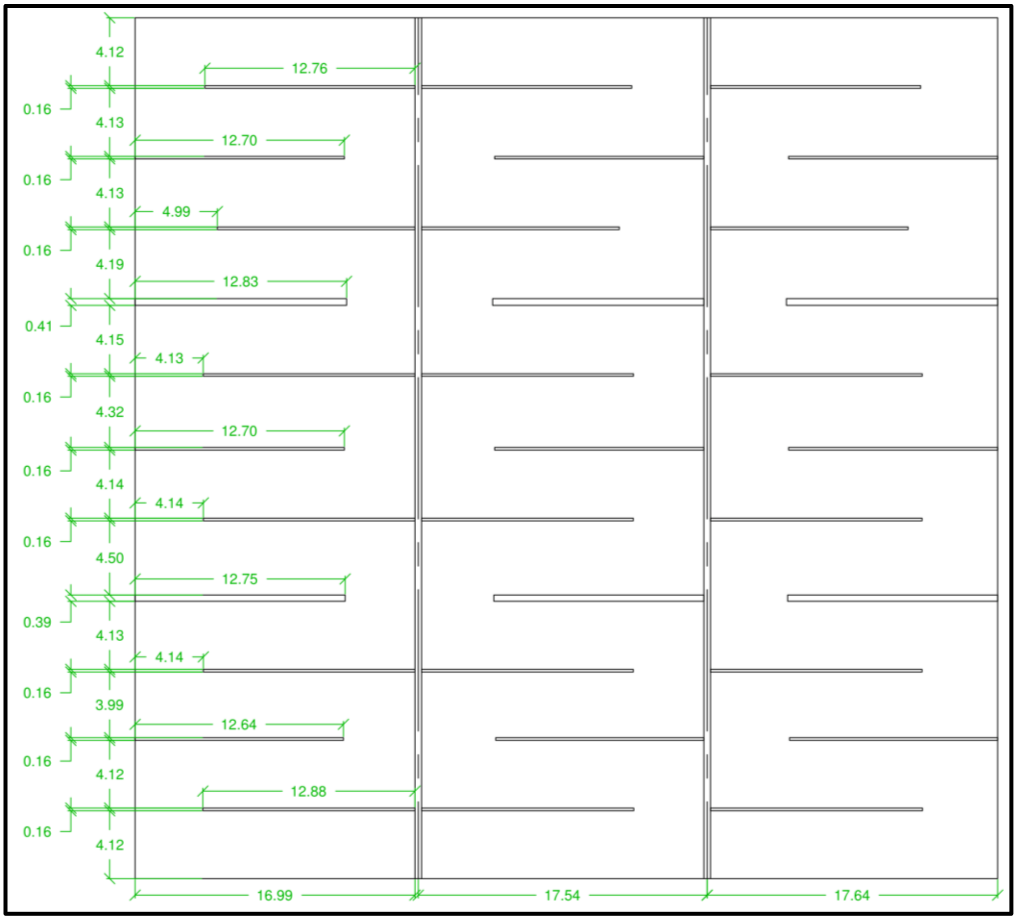


Figure 73: Measurements taken for the sedimentation basin during the second site visit (elevation view) (Ring, 2016a)

Estimation of Volume of One Sedimentation Pathway when Flocculators are Off (Larger Volume)

$V = xyz$

1. $V = (16.99\ m)(4.12\ m)(3.66\ m) = 256.1956\ m^3$
2. $V = (4.23\ m)(0.16\ m)(3.66\ m) = 2.4771\ m^3$
3. $V = (16.99\ m)(4.13\ m)(3.66\ m) = 256.8175\ m^3$
4. $V = (4.29\ m)(0.16\ m)(3.66\ m) = 2.5122\ m^3$
5. $V = (16.99\ m)(4.13\ m)(3.66\ m) = 256.8175\ m^3$
6. $V = (4.99\ m)(0.16\ m)(3.66\ m) = 2.9221\ m^3$
7. $V = (16.99\ m)(4.19\ m)(3.66\ m) = 260.5484\ m^3$
8. $V = (4.16\ m)(0.41\ m)(3.66\ m) = 6.2425\ m^3$
9. $V = (16.99\ m)(4.15\ m)(3.66\ m) = 258.0611\ m^3$

10. $V = (4.13\ m)(0.16\ m)(3.66\ m) = 2.4185\ m^3$
11. $V = (16.99\ m)(4.32\ m)(3.66\ m) = 268.6323\ m^3$
12. $V = (4.29\ m)(0.16\ m)(3.66\ m) = 2.5122\ m^3$
13. $V = (16.99\ m)(4.14\ m)(3.66\ m) = 257.4393\ m^3$
14. $V = (4.14\ m)(0.16\ m)(3.66\ m) = 2.4244\ m^3$
15. $V = (16.99\ m)(4.50\ m)(3.66\ m) = 279.8253\ m^3$
16. $V = (4.24\ m)(0.39\ m)(3.66\ m) = 6.0522\ m^3$
17. $V = (16.99\ m)(4.13\ m)(3.66\ m) = 256.8175\ m^3$
18. $V = (4.14\ m)(0.16\ m)(3.66\ m) = 2.4244\ m^3$
19. $V = (16.99\ m)(3.99\ m)(3.66\ m) = 248.1118\ m^3$
20. $V = (4.35\ m)(0.16\ m)(3.66\ m) = 2.5474\ m^3$
21. $V = (16.99\ m)(4.12\ m)(3.66\ m) = 256.1956\ m^3$
22. $V = (4.11\ m)(0.16\ m)(3.66\ m) = 2.4068\ m^3$
23. $V = (16.99\ m)(4.12\ m)(3.66\ m) = 256.1956\ m^3$

$$V_{tot} = \sum_{i=1}^{3} V_i$$

- $V_{tot} = 256.1956 + 2.4771 + 256.8175 + 2.5122\ m^3 + 256.8175\ m^3 + 2.9221\ m^3 + 260.5484\ m^3 + 6.2425\ m^3 + 258.0611\ m^3 + 2.4185\ m^3 + 268.6323\ m^3 + 2.5122\ m^3 + 257.4393\ m^3 + 2.4244\ m^3 + 279.8253\ m^3 + 6.0522\ m^3 + 256.8175\ m^3 + 2.4244\ m^3 + 248.1118\ m^3 + 2.5474\ m^3 + 256.1956\ m^3 + 2.4068\ m^3 + 256.1956\ m^3 = \mathbf{3146.5972\ m^3}$

Estimation of Volume of One Sedimentation Pathway when Flocculators are On (Smaller Volume)

$V = xyz$

1. $V = (4.29\ m)(0.16\ m)(3.66\ m) = 2.5122\ m^3$
2. $V = (16.99\ m)(4.13\ m)(3.66\ m) = 256.8175\ m^3$
3. $V = (4.99\ m)(0.16\ m)(3.66\ m) = 2.9221\ m^3$
4. $V = (16.99\ m)(4.19\ m)(3.66\ m) = 260.5484\ m^3$
5. $V = (4.16\ m)(0.41\ m)(3.66\ m) = 6.2425\ m^3$

6. $V = (16.99\ m)(4.15\ m)(3.66\ m) = 258.0611\ m^3$
7. $V = (4.13\ m)(0.16\ m)(3.66\ m) = 2.4185\ m^3$
8. $V = (16.99\ m)(4.32\ m)(3.66\ m) = 268.6323\ m^3$
9. $V = (4.29\ m)(0.16\ m)(3.66\ m) = 2.5122\ m^3$
10. $V = (16.99\ m)(4.14\ m)(3.66\ m) = 257.4393\ m^3$
11. $V = (4.14\ m)(0.16\ m)(3.66\ m) = 2.4244\ m^3$
12. $V = (16.99\ m)(4.50\ m)(3.66\ m) = 279.8253\ m^3$
13. $V = (4.24\ m)(0.39\ m)(3.66\ m) = 6.0522\ m^3$
14. $V = (16.99\ m)(4.13\ m)(3.66\ m) = 256.8175\ m^3$
15. $V = (4.14\ m)(0.16\ m)(3.66\ m) = 2.4244\ m^3$
16. $V = (16.99\ m)(3.99\ m)(3.66\ m) = 248.1118\ m^3$
17. $V = (4.35\ m)(0.16\ m)(3.66\ m) = 2.5474\ m^3$
18. $V = (16.99\ m)(4.12\ m)(3.66\ m) = 256.1956\ m^3$
19. $V = (4.11\ m)(0.16\ m)(3.66\ m) = 2.4068\ m^3$
20. $V = (16.99\ m)(4.12\ m)(3.66\ m) = 256.1956\ m^3$

$$V_{tot} = \sum_{i=1}^{3} V_i$$

- $V_{tot} = 2.5122\ m^3 + 256.8175\ m^3 + 2.9221\ m^3 + 260.5484\ m^3 + 6.2425\ m^3 + 258.0611\ m^3 + 2.4185\ m^3 + 268.6323\ m^3 + 2.5122\ m^3 + 257.4393\ m^3 + 2.4244\ m^3 + 279.8253\ m^3 + 6.0522\ m^3 + 256.8175\ m^3 + 2.4244\ m^3 + 248.1118\ m^3 + 2.5474\ m^3 + 256.1956\ m^3 + 2.4068\ m^3 + 256.1956\ m^3 = \mathbf{2631.1070\ m^3}$

Table 51: Excel calculations solving for detention time in the sedimentation basin when the flocculators are off

$$t = \frac{V}{Q}$$

		When Flocculators are Off (Max Volume)									
volume	V (m^3)	3146.5972	3146.5972	3146.5972	3146.5972	3146.5972	3146.5972	3146.5972	3146.5972	3146.5972	3146.5972
flow rate	Q (m^3/s)	0.4965	0.5258	0.555	0.5842	0.437027	0.374595	0.327771	0.29135	0.238379	0.218514
detention time	t (s)	6337.5573	5984.3994	5669.54451	5386.1643	7200	8399.9999	9600	10799.999	13200.000	14399.999

Table 52: Excel calculations solving for detention time in the sedimentation basin when the flocculators are on

		When Flocculators are On (Min Volume)									
volume	V (m^3)	2631.107	2631.107	2631.107	2631.107	2631.107	2631.107	2631.107	2631.107	2631.107	2631.107
flow rate	Q (m^3/s)	0.4965	0.5258	0.555	0.5842	0.3654315	0.3132270	0.2740737	0.2436210	0.1993263	0.1827158
detention time	t (s)	5299.31	5004.01	4740.73	4503.78	7200.00	8400.00	9600.00	10800.00	13200.00	14400.00

Appendix E: General Inspection Items for Dams and Spillways

Table 53: Dam and spillway items to be inspected

Element	Alignment	Erosion	Concrete Condition	Cavitation	Deterioration	Displacement	Joint Separation	Leakage	Damaged/Missing Seals	Metal Corrosion	Obstructions/Debris	Paths and Ruts	Seepage	Cloudy Drainage	Flow Rate	Settlement	Undermining	Sedimentation	Vegetation	Operation	Emergency Operation
Approach Channel		■	■	■	■	■	■	■	■	■			■	■	■	■	■			■	■
Inlets/Control Sections		■		■		■		■	■				■	■	■		■	■		■	■
Discharge Conduit		■			■	■			■					■	■			■		■	■
Discharge Channel			■	■	■	■	■	■	■	■				■	■	■	■	■		■	■
Outlet Structure		■		■	■		■	■	■	■		■		■	■	■		■	■	■	■
Joints		■		■		■		■			■	■		■	■	■	■	■	■	■	■
Control Features	■	■	■	■		■	■		■		■	■	■	■	■	■	■	■	■		
Debris Control		■	■	■	■	■	■	■	■			■	■	■	■	■	■	■	■		■
Drains/Pressure Relief	■	■	■	■	■	■	■	■	■	■		■	■			■	■	■	■	■	■
Sidewalls		■		■	■		■	■	■	■	■	■		■	■	■	■	■	■	■	■

Appendix F: Gatún Spillway Inspection Checklist

The first column of this table is used to record the general condition (poor, fair, good, excellent) of each element and the following columns are used to refer the reader to a later portion of the inspection report where detail regarding the damage are located.

Table 54: Gatún Spillway Concrete Inspection

	Concrete Condition	**Cracks**	**Seepage**	**Erosion**	**Settlement**	**Relative Movement**	**Drains and Drainage**	**Instrumentation**
Upstream Face								
Downstream Face								
Downstream Toe								
Left Lateral Wall								
Right Lateral Wall								
Spillway Bridge Deck and Framing (Concrete)								
Machinery Tunnel								
Upstream Gallery								
Downstream Gallery								

	Concrete Condition	**Cracks**	**Seepage**	**Relative Movement**	**Drains and Drainage**	**Instrumentation**
Counterweight Pit 1						
Counterweight Pit 2						
Counterweight Pit 3						
Counterweight Pit 4						
Counterweight Pit 5						
Counterweight Pit 6						
Counterweight Pit 7						
Counterweight Pit 8						
Counterweight Pit 9						
Counterweight Pit 10						
Counterweight Pit 11						
Counterweight Pit 12						
Counterweight Pit 13						
Counterweight Pit 14						
Counterweight Pit 15						
Counterweight Pit 16						
Counterweight Pit 17						
Counterweight Pit 18						
Counterweight Pit 19						
Counterweight Pit 20						

	Concrete Condition	Cracks	Seepage	Relative Movement	Drains and Drainage	Instrumentation
Counterweight Pit 21						
Counterweight Pit 22						
Counterweight Pit 23						
Counterweight Pit 24						
Counterweight Pit 25						
Counterweight Pit 26						
Counterweight Pit 27						
Counterweight Pit 28						

	Concrete Condition	**Cracks**	**Seepage**	**Settlement**	**Relative Movement**	**Drains and Drainage**	**Instrumentation**
Spillway Pier 1 Upstream Face							
Spillway Pier 1 Downstream Face							
Spillway Pier 2 Upstream Face							
Spillway Pier 2 Downstream Face							
Spillway Pier 3 Upstream Face							
Spillway Pier 3 Downstream Face							
Spillway Pier 4 Upstream Face							
Spillway Pier 4 Downstream Face							
Spillway Pier 5 Upstream Face							
Spillway Pier 5 Downstream Face							
Spillway Pier 6 Upstream Face							
Spillway Pier 6 Downstream Face							
Spillway Pier 7 Upstream Face							
Spillway Pier 7 Downstream Face							
Spillway Pier 8 Upstream Face							
Spillway Pier 8 Downstream Face							

	Concrete Condition	**Cracks**	**Seepage**	**Settlement**	**Relative Movement**	**Drains and Drainage**	**Instrumentation**
Spillway Pier 9 Upstream Face							
Spillway Pier 9 Downstream Face							
Spillway Pier 10 Upstream Face							
Spillway Pier 10 Downstream Face							
Spillway Pier 11 Upstream Face							
Spillway Pier 11 Downstream Face							
Spillway Pier 12 Upstream Face							
Spillway Pier 12 Downstream Face							
Spillway Pier 13 Upstream Face							
Spillway Pier 13 Downstream Face							

	Concrete Condition	Cracks	Seepage	Settlement	Relative Movement	Drains and Drainage	Instrumentation
Gate Bay 1							
Gate Bay 2							
Gate Bay 3							
Gate Bay 4							
Gate Bay 5							
Gate Bay 6							
Gate Bay 7							
Gate Bay 8							
Gate Bay 9							
Gate Bay 10							
Gate Bay 11							
Gate Bay 12							
Gate Bay 13							
Gate Bay 14							

Table 55: Gatún Spillway Steel Inspection

	Steel Condition	Cracks	Corrosion	Deformation	Skin Plate	Horizontal Girders	End Bearing Assembly	Sill/Seals
Upstream Face of Gate 1								
Upstream Face of Gate 2								
Upstream Face of Gate 3								
Upstream Face of Gate 4								
Upstream Face of Gate 5								
Upstream Face of Gate 6								
Upstream Face of Gate 7								
Upstream Face of Gate 8								
Upstream Face of Gate 9								
Upstream Face of Gate 10								
Upstream Face of Gate 11								
Upstream Face of Gate 12								
Upstream Face of Gate 13								
Upstream Face of Gate 14								

	Steel Condition	**Cracks**	**Corrosion**	**Deformation**	**Skin Plate**	**Horizontal Girders**	**End Bearing Assembly**	**Sill/Seals**
Downstream Face of Gate 1								
Downstream Face of Gate 2								
Downstream Face of Gate 3								
Downstream Face of Gate 4								
Downstream Face of Gate 5								
Downstream Face of Gate 6								
Downstream Face of Gate 7								
Downstream Face of Gate 8								
Downstream Face of Gate 9								
Downstream Face of Gate 10								
Downstream Face of Gate 11								
Downstream Face of Gate 12								
Downstream Face of Gate 13								
Downstream Face of Gate 14								

	Steel Condition	Cracks	Corrosion	Deformation
Pier 1 Castings				
Pier 2 Castings				
Pier 3 Castings				
Pier 4 Castings				
Pier 5 Castings				
Pier 6 Castings				
Pier 7 Castings				
Pier 8 Castings				
Pier 9 Castings				
Pier 10 Castings				
Pier 11 Castings				
Pier 12 Castings				
Pier 13 Castings				

	Steel Condition	Cracks	Corrosion	Deformation
Trash Racks				
Deck Grating Above Trash Racks				
Deck Grating Supporting Structure				
Footbridge Steel Floor Plates				
Footbridge Beam Bracing				

Appendix G: Miraflores Dam and Spillway Inspection Checklist

The first column of this table is used to record the general condition (poor, fair, good, excellent) of each element and the following columns are used to refer the reader to a later portion of the inspection report where detail regarding the damage are located.

Table 56: Miraflores Dam and Spillway Concrete Inspection

	Concrete Condition	**Cracks**	**Seepage**	**Erosion**	**Settlement**	**Relative Movement**	**Drains and Drainage**	**Instrumentation**
Upstream Face								
Downstream Face								
Downstream Toe								
Left Lateral Wall								
Right Lateral Wall								
Spillway Bridge Deck and Framing (Concrete)								
Machinery Tunnel								
Upstream Gallery								
Downstream Gallery								

	Concrete Condition	Cracks	Seepage	Relative Movement	Drains and Drainage	Instrumentation
Counterweight Pit 1						
Counterweight Pit 2						
Counterweight Pit 3						
Counterweight Pit 4						
Counterweight Pit 5						
Counterweight Pit 6						
Counterweight Pit 7						
Counterweight Pit 8						
Counterweight Pit 9						
Counterweight Pit 10						
Counterweight Pit 11						
Counterweight Pit 12						
Counterweight Pit 13						
Counterweight Pit 14						
Counterweight Pit 15						
Counterweight Pit 16						

	Concrete Condition	Cracks	Seepage	Settlement	Relative Movement	Drains and Drainage	Instrumentation
Spillway Pier 1 Upstream Face							
Spillway Pier 1 Downstream Face							
Spillway Pier 2 Upstream Face							
Spillway Pier 2 Downstream Face							
Spillway Pier 3 Upstream Face							
Spillway Pier 3 Downstream Face							
Spillway Pier 4 Upstream Face							
Spillway Pier 4 Downstream Face							
Spillway Pier 5 Upstream Face							
Spillway Pier 5 Downstream Face							
Spillway Pier 6 Upstream Face							
Spillway Pier 6 Downstream Face							
Spillway Pier 7 Upstream Face							
Spillway Pier 7 Downstream Face							

	Concrete Condition	Cracks	Seepage	Settlement	Relative Movement	Drains and Drainage	Instrumentation
Gate Bay 1							
Gate Bay 2							
Gate Bay 3							
Gate Bay 4							
Gate Bay 5							
Gate Bay 6							
Gate Bay 7							
Gate Bay 8							

Table 57: Miraflores Dam and Spillway Steel Inspection

	Steel Condition	**Cracks**	**Corrosion**	**Deformation**	**Skin Plate**	**Horizontal Girders**	**End Bearing Assembly**	**Sill/Seals**
Upstream Face of Gate 1								
Upstream Face of Gate 2								
Upstream Face of Gate 3								
Upstream Face of Gate 4								
Upstream Face of Gate 5								
Upstream Face of Gate 6								
Upstream Face of Gate 7								
Upstream Face of Gate 8								

	Steel Condition	Cracks	Corrosion	Deformation	Skin Plate	Horizontal Girders	End Bearing Assembly	Sill/Seals
Downstream Face of Gate 1								
Downstream Face of Gate 2								
Downstream Face of Gate 3								
Downstream Face of Gate 4								
Downstream Face of Gate 5								
Downstream Face of Gate 6								
Downstream Face of Gate 7								
Downstream Face of Gate 8								

	Steel Condition	Cracks	Corrosion	Deformation
Pier 1 Castings				
Pier 2 Castings				
Pier 3 Castings				
Pier 4 Castings				
Pier 5 Castings				
Pier 6 Castings				
Pier 7 Castings				

	Steel Condition	Cracks	Corrosion	Deformation
Transmission Tower Foundation				
Transmission Tower Castings				
Transmission Tower Structure				
Footbridge Steel Floor Plates				
Footbridge Beam Bracing				

Appendix H: Madden Dam and Spillway Inspection Checklist

The first column of this table is used to record the general condition (poor, fair, good, excellent) of each element and the following columns are used to refer the reader to a later portion of the inspection report where detail regarding the damage are located.

Table 58: Madden Dam and Spillway Concrete Inspection

	Concrete Condition	**Cracks**	**Seepage**	**Erosion**	**Settlement**	**Relative Movement**	**Drains and Drainage**	**Instrumentation**
Upstream Face								
Downstream Face								
Downstream Toe								
Left Lateral Wall								
Right Lateral Wall								
Left Abutment								
Right Abutment								
Left Concrete Dam								
Right Concrete Dam								
Bridge over Spillway								
Needle Valve Slab Discharge Area								
Drum Gate Gallery								
Drum Gate 1 Operating Chamber								
Drum Gate 2 Operating Chamber								
Drum Gate 3 Operating Chamber								

	Concrete Condition	**Cracks**	**Seepage**	**Erosion**	**Settlement**	**Relative Movement**	**Drains and Drainage**	**Instrumentation**
Drum Gate 4 Operating Chamber								
Sluice Gate Gallery								
Sluice Gate 1 & 2 Operating Chamber								
Sluice Gate 3 & 4 Operating Chamber								
Sluice Gate 5 & 6 Operating Chamber								
Needle Valve Gallery								
Needle Valve Operating Chamber								
Cross-cut Galleries								
Cable Tunnel								
Freight Shaft								

	Concrete Condition	Cracks	Seepage	Settlement	Relative Movement	Drains and Drainage	Instrumentation
Spillway Pier 1 Upstream Face							
Spillway Pier 1 Downstream Face							
Spillway Pier 2 Upstream Face							
Spillway Pier 2 Downstream Face							
Spillway Pier 3 Upstream Face							
Spillway Pier 3 Downstream Face							

	Concrete Condition	Cracks	Seepage	Settlement	Relative Movement	Drains and Drainage	Instrumentation
Float Well 1							
Float Well 2							
Float Well 3							
Float Well 4							

	Concrete Condition	**Cracks**	**Seepage**	**Settlement**	**Relative Movement**	**Drains and Drainage**	**Instrumentation**
Sluice Outlet 1							
Sluice Outlet 2							
Sluice Outlet 3							
Sluice Outlet 4							
Sluice Outlet 5							
Sluice Outlet 6							

Table 59: Madden Dam and Spillway Steel Inspection

	Steel Condition	Cracks	Corrosion	Deformation	Skin Plate	Reinforcing Beams	End Bearing Assembly	Seals
Interior Face of Gate 1								
Interior Face of Gate 2								
Interior Face of Gate 3								
Interior Face of Gate 4								
Exterior Face of Gate 1								
Exterior Face of Gate 2								
Exterior Face of Gate 3								
Exterior Face of Gate 4								

	Steel Condition	Cracks	Corrosion	Deformation
Gate 1 Hinges				
Gate 2 Hinge Coverings				
Gate 2 Hinges				
Gate 2 Hinge Coverings				
Gate 3 Hinges				
Gate 3 Hinge Coverings				
Gate 4 Hinges				
Gate 4 Hinge Coverings				

	Steel Condition	**Cracks**	**Corrosion**	**Deformation**	**Skin Plate**	**Horizontal Girders**	**End Bearing Assembly**	**Seals**
Service Sluice Gate 1 Upstream Face								
Service Sluice Gate 2 Upstream Face								
Service Sluice Gate 3 Upstream Face								
Service Sluice Gate 4 Upstream Face								
Service Sluice Gate 5 Upstream Face								
Service Sluice Gate 6 Upstream Face								

	Steel Condition	**Cracks**	**Corrosion**	**Deformation**	**Skin Plate**	**Horizontal Girders**	**End Bearing Assembly**	**Seals**
Service Sluice Gate 1 Downstream Face								
Service Sluice Gate 2 Downstream Face								
Service Sluice Gate 3 Downstream Face								
Service Sluice Gate 4 Downstream Face								
Service Sluice Gate 5 Downstream Face								
Service Sluice Gate 6 Downstream Face								

	Steel Condition	Cracks	Corrosion	Deformation	Skin Plate	Horizontal Girders	End Bearing Assembly	Seals
Emergency Sluice Gate 1 Upstream Face								
Emergency Sluice Gate 2 Upstream Face								
Emergency Sluice Gate 3 Upstream Face								
Emergency Sluice Gate 4 Upstream Face								
Emergency Sluice Gate 5 Upstream Face								
Emergency Sluice Gate 6 Upstream Face								

	Steel Condition	Cracks	Corrosion	Deformation	Skin Plate	Horizontal Girders	End Bearing Assembly	Seals
Emergency Sluice Gate 1 Downstream Face								
Emergency Sluice Gate 2 Downstream Face								
Emergency Sluice Gate 3 Downstream Face								
Emergency Sluice Gate 4 Downstream Face								
Emergency Sluice Gate 5 Downstream Face								
Emergency Sluice Gate 6 Downstream Face								

	Steel Condition	**Cracks**	**Corrosion**	**Deformation**
Sluice Gate Framework				
Stairs				
Generation Building Roof				
Transformer Deck				
Sluice Gate Outlet Trash Rack Structure				
Power and Outlet Trash Rack Structure				

Appendix I: Inspection Report Suggested Outline

This outline was adapted from the Indiana Department of Natural Resources' *Indiana Dam Safety Inspection Manual* and the Center for Advanced Technology for Large Structural Systems' *Structural Evaluation of Riveted Spillway Gates* for the Autoridad del Canal de Panamá.

I. **Heading/Title Sheet**
   a. Name of dam or spillway
   b. Date of inspection
   c. Responsible inspector

II. **Table of Contents**

III. **Executive Summary**
   a. Name of dam or spillway
   b. Date of inspection
   c. Inspection team
   d. General condition of structure

IV. **Background Information**
   a. Availability of design and "as built" plans
   b. Past modifications
   c. Operational records
   d. Incidents or equipment failures
   e. Historical events impacting structure (ex. floods)

V. **Project Information**
   a. Purpose of dam
   b. Current site conditions
   c. Current geologic conditions
   d. Seismic activity
   e. Description of structural features including relevant data
   f. Current status of past suggested repair/replacements

VI. **List of all data reviewed and organizations contacted during review stage**

VII. **Structural Safety Inspection**
   a. Checklists of items inspected
   b. Condition of each item inspected
      i. Assessment of condition
      ii. Is the condition major or minor?
      iii. Description of damage
      iv. Condition of surrounding elements
      v. Possible cause/source of damage
      vi. Effect of damage on performance of the element

VIII. **Conclusions**
   a. Overall evaluation of the structure
      i. Condition of structure
      ii. Ability to perform as designed
      iii. Structural integrity
   b. Determination of risk of failure

i. Considering the condition of the elements, what is the possibility that the structure will fail?
ii. Risk of each component failure
iii. Risk of failure due to external factors
    1. Flooding
    2. Seismic Activity
    3. Etc.

IX. Recommendations

a. Recommended maintenance, repairs, and alterations
b. Recommended additional studies or investigations

X. Appendices

a. Extra pictures taken during the inspection with descriptive captions
b. Engineering plans of the dam
c. Other calculations done to ensure stability of structure

Appendix J: Madden Spillway Drum Gate Maintenance Log

Table 60: Madden Spillway Drum Gate Maintenance Log

Legend: Seals indicated in pink, Interior Framing indicated in orange, Skin Plates and Cylinder Heads indicated in green, Hinges indicated in yellow

Year	Gate 1		Gate 2		Gate 3		Gate 4	
	Finding	Recommendation/ Immediate Action	Finding	Recommendation/ Immediate Action	Finding	Recommendation/ Immediate Action	Finding	Recommendation/ Immediate Action
1982								
1988								
1989							Leak into Drum Gate No. 4, no visible damage or distortion along the length of the outside	Recommend an inspection when the lake level is low
							Broken seal weld at the bottom of the drum gate tip	Length of distortion drum gate tip removed and replaced w/ a new tip section and re-welded
							Cracked upstream end seal plate on side of the drum gate	Remove and replace w/ a new section of upstream end seal plate
								All repaired areas repainted and drum gate pressure tested
1990	Seal of Drum Gate not working properly; leaks of water through seals increased	Materials and specifications of the seals should be revised by ECEG before future purchases	Seal of Drum Gate not working properly; leaks of water through seals increased	Materials and specifications of the seals should be revised by ECEG before future purchases	Seal of Drum Gate not working properly; leaks of water through seals increased	Materials and specifications of the seals should be revised by ECEG before future purchases	Seal of Drum Gate not working properly; leaks of water through seals increased	Materials and specifications of the seals should be revised by ECEG before future purchases
1992	Seals of Drum Gate not working properly	Materials and specifications of the seals should be revised by ECEG before future purchases	Seals of Drum Gate not working properly	Materials and specifications of the seals should be revised by ECEG before future purchases	Seals of Drum Gate not working properly	Materials and specifications of the seals should be revised by ECEG before future purchases	Seals of Drum Gate not working properly	Materials and specifications of the seals should be revised by ECEG before future purchases
		Seals of Drum Gate No. 1 are scheduled to be replaced in 1993		Seals of Drum Gate No. 2 are scheduled to be replaced in 1994		Seals of Drum Gate No. 3 are scheduled to be replaced in 1995		
1993-1994		The exterior of Drum Gate No. 1 was painted in 1994 under Contract No. CC-3-008		The exterior of Drum Gate No. 2 was painted in 1994 under Contract No. CC-3-088				

		Lateral and back seals of Drum Gate No. 1 have been replaced by Industrial Division		Lateral and back seals of Drum Gate No. 2 have been replaced by Industrial Division				
1995-1996	Superficial rust detected at the corner of the bottom and downstream plates, the upstream plate, the south end plate stiffeners and some rivets of the interior of Drum Gate No. 1	Clean and paint 2 feet either side along the bottom and downstream plate connection including the girders and the end plates stiffeners bottom plate connection	Drum Gate No. 2 interior not inspected, expected to be in the same condition as Gate No. 1					
		A drain hose one inch diameter at all end plates stiffeners to a side of the web connected to the bottom plate is recommended for water drainage	Two hair width cracks in the downstream face skin plates run vertically along the edges of the plate butt welds on Drum Gate No. 2; First crack about 200 mm long, located 7 m from the north side seals; Second crack about 750 mm long, located 10 m from the north side seals	Industrial Division marks cracks with paint to monitor if they grow in length; Recommend ultrasonic or X-ray inspection of the affected areas to determine the depth of the cracks and the correction needed				
1997-1998					The exterior of the downstream face of Drum Gate No. 3 presents rust		The exterior of the downstream face of Drum Gate No. 4 presents rust	
2000	Considerable water leak observed at the side seals of the Drum Gates	Replace the side seals of the Drum Gates in the next maintenance	Considerable water leak observed at the side seals of the Drum Gates	Replace the side seals of the Drum Gates in the next maintenance	Considerable water leak observed at the side seals of the Drum Gates	Replace the side seals of the Drum Gates in the next maintenance	Considerable water leak observed at the side seals of the Drum Gates	Replace the side seals of the Drum Gates in the next maintenance
					The exterior of the downstream face of Drum Gate No. 3 presents rust	Schedule full maintenance of paint on Drum Gate No. 3	The exterior of the downstream face of Drum Gate No. 4 presents rust	Schedule full maintenance of paint on Drum Gate No. 4
2001	Considerable water leak observed at the side seals of the Drum Gates	Check and adjust or replace all seals of the Drum Gates in the next maintenance	Considerable water leak observed at the side seals of the Drum Gates	Check and adjust or replace all seals of the Drum Gates in the next maintenance	Considerable water leak observed at the side seals of the Drum Gates	Check and adjust or replace all seals of the Drum Gates in the next maintenance	Considerable water leak observed at the side seals of the Drum Gates	Check and adjust or replace all seals of the Drum Gates in the next maintenance
		Repair or replace any area or bolt having corrosion		Repair or replace any area or bolt having corrosion		Repair or replace any area or bolt having corrosion		Repair or replace any area or bolt having corrosion

	Drum Gate No. 1 out of service due to leaks in drainage hose, use only in case of emergency	More detailed inspection scheduled for next dry season to find and repair damage or cracks in the drainage hose	Drum Gate No. 2 out of service due to leaks in drainage hose, use only in case of emergency	More detailed inspection scheduled for next dry season to find and repair damage or cracks in the drainage hose		Investigate the cause of the tears of the downstream face of Drum Gate No. 3		Investigate the cause of the tears of the downstream face of Drum Gate No. 4
		Buy several spare joints and hose drains for the Drum Gates		Buy several spare joints and hose drains for the Drum Gates		Buy several spare joints and hose drains for the Drum Gates		Buy several spare joints and hose drains for the Drum Gates
2002	Considerable water leak observed at the side and bottom seals of all Drum Gates	Check and adjust or replace all seals of the Drum Gates in the next maintenance	Considerable water leak observed at the side and bottom seals of all Drum Gates	Check and adjust or replace all seals of the Drum Gates in the next maintenance	Considerable water leak observed at the side and bottom seals of all Drum Gates	Check and adjust or replace all seals of the Drum Gates in the next maintenance	Considerable water leak observed at the side and bottom seals of all Drum Gates	Check and adjust or replace all seals of the Drum Gates in the next maintenance
		Buy or maintain an inventory of a least two replacement hoses and joints for the Drum Gates		Buy or maintain an inventory of a least two replacement hoses and joints for the Drum Gates		Buy or maintain an inventory of a least two replacement hoses and joints for the Drum Gates		Buy or maintain an inventory of a least two replacement hoses and joints for the Drum Gates
			Drum Gate No. 2 has visible damage to the paint on the downstream side		Larger leaks in the side and top seals of Drum Gate No. 3		Larger leaks in the side seal of Drum Gate No. 4	
					Drum Gate No. 3 presents rust stains on the downstream face		Drum Gate No. 4 presents rust stains on the downstream face	
2003	All metal surfaces of all Drum Gates show signs of corrosion	Must be painted	All metal surfaces of all Drum Gates show signs of corrosion	Must be painted	All metal surfaces of all Drum Gates show signs of corrosion	Must be painted	All metal surfaces of all Drum Gates show signs of corrosion	Must be painted
	Water leaks observed on the sides and bottom seals of all the Drum Gates	Check and adjust or replace the side seals of the Drum Gates	Water leaks observed on the sides and bottom seals of all the Drum Gates	Check and adjust or replace the side seals of the Drum Gates	Water leaks observed on the sides and bottom seals of all the Drum Gates	Check and adjust or replace the side seals of the Drum Gates	Water leaks observed on the sides and bottom seals of all the Drum Gates	Check and adjust or replace the side seals of the Drum Gates
		Repair seating surfaces of the side seals of the Drum Gates		Repair seating surfaces of the side seals of the Drum Gates		Repair seating surfaces of the side seals of the Drum Gates		Repair seating surfaces of the side seals of the Drum Gates
	The hinges of the Drum Gates show severe corrosion	Repair the hinges of the Drum Gates	The hinges of the Drum Gates show severe corrosion	Repair the hinges of the Drum Gates	The hinges of the Drum Gates show severe corrosion	Repair the hinges of the Drum Gates	The hinges of the Drum Gates show severe corrosion	Repair the hinges of the Drum Gates
2004	Noted that the work recommended from the 2003 visual inspection of the inner galleries of the dam was not completed		Noted that the work recommended from the 2003 visual inspection of the inner galleries of the dam was not completed		Noted that the work recommended from the 2003 visual inspection of the inner galleries of the dam was not completed		Noted that the work recommended from the 2003 visual inspection of the inner galleries of the dam was not completed	

	All metal surfaces of all Drum Gates show signs of corrosion	Repair or replace any area of metal, structural steel member, and any bolt or nut that is corroded	All metal surfaces of all Drum Gates show signs of corrosion	Repair or replace any area of metal, structural steel member, and any bolt or nut that is corroded	All metal surfaces of all Drum Gates show signs of corrosion	Repair or replace any area of metal, structural steel member, and any bolt or nut that is corroded	All metal surfaces of all Drum Gates show signs of corrosion	Repair or replace any area of metal, structural steel member, and any bolt or nut that is corroded
	Water leaks observed on the sides and bottom seals of all the Drum Gates	Check, adjust, or replace the side seal (upper and lower) of the Drum Gates	Water leaks observed on the sides and bottom seals of all the Drum Gates	Check, adjust, or replace the side seal (upper and lower) of the Drum Gates	Water leaks observed on the sides and bottom seals of all the Drum Gates	Check, adjust, or replace the side seal (upper and lower) of the Drum Gates	Water leaks observed on the sides and bottom seals of all the Drum Gates	Check, adjust, or replace the side seal (upper and lower) of the Drum Gates
		Repair seating surfaces of the side seals (upper and lower) of the Drum Gates		Repair seating surfaces of the side seals (upper and lower) of the Drum Gates		Repair seating surfaces of the side seals (upper and lower) of the Drum Gates		Repair seating surfaces of the side seals (upper and lower) of the Drum Gates
	The hinges of the Drum Gates show severe corrosion		The hinges of the Drum Gates show severe corrosion		The hinges of the Drum Gates show severe corrosion	Abrasive blasting pressure cleaning of the hinges in Drum Gate No. 3	The hinges of the Drum Gates show severe corrosion	Abrasive blasting pressure cleaning of the hinges in Drum Gate No. 4
						Manufacturing pins and repairing hinge casings, plus the gate seat seals of Drum Gate No. 3		Manufacturing pins and repairing hinge casings, plus the gate seat seals of Drum Gate No. 4
						There was boring of two middle hinges Nos. 7 and 9 of Drum Gate No. 3		
						The middle hinges Nos. 2, 5, 11, 13, 14, 21, 23, 26, and 38 of Drum Gate No. 3 were bored during this contract; Middle hinge No. 40 was bored during a previous contract		
						The middle hinges Nos. 14, 21, 26, and 29 of Drum Gate No. 3 had pins installed; Middle hinge No, 40 had a pin installed in a previous contract		
2005	The hinges of the Drum Gates show severe corrosion	Replaced the pins in the hinges for Drum Gate No. 1	The hinges of the Drum Gates show severe corrosion	Replaced the pins in the hinges for Drum Gate No. 2	The gate seal seat assembly was removed and the nuts and bolts had to be torched off because of the amount of corrosion	The casting where the seal seat assembly goes was cleaned and painted because of all the rust	The gate seal seat assembly was removed and the nuts and bolts had to be torched off because of the amount of corrosion	The casting where the seal seat assembly goes was cleaned and painted because of all the rust

		Thorough cleaning of the hinge area was done before placing the guards, then they were painted and finished in gray		Thorough cleaning of the hinge area was done before placing the guards, then they were painted and finished in gray		A new seal seat assembly was install and adjusted with clamps and new screws		A new seal seat assembly was installed and adjusted with clamps and new screws
		The lower side seals were checked and oiled		The lower side seals were checked and oiled		The lower side seals were checked and oiled		The lower side seals were checked and oiled
		The upper side seals were removed and replaced with new seals; the area was cleaned and painted before installation		The upper side seal were removed and replaced with new seals; the area was cleaned and painted before installation		Horizontal bronze seals on the downstream side had been removed to be replaced with new ones		The Drum Gate hose was removed and air tested to check for damage, then reinstalled
		The bronze cover seals and side seals of both ends of the upstream side of Drum Gate No. 1 were removed and replaced with new ones		The bronze cover seals and side seal of both ends of the upstream side of Drum Gate No. 2 were removed and replaced with new ones		The top of the casting anchor of these seal had been cleaned and painted with a green paint and their thread holes were cleaned and verified		
		The Drum Gate hose was removed and air tested to check for damage, then reinstalled		The Drum Gate hose was removed and air tested to check for damage, then reinstalled		The Drum Gate hose was removed and air tested to check for damage, then reinstalled		
	The areas of the upper surface of Drum Gate No. 1 were corroded	The upper plates were removed and painted and the handles were replaced with ones of a larger diameter	The areas of the upper surface of Drum Gate No. 2 were corroded	The upper plates were removed and painted and the handles were replaced with ones of a larger diameter		The pool was dried to clean and paint the inner and lower sides of the casting		
		Drum Gate No. 1 was pressure tested at 2 psi for 4 hours on the inside of the gate		Drum Gate No. 2 was pressure tested at 2 psi for 4 hours on the inside of the gate				
	The steel side plates for contact with the upstream side seal of both ends of Drum Gate No. 1 were in rough condition	Maintenance is limited to cleaning and grease	The steel side plates for contact with the upstream side seal of both ends of Drum Gate No. 2 were in rough condition	Maintenance is limited to cleaning and grease				
		Recommended to touch up the paint at the end of maintenance work		Recommended to touch up the paint at the end of maintenance work				
2006		Security guards are removed, painted, and reinstalled		Security guards are removed, painted, and reinstalled		Hydrostatic test of the drain hose in Drum Gate No. 3		Hydrostatic test of the drain hose in Drum Gate No. 4
		The side seals are replaced and the area of the seals are painted		The side seals are replaced and the area of the seals are painted		Purchase and installation of upstream and downstream seals for Drum Gate No. 3		Purchase and installation of upstream and downstream seals for Drum Gate No. 4

		The seat seal assembly is modified by installing a screen on its inner side along the length (100 ft) to reduce water leakage in between the seals and the area of the seat assembly is painted		The seat seal assembly is modified by installing a screen on its inner side along the length (100 ft) to reduce water leakage in between the seals and the area of the seat assembly is painted	Several corrosion points across the bottom plate of the gate and a high degree of chalking paint			
		Replacement of 100 ft of the rubber seat seal and vulcanization of a stretch of 25 ft above measure to compensate for wear on the casting on the north side; the area of the rubber seal is painted		Replacement of 100 ft of the rubber seat seal and vulcanization of a stretch of 25 ft above measure to compensate for wear on the casting on the north side; the area of the rubber seal is painted				
	Sections of downstream seals are in poor condition	The sections are replaced and the seal area is painted	Sections of downstream seals are in poor condition	The sections are replaced and the seal area is painted				
		The drain hoses are removed and hydrostatic tested, and vulcanization of their coupling terminals occurs		The drain hoses are removed and hydrostatic tested, and vulcanization of their coupling terminals occurs				
	The bottom bronze seals showed thinning of the contact area that ended in fracture and were removed	Recommended laboratory analysis of the material for more clues about the cause of the problem	The bottom bronze seals showed thinning of the contact area that ended in fracture and were removed	Recommended laboratory analysis of the material for more clues about the cause of the problem				
		The new seal elements have holes that show the position of the transverse cuts that are planned on being made		The new seal elements have holes that show the position of the transverse cuts that are planned on being made				
	The bottom seat seal is fully painted with gray paint, but some surface roughening is observed, indicating corrosion		The bottom seat seal on the downstream side of the Gate No. 2 was completely devoid of paint, corroded and offers a very uneven surface	The surface of the seat is to be lowered to become parallel and aligned and a stainless steel plate is attached with screw, covered in protective coating				

	The top rubber seal has some little deformation, leading to some sections having no contact with the seat		The area of the downstream face of the gate was generally well painted except a one square foot area in its lower left corner where the paint had fallen and revealed the bare metal surface corrosion					
2007		Operational tests of the four drum gates was performed without spilling water		Operational tests of the four drum gates was performed without spilling water		Operational tests of the four drum gates was performed without spilling water		Operational tests of the four drum gates was performed without spilling water
		Calibration of the inclinometers that are installed on each gate		Calibration of the inclinometers that are installed on each gate		Calibration of the inclinometers that are installed on each gate		Calibration of the inclinometers that are installed on each gate
		The drain hoses were replaced		The drain hoses were replaced		The drain hoses were replaced		The drain hoses were replaced
		In all drum gates the lower side seals were changed, including refurbishment of the guards, plates and certain damaged pins		In all drum gates the lower side seals were changed, including refurbishment of the guards, plates and certain damaged pins		In all drum gates the lower side seals were changed, including refurbishment of the guards, plates and certain damaged pins		In all drum gates the lower side seals were changed, including refurbishment of the guards, plates and certain damaged pins
	Leaks in the gate seat seal assembly	Extensions to the ends of the gate seat seal assembly were placed to correct the leaks	Leaks in the gate seat seal assembly	Extensions to the ends of the gate seat seal assembly were placed to correct the leaks	Leaks in the gate seat seal assembly	The gate seat seal assembly was completely replaced	Leaks in the gate seat seal assembly	The gate seat seal assembly was completely replaced
		The rubber seat seal was changed and placed entirely with countersink stainless screws		The rubber seat seal was changed and placed entirely with countersink stainless screws		The rubber seat seal was changed and placed with hexagonal screws and combined countersink iron grade 5		The rubber seat seal was changed and placed with hexagonal screws and combined countersink iron grade 5
		Recommended replacement of gate casting seat seal and gate seat casting rubber stop and gate end seals		Recommended replacement of gate casting seat seal and gate seat casting rubber stop and gate end seals	The lower filler seals were worn and caused leaks	They were removed and the wear was corrected and then they were reinstalled	The lower filler seals were worn and caused leaks	They were removed and the wear was corrected and then they were reinstalled
	Corrosion observed in the structural side extensions of the ends of the gates and the mounting surfaces of the structural member where they install the end seals		Corrosion observed in the structural side extensions of the ends of the gates and the mounting surfaces of the structural member where they install the end seals					
	The lower filler seals were worn and caused leaks	They were removed and the wear was corrected and then they were reinstalled						

2009	Slight leakage of water in the bottom and side seals of the 4 drum gates		Slight leakage of water in the bottom and side seals of the 4 drum gates		Slight leakage of water in the bottom and side seals of the 4 drum gates		Slight leakage of water in the bottom and side seals of the 4 drum gates	
		Cleaning and touch-up of paint of the outside of the drum gate No. 1 in the most damaged areas		Cleaning and touch-up of paint of the outside of the drum gate No. 2 in the most damaged areas	The side channel has no paint and advanced deterioration from the effects of corrosion	The channel could only be cleaned and painted inside due to the lack of access to the outer side facing the concrete wall of the pool		New seal were installed on the channels in the downstream part
					A hole approximately 2" in the core/web of the exterior channel of the south end, located adjacent to the support fixing it to the side of the hinge casting	Strengthening of channel section by installing a plate 1/4" minimum protruding 25 mm from the periphery of the hole with fillet weld 5 mm around the plate	Old paint and corrosion crusts could be observed below the new paint on the inner and outer channels	
					20-30% of the rivets in the channel and south end support have at least 75-80% affectation in their heads	Recommended to repair damaged heads by welding		
					The cylinder head plate at the south end presented corrosion of up to 3/8" to 1/4" of the form, estimated loss of thickness close to 50%	Concentrate efforts to clean and paint the cylinder heads at both ends of the caisson No. 3. Because of the loss of surface hardness of the metal it is not recommended to use harsh abrasive tools or pressure jet, so tools with less impact on the metal should be used, which can produce a roughness in the metal to improve paint adhesion		
					At the top of the cylinder had plates had been cleaned to remove all traces of rust and loose paint revealing 40% of the area with undercuts of up to 1/8" deep			
					At the top of the cylinder head plate on that side, bites/stings about 1 ½" in diameter and 120 to 180 mils depth was observed			
					At the bottom of the cylinder plate on the south end multiple tubers were observed			
					Cylinder head plate at the north end had a thickness loss of up to 1/8"			

					The angles of the triangular supports of the south end channel are affected by corrosion	After structural repairs, clean and paint the channels, brackets, cylinder heads, and other surfaces that have been left unpainted		
					No holes in the core/web of the channel but losses of thicknesses of up to 50% in both the core/web and the lower wing of the channel at the north end with the greatest losses in the section near the hinge channel	The channel that connects with the cylinder head at the top upstream at the north end was fully painted		
					Corrosion of the rivet heads worn by 30-60%, several of them totally absent	Heads of rivets marked in the north end cylinder head channel recommended to be repaired with welding		
					The rivet heads and top hardware of the drum inlet were corroded	They were retouched with paint but maintenance was limited to the bottom where scaffolding had access		
					The channels that support the side seal and their supports at the end of the gate have affectations of corrosion, observed tubers, blistering, laminations of rust and pitting that measure from 70 to 120 mils deep with amplitude up to ¾" diameter in the channels	After structural repairs, clean and paint the channels, brackets, cylinder heads, and other surfaces that have been left unpainted		
					The plate on the downstream side of the gate presents bites/stings measuring from 70-80 mils deep with amplitude up to 3/4" diameter	After structural repairs, clean and paint the channels, brackets, cylinder heads, and other surfaces that have been left unpainted		

					The underside plate of the gate has uncoated areas 3” to 4” diameter, where the coating had been removed previously for plate thickness measurements	After structural repairs, clean and paint the channels, brackets, cylinder heads, and other surfaces that have been left unpainted		
						These structural repairs are considered temporary and aim to extend its life for a year, when the next operation should perform maintenance and replace the channel and damaged rivets with bolts		
						If necessary repair inside the gate, areas where the coating (tar) is removed after structural repair, must touch up affected areas with paint		
2010	Vibrations in the drum gates were observed when they are in a position greater than a height of 251.9 ft, has a frequency of 20 Hz and an amplitude between 5 and 15 cm	Design and schedule the installation of additional flow switches (spoilers starting with the first in 2012	Vibrations in the drum gates were observed when they are in a position greater than a height of 251.9 ft, has a frequency of 20 Hz and an amplitude between 5 and 15 cm	Design and schedule the installation of additional flow switches (spoilers starting with the first in 2012	Vibrations in the drum gates were observed when they are in a position greater than a height of 251.9 ft, has a frequency of 20 Hz and an amplitude between 5 and 15 cm	Design and schedule the installation of additional flow switches (spoilers starting with the first in 2012	Vibrations in the drum gates were observed when they are in a position greater than a height of 251.9 ft, has a frequency of 20 Hz and an amplitude between 5 and 15 cm	Design and schedule the installation of additional flow switches (spoilers starting with the first in 2012
	The drum gates are in deteriorating condition and have various elements that need to be repaired or replaced	Program for replacement/ repair of structural/ mechanical deteriorated drum gate elements	The drum gates are in deteriorating condition and have various elements that need to be repaired or replaced	Program for replacement/ repair of structural/ mechanical deteriorated drum gate elements	The drum gates are in deteriorating condition and have various elements that need to be repaired or replaced	Program for replacement/ repair of structural/ mechanical deteriorated drum gate elements	The drum gates are in deteriorating condition and have various elements that need to be repaired or replaced	Program for replacement/ repair of structural/ mechanical deteriorated drum gate elements
		Until structural repairs and installation of additional spoilers, avoid free flow spilling as much as possible		Until structural repairs and installation of additional spoilers, avoid free flow spilling as much as possible		Until structural repairs and installation of additional spoilers, avoid free flow spilling as much as possible		Until structural repairs and installation of additional spoilers, avoid free flow spilling as much as possible
			The section of plates of the downstream face where two cracks were found along the welds of the plates in 1995 were replaced		Drum gate No. 3 was inspected externally and internally, including the downstream face		Observed signs of corrosion must be repaired on the gate No. 4 to avoid further deterioration	Scheduled weld repair or replacement of plates of the downstream face probably for gate No. 4 and a cleaning job and complete painting of the downstream face for 2012

					Estimated that 30% of the buckle plates are chopped and must be replaced	Recommended to take thickness measurements of all buckle plate 3/8" thick, from the inside of the gate	Measurements verified the poor state of the cylinder heads and channels supporting the side seals	Program replacing of the channels that support the side seals of caisson 4 for 2012
					Buckle plates measured from the outside, in the pool, and determined thickness are close to the nominal thickness of 3/8", except where it is corroded by pitting	Program replacement of the buckle plates presenting loss of 1/8" material scheduled for 2012		Request a quote to run and schedule the project for cleaning and painting caisson 4 to take place in 2013
					Corrosion inside the caisson on the flat face of the gate and along the entire board of the upstream face; an area of about one square meter in each pocket	Schedule a complete cleaning and maintenance paint of the areas affected by corrosion		
					Heavily corroded areas of the downstream side (belly) of the drum gate No. 3 at the north end	Thickness measurements should be made on the downstream plate of the gate and a corrosion expert should inspect to determine whether it is necessary to remove part of the plate or if repair is possible		
						Scheduled weld repair or replacement of plates of the downstream face of the gate No. 3 and a cleaning job and complete painting of the downstream face for 2012		
					Measurements verified the poor state of the cylinder heads and channels supporting the side seals	Program replacing of the channels that support the side seals of caisson 3 for 2012		
						Request a quote to run and schedule the project for cleaning and painting caisson 3 to take place in 2013		

	In the area of the hinges of all caissons sandy sedimentation was noted contaminating all surfaces	Clean with water pressure jet to remove the sediment and minimize the possibility of damage to the bushings of the hinges	In the area of the hinges of all caissons sandy sedimentation was noted contaminating all surfaces	Clean with water pressure jet to remove the sediment and minimize the possibility of damage to the bushings of the hinges	In the area of the hinges of all caissons sandy sedimentation was noted contaminating all surfaces	Clean with water pressure jet to remove the sediment and minimize the possibility of damage to the bushings of the hinges	In the area of the hinges of all caissons sandy sedimentation was noted contaminating all surfaces	Clean with water pressure jet to remove the sediment and minimize the possibility of damage to the bushings of the hinges
	The rivet heads on the upstream face of the gate have corrosion damage	Repair the rivet heads in poor condition and touch up the paint of about 70 rivet heads of the gate	The rivet heads on the upstream face of the gate have corrosion damage	Repair the rivet heads in poor condition and touch up the paint of about 70 rivet heads of the gate	Corrosion was observed on the rivets and there was a presence of living beings (possibly fungi or aquatic life) on the outer surface of the gate	Look for corrosion protection that is more effective for the material of the rivets	The rivet heads on the upstream face of the gate have corrosion damage	Repair the rivet heads in poor condition and touch up the paint of about 70 rivet heads of the gate
2011	A dirty white growth in some parts of the riveted surface, it is easily removable substance that is spongy and crumbly in consistency	A sample of this material was taken and the pH was measured at 5.7, it was sent to the microbiology laboratory	A dirty white growth in some parts of the riveted surface, it is easily removable substance that is spongy and crumbly in consistency	A sample of this material was taken and the pH was measured at 5.7, it was sent to the microbiology laboratory	The downstream face of the gate has increased deterioration, corrosion points in isolated areas with some cracks	A comprehensive study of the damage must be made on the downstream plate of the gate and schedule repairs	Corrosion observed on the downstream face in isolated areas where there were crack 1/8" deep, nominal thickness of the plate is 5/8"	Perform thickness measurements on the downstream plate and determine the need for repair/replacement
					High corrosion of the downstream plate and the sides at both ends and also many of the rivet heads	Repair of the downstream and lateral plates scheduled for 2012	Several heads of the rivets on the downstream face of the gate are deteriorated, on where the head is no there only the hole	Repair the hole and the rivet heads in poor condition before putting the caisson in service
					There was corrosion on the nuts, washers, and bolts that attach the seals to the support beam channel		Some nuts and bolts of the side seals were corroded and unpainted	Clean and paint the screws and rivet heads with corrosion
							Removed nearly 18" of silty sediment accumulated in the pool of the gate No. 4	Sediment samples were removed from the floor of the pool for microbiological analysis
	The top of the gate, viewed from the bridge, seemed satisfactory, except some rivets with corrosion		The top of the gate, viewed from the bridge, seemed satisfactory, except some rivets with corrosion		The top of the gate, viewed from the bridge, seemed satisfactory, except some rivets with corrosion		The top of the gate, viewed from the bridge, seemed satisfactory, except some rivets with corrosion	
2012		Replacement of the upstream and downstream seals		Replacement of the upstream and downstream seals		Replacement of the upstream and downstream seals		Replacement of the upstream and downstream seals
						Repair work of drum gate No. 3 from the recommendation of previous years		

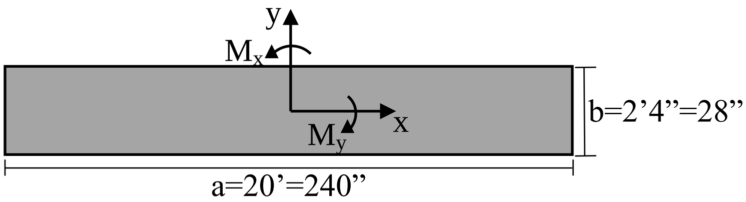
2013			The downstream face of gate No. 2 shows some scratches where corrosion has started		The coating of the gate and assemblages of the hinges is deteriorated by corrosion and tubers		The coating of the gate and assemblages of the hinges is deteriorated by corrosion and tubers	
					The veneer belly of the gate No. 3 showed undercuts of about 3/16" deep		The veneer belly of the gate No. 4 showed undercuts of about 3/16" deep	
					The underside has 10% of its rivet heads with corrosion	Repair of the rivet heads in poor condition and touch up the paint on exposed metal areas		
					The downstream face has scratches where corrosion has started and points of concentrated corrosion with depths of more than half a centimeter			
					The upstream face corroded by almost 50% of the rivet heads with 20% of them fully corroded			
2014	The veneer gray coating of the underside of the gate was found with timely random corrosion in some of the rivet heads of the structure, showing affectation of approximately 5% of the volume of their heads		The veneer gray coating of the underside of the gate was found with timely random corrosion in some of the rivet heads of the structure, showing affectation of approximately 5% of the volume of their heads		The black coating of the underside of the gate was found deteriorated by corrosion and tubers, in approximately 25% of the extension of its surface, mostly on the rivets heads of the structure that show an affectation of approximately 10% of the volume of their heads		The black coating of the underside of the gate was found deteriorated by corrosion and tubers, in approximately 20% of the extension of its surface, mostly on the rivets heads of the structure that show an affectation of approximately 10% of the volume of their heads	
	The veneer gray coating of the upstream side of the gate was found with random full extent corrosion, mainly in the rivet heads of the structure, showing affectation of approximately 5% of the volume of their heads and with different layers of coating exposed		The veneer gray coating of the upstream side of the gate was found with random full extent corrosion, mainly in the rivet heads of the structure, showing affectation of approximately 5% of the volume of their heads and with different layers of coating exposed		The veneer gray coating on the upstream side of the gate was found with random corrosion points in some of the rivet heads of the structure, showing affectation of approximately 5% of the volume of their heads and with a uniform layer of gray coating	Some paint touch ups in the upstream face of the gate were made, mainly in the covers of the hinges and some heads of bolts holding plates to the gate	The veneer gray coating on the upstream side of the gate was found with random corrosion points in some of the rivet heads of the structure, showing affectation of approximately 5% of the volume of their heads and multiple places of exposed primary coating	

	Not a finding, so not sure why this recommendation was made	Remove the existing white metal corrosion, fill with welding and grinding flush with the surface adjacent to the undercuts on the plate on the downstream side and the other sides of the gate if required	Not a finding, so not sure why this recommendation was made	Remove the existing white metal corrosion, fill with welding and grinding flush with the surface adjacent to the undercuts on the plate on the downstream side and the other sides of the gate if required	The sheet on the downstream side of the gate, coated gray, shows undercuts from corrosion of about 1 to 1.5” diameter and 3/16” to ¼” deep in approximately 10% of the extension of its surface, especially at its ends, and streaks of corrosion along most of its length	Remove the existing white metal corrosion, fill with welding and grinding flush with the surface adjacent to the undercuts on the plate on the downstream side and the other sides of the gate if required	The sheet on the downstream side of the gate, coated gray, shows undercuts from corrosion of about 1 to 1.5” diameter and 3/16” to ¼” deep in approximately 10% of the extension of its surface, especially at its ends, and streaks of corrosion along most of its length	Remove the existing white metal corrosion, fill with welding and grinding flush with the surface adjacent to the undercuts on the plate on the downstream side and the other sides of the gate if required
	The gate hinge assemblies were found corroded	Perform cleaning and retouching of paint on corroded areas of the structure and hinge assemblies	The gate hinge assemblies were found corroded	Perform cleaning and retouching of paint on corroded areas of the structure and hinge assemblies	The gate hinge assemblies were found corroded	Perform cleaning and retouching of paint on corroded areas of the structure and hinge assemblies	Universal joints of drain hoses had corrosion on its hardware and its adjacent flanges accessories for incompatibility of materials	Replace all corroded hardware used for coupling flanges of the universal joints at their adjacent accessories
	The elements of the hinge of the damper, bases and shaft are with advanced corrosion throughout. No appreciated evidence to suggest a system malfunction of the hinge gate.		The elements of the hinge of the damper, bases and shaft are with advanced corrosion throughout. No appreciated evidence to suggest a system malfunction of the hinge gate.		The right side seals had been removed; and the outer support channels of the existing right seal of the upstream side of the gate also had been removed	Work began on bending and installation of new sections of support channels of the right seals	Universal joints and flanges found partially painted with a layer of epoxy primer	Perform complete cleaning and painting of the whole body of the universal joints including hardware and coupling flanges and adjacent bodies of all its accessories
	Universal joints of drain hoses had corrosion on its hardware and its adjacent flanges accessories for incompatibility of materials	Replace all corroded hardware used for coupling flanges of the universal joints at their adjacent accessories	Universal joints of drain hoses had corrosion on its hardware and its adjacent flanges accessories for incompatibility of materials	Replace all corroded hardware used for coupling flanges of the universal joints at their adjacent accessories	Universal joints of drain hoses had corrosion on its hardware and its adjacent flanges accessories for incompatibility of materials	Replace all corroded hardware used for coupling flanges of the universal joints at their adjacent accessories	The hinges of the gate, bases, and shaft have corrosion in its entirety	Thorough cleaning and inspection of components (shafts and bearings base plates) to decide its replacement if necessary
		Perform complete cleaning and painting of the whole body of the universal joints including hardware and coupling flanges and adjacent bodies of all its accessories		Perform complete cleaning and painting of the whole body of the universal joints including hardware and coupling flanges and adjacent bodies of all its accessories		Perform complete cleaning and painting of the whole body of the universal joints including hardware and coupling flanges and adjacent bodies of all its accessories		Project for thorough cleaning and complete painting of the inside and outside body of the structure and assemblies hinges, foundries and covers hinges, foundries seat, foundries covers-seals of the side seals and any other accessory that requires, in FY 2017

		Project for thorough cleaning and complete painting of the inside and outside body of the structure and assemblies hinges, foundries and covers hinges, foundries seat, foundries covers-seals of the side seals and any other accessory that requires, in FY 2018		Project for thorough cleaning and complete painting of the inside and outside body of the structure and assemblies hinges, foundries and covers hinges, foundries seat, foundries covers-seals of the side seals and any other accessory that requires, in FY 2018		Project for thorough cleaning and complete painting of the inside and outside body of the structure and assemblies hinges, foundries and covers hinges, foundries seat, foundries covers-seals of the side seals and any other accessory that requires, in FY 2017		
			Measured dry film thickness of the existing coating on the underside, obtaining 61.39 mils average thickness, maximum thickness 79.6 mils and minimum thickness 40 mils		The horizontal seals "Gate Seat Seal" are between 70% to 80% regularly, so they stay and are not replaced this time			
					Seals side guards on the right side are 100%, as they are newly installed and painted			
					Surface corrosion of the tops of the accesses that are in the upstream face of the gate	Clean with power tool and paint the exposed metal lids and the tops of hardware side seals, as well as covers of entrances		
					Corrosion deterioration in the wings and the core/web of the upstream side seal support (channel), the right side of the gate	Replace the support (channel) on the right side door seal.		
2015		Replacement of the pins and castings at the ends of the caissons 1 and 2 through the services of an outside contractor		Replacement of the pins and castings at the ends of the caissons 1 and 2 through the services of an outside contractor	Opened and inspected internally, as the outer surfaces have a coating in very poor condition		Opened and inspected internally, as the outer surfaces have a coating in very poor condition	

					Inside the gate, significant areas with mostly light corrosion along the board edge, at the bottom of the structural frames in the bottom corner and the belly of the gate		Inside the gate, significant areas with mostly light corrosion along the board edge, at the bottom of the structural frames in the bottom corner and the belly of the gate	
					Garbage and waste material of all kinds such as newspapers, plastic lenses, cables, rags, and a bag of used screws were found	Reported verbally to the onsite supervisor to have it corrected immediately	Garbage and waste material of all kinds such as newspapers, plastic lenses, cables, rags, and a bag of used screws were found	Reported verbally to the onsite supervisor to have it corrected immediately
					An existing lighting system inside the gate was abandoned and deteriorated and apparently not working	For security reasons it must be removed	An existing lighting system inside the gate was abandoned and deteriorated and apparently not working	
					The outer covering of the body and cylinder heads were found in a very deteriorated condition	Require maintenance of its outer coating on the bottom, back, belly, and cylinder heads	The outer covering of the body and cylinder heads were found in a very deteriorated condition	
						Cleaning and touch up of paint in the areas affected by corrosion of the plates and rivets on the outside of the gate		Cleaning and touch up of paint in the areas affected by corrosion of the plates and rivets on the outside of the gate
						"Hot" spot repairs in the most critical parts of the belly of the gate No. 3		Replace the south end channels of the gate No. 4
					The metal substrate steel 3/8" thick buckle plates of the cylinder heads found significantly affected by corrosion	Measurements taken in the undercuts of the buckle plates showed values between 0.100" to 0.120" on the left side and between 0.070" and 0.120" on the right	The metal substrate steel 3/8" thick buckle plates of the cylinder heads found significantly affected by corrosion	Measurements taken in the undercuts of the buckle plates showed values between 0.100" to 0.150" on the left side and between 0.100" and 0.230" on the right
						Outside of cylinder head depth testing of critical points was performed, found max value of 0.180"		Outside of cylinder head depth testing of critical points was performed, found max value of 0.210"

Appendix K: Bottom and Upstream Skin Plate Calculations



$$\sigma = \frac{M}{Z}$$

Bottom Skin Plate

Using *Table 56* from *Theory of Plates and Shells*

$$\frac{b}{a} = \frac{28"}{240"} = 0.117 => \ \delta = 0.0833$$

$$q = \gamma_w h = (62.4\, pcf) * (23.23') = 1449.552\, psf\ = 10.066\, psi$$

$$M\ = \delta q a b^2\ = 0.0833 * (10.066\, psi) * (240") * (28")^2\ = 157771.746\ lb - in$$

$$= 157.77 k - in$$

$$Z = \frac{at^2}{6} = \frac{(240")*(5/8\ ")^2}{6} = 15.625\ in^3$$

$$\sigma = \frac{M}{Z} = \frac{157.77\ k - in}{15.625\ in^3} = \mathbf{10.10\ ksi}$$

Upstream Skin Plate

Using *Table 14* from *Theory of Plates and Shells*

$$\frac{a}{b} = \frac{240"}{28"} = 8.57 => \ \beta_1 = 0.0937$$

$$q = \gamma_w h = (62.4\, pcf) * (19.52') = 1218.048\, psf\ = 8.46\, psi$$

$$M\ = \beta_1 q a b^2\ = 0.0937 * (8.46\, psi) * (240") * (28")^2\ = 149154.808\ lb - in$$

$$= 149.15\ k - in$$

$$Z = \frac{at^2}{6} = \frac{(240")*(1/2\ ")^2}{6} = 10\ in^3$$

$$\sigma = \frac{M}{Z} = \frac{149.15\ k - in}{10\ in^3} = \mathbf{14.91\ ksi}$$

Allowable Stress on Both Plates

$$\sigma_{allow} = 0.6F_y$$

$$\sigma_{allow} = 0.6 * (33\ ksi) = \mathbf{19.8\ ksi}$$

Critical Thickness of the Bottom Skin Plate

$$\sigma_{allow} = \frac{6\delta q b^2}{t^2}$$

$$t = \sqrt{\frac{6\delta q b^2}{\sigma_{allow}}} = \sqrt{\frac{6 * 0.0833 * (10.066\ psi) * (28")^2}{19800\ psi}} = \mathbf{0.446\ in} \approx \mathbf{\frac{4}{9}\ in}$$

$$\frac{0.625 - 0.446}{0.625} * 100\% = \mathbf{28.64}\%\ \mathbf{section\ loss}$$

Critical Thickness of the Upstream Skin Plate

$$\sigma_{allow} = \frac{6\beta_1 q b^2}{t^2}$$

$$t = \sqrt{\frac{6\beta_1 q b^2}{\sigma_{allow}}} = \sqrt{\frac{6 * 0.0937 * (8.46\ psi) * (28")^2}{19800\ psi}} = \mathbf{0.434\ in} \approx \mathbf{\frac{3}{7}\ in}$$

$$\frac{0.5 - 0.434}{0.5} * 100\% = \mathbf{13.2}\%\ \mathbf{section\ loss}$$