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SALT INTRUSION IN GATUN LAKE

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1. Gatun Lake
2. Salt Intrusion
3. Panama Canal

Abstract

The expansion of the Panama Canal is adding another lock lane to the canal, allowing passage of larger ships. Increases in the number of transits and the size of the locks may displace more salt from the oceans into the freshwater lake, Gatun Lake, which is a drinking water source for Panama City. This project evaluated future salinity levels in Gatun Lake. Water quality and hydrometeorological data were input into a predictive hydrodynamic software package to project salinity levels in the lake after the new lock system is completed. Modeling results showed that salinity levels are expected to remain in the freshwater range. In the event that the lake becomes brackish, the team designed a water treatment plant using electrodialysis reversal for salt removal and UV light disinfection.

Executive Summary

The Panama Canal runs from the Pacific Ocean in the southeast to the Atlantic Ocean in the northwest over a watershed area containing the freshwater lake, Gatun Lake. The canal facilitates the transit of 36 ships daily using three sets of locks, which displace large volumes of water into and out of Gatun Lake. The displacement of water has the potential to cause salt intrusion into the freshwater Gatun Lake. The ACP is currently expanding the Panama Canal by constructing a new series of locks, Post-Panamax locks, which will accommodate the transit of larger ships through the channel. The ACP does not expect that new locks to change the salinity levels of Gatun Lake (Jongeling, 2008). However, since the lake acts as a fresh drinking water source for Colon and Panama City, predicting future salinity levels in the lake is important.

The primary goal of this project was to model future salinity levels in Gatun Lake. In order to meet this goal, three objectives were completed: (1) collection of current water quality conditions in the lake, (2) modeling of current salinity levels based on historical data and comparison of those modeled levels to measured values and (3) modeling of future salinity levels after the expansion project is complete. First, current lake conditions were measured during a two-day water quality campaign in which water quality was determined at 13 stations within Gatun Lake. In-situ data in real-time were collected using a SBE 19*plus* SEACAT Profiler (Sea-Bird Electronics, Inc., Bellevue, Washington), which measures conductivity, temperature, and pressure in marine or fresh-water environments at depths of up to 7,000 meters. Then, water samples at various depths were collected in bottles and transported to the laboratory for measurement of salinity. Results showed salinity levels were below 0.5 ppt at all stations, salinity levels tended to increase below an elevation of 5 meters, and of all stations, Buoy D showed to have the highest salinity levels at the bottom layers of the lake due to its location in front of the Gatun Locks.

The second objective was to model current salinity levels. Hydrometeorological data, including air temperature, wind velocity, runoff, precipitation, and evaporation measurements, were obtained from ACP for the years 2003 – 2005. Saltwater intrusion and dispersion simulations were run by inputting these data into hydrodynamic software, Delft3D, which considers the hydrology within natural as well as artificial environments such as the Panama Canal lock system. In a contract with ACP, Deltares, the developer of the Delft3D software, created multiple scenarios to analyze the salt intrusion within the particular environment of

Gatun Lake. Year 2011 salinity levels were predicted using the 2003 – 2005 data and the current shipping schedules (prior to expansion). Results showed that these salinity levels were consistent with the in-situ salinity measurements gathered during the water quality campaign, verifying that the software was representative of the real situation.

The third objective was to model future salinity levels considering the large Post-Panamax locks and increased ship transits. Predictions were made using hydrometeorological data from 2003 to 2005 and also for data from 2008 to 2009. For all locations in the lake that were simulated, future salt levels were within the freshwater range (0 ppt – 0.5 ppt). These results are consistent with ACP expectations that the expanded lock system will not negatively impact the water quality in Gatun Lake with regard to salinity.

Delft3D modeling results showed that salt levels within Gatun Lake have remained consistent and are predicted to stay within the freshwater range, with salt levels less than 0.5 ppt. However, it is still possible that modeling efforts have not fully captured future water quality scenarios, or that changes in shipping schedules or operation of the locks could result in increased salt levels in Gatun Lake after the expansion project is completed. Therefore, a drinking water treatment plant was designed to produce potable water for the city of Colon and the Panama City metro area considering a brackish water range of 0.5 ppt to 15 ppt conditions in Gatun Lake. Panamanian law requires some form of flocculation, coagulation, sedimentation, or filtration in addition to disinfection. The design complies with Panamanian law, and includes cartridge filters for pretreatment, an electrodialysis reversal (EDR) system for salt removal and ultraviolet (UV) light for disinfection.

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1.0 Introduction

The Panama Canal spans from the Pacific Ocean to the Atlantic Ocean traversing the freshwater lake, Gatun Lake. Ships traveling through the canal’s series of locks facilitate the conveyance of salt from the ocean into the freshwater lake. Currently, La Autoridad del Canal de Panamá (ACP; Panama Canal Authority) is expanding the canal and its operations, including the installation of a new series of locks to the route. Although the salinity level in Gatun Lake is not a present concern, increased activity due to the expanded lock system may cause salt intrusion problems in the future.

The goals of this project were to (1) model salt water intrusion through the Panama Canal and salt water dispersion into Gatun Lake using hydrometeorological data and (2) monitor current water quality in the lake. Delft3D hydrological modeling software was used to model salt levels based on hydrometeorological data from 2003 – 2005 and 2008 – 2010. Results from the two data sets were then compared. In conjunction with a water quality campaign held by ACP, samples were collected at 68 locations in Gatun Lake and analyzed for conductivity, salinity, temperature and chlorides. The modeling and sampling results were used to assess changes in potential salt intrusion scenarios.

The following chapters provide background information on the Panama Canal, salt intrusion, and ACP’s water quality monitoring efforts. Then, the methods used to model salt intrusion using Delft3D software and test the water quality in Gatun Lake are presented. Results from the modeling efforts and water quality sampling campaign are presented and compared, and conclusions are drawn regarding the expected hydrometeorological conditions and salinity levels within Gatun Lake as a result of operating the future Post-Panamax locks. Lastly, the design for a water treatment plant is presented to address the hypothetical situation in which the salinity levels within Gatun Lake enter the brackish water range.

2.0 Background

A modern engineering marvel, the Panama Canal facilitates global trade and cross-oceanic travel as it runs southeast to northwest from the Pacific to the Atlantic Ocean (see Figure 1). A freshwater lake, Gatun Lake, comprises the largest part of the naval transit between the two oceans. Through a series of locks, ships entering via the Pacific Ocean are raised 26 meters above sea level into Gatun Lake and are then lowered on the northwest end into the Atlantic Ocean. To meet the ever-growing demands of maritime trade and to accommodate the transit of larger vessels, the ACP, which maintains sole ownership of the canal, approved the Panama Canal expansion program in 2006. The expansion will add a third series of locks to the canal. Since ships travel from the saltwater Pacific and Atlantic Oceans to the freshwater of Gatun Lake, salt intrusion is a potential concern with the canal expansion.

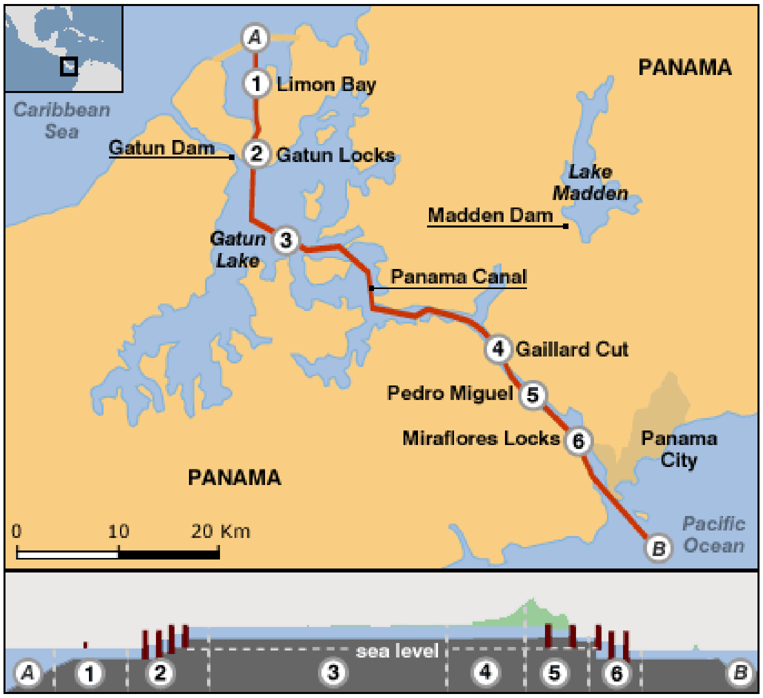

Figure 1: Passage of ships through Panama Canal (BBC News, 2006)

2.1 Panama Canal

The construction of Panama Canal was an exceptional accomplishment of engineering that affected the lives of thousands of people. Multiple countries were involved in the planning, design and construction, including Spain and the United States. The Republic of Panama was created, which turned into a world trade and transportation center. The United States of America became more globally involved through direct involvement in the construction of the canal (McCullough, 1977).

2.1.1 Construction History

In the beginning of the 16th century, the Spanish discovered valuable natural resources in Peru, Ecuador, and Asia, but they were not satisfied by the time it took for those resources to reach Spain. In 1534, Charles V, the ruler of Holy Roman Empire, suggested that a piece of land be cut out somewhere in Panama to make the trips from South America to Spain shorter. The plan for the canal was drawn up by 1529. However, the project was set aside because of various wars that were going on in Europe at that time.

From 1850 to 1870, numerous surveys were made and two reasonable routes for the canal were determined. The first route would go across Panama, and the second would go across Nicaragua. For various geographical reasons, the Panama location was pursued. Nicaragua had some serious earthquakes in the past, as well as active volcanoes that could cause problems with the canal maintenance. Most importantly, the crossing from the Caribbean Sea to the Pacific Ocean was much shorter in Panama than in Nicaragua (McCullough, 1977).

From 1880 to 1889, a French company led by Ferdinand Marie de Lesseps started working on the construction of the Panama Canal. However, the project was wrought with mismanagement, devastating disease, financial problems, and engineering mistakes. Lesseps' plan to build the canal at sea level failed.

An Isthmian Canal Commission was created by the United States Congress in 1899. Its mission was to recommend a feasible route for the canal and to examine different possibilities for a Central American canal. The French company offered its assistance to the United States at a price of $40 million. In 1904, the U.S., led by President Theodore Roosevelt, took over the Panama Canal construction and succeeded due to innovations in medicine and technology, and wise engineering decisions. Engineers that took part in the construction were challenged by digging through the Continental Divide, disposing of the dredged material, and handling the mudslides. The most important decision was to rely on locks for raising and lowering the ships going through the canal, instead of trying to build the canal at sea level (Greene, 2009). The construction of the Panama Canal was completed in 1914 (McCullough, 1977).

2.1.2 Canal: 1914 – 2006

The Panama Canal is 77 kilometers long and joins the Atlantic Ocean and the Pacific Ocean (see Figure 1). On average, vessels take 8 – 10 hours to transit across the canal. The canal has three sets of locks: Miraflores, Pedro Miguel, and Gatun. Each lock has chambers that are 33.5 m (110 ft) wide and 305 m (1000 ft) long. Each lock chamber uses 101,000 cubic meters of fresh water to fill and raise a ship and this water comes from Gatun Lake. Vessels that travel through the Panama Canal get raised 26 m (85 feet) above sea level, which is the level of Gatun Lake.

The canal is a center of international maritime trade. Since the first day of opening on August 15, 1914, the canal has been a waterway transit for more than 922,000 vessels. Due to the efficiency of people working at the canal, each vessel spends less than 10 hours in transit through the Panama Canal, even though the daily number of vessels has significantly increased since 1914 (Panama Canal Authority, 2011c).

2.1.3 Panama Canal Expansion Project

On October 22, 2006, the Panama Canal expansion project was approved in a national referendum. The goal of the expansion project is to maintain the canal's competitiveness as a global transportation provider and to maintain the value of the Panama maritime route to the national economy. More specifically, the project is intended to increase the canal's capacity for capturing the growing demand with the appropriate service, and increase the canal's productivity, safety and efficiency (Martinez, 2006).

As shown in Figure 1, the Panama Canal had three sets of locks: Gatun Locks, Pedro Miguel Locks and Miraflores Locks. Each set of locks had two lanes – one for northbound ships and one for southbound ships. The expansion project will add a third lane, through the construction of two new lock facilities, one at the Pacific side and one at the Atlantic side of the canal. On the Pacific side, the new locks and a new channel will bypass the existing Miraflores and San Pedro Locks. On the Atlantic side, the new locks and a channel will parallel the Gatun Locks. The new locks will allow for increased capacity and for larger ships to transverse the canal. The location of current and new sets of locks can be seen in Figure 2 (Panama Canal Authority, 2006b).

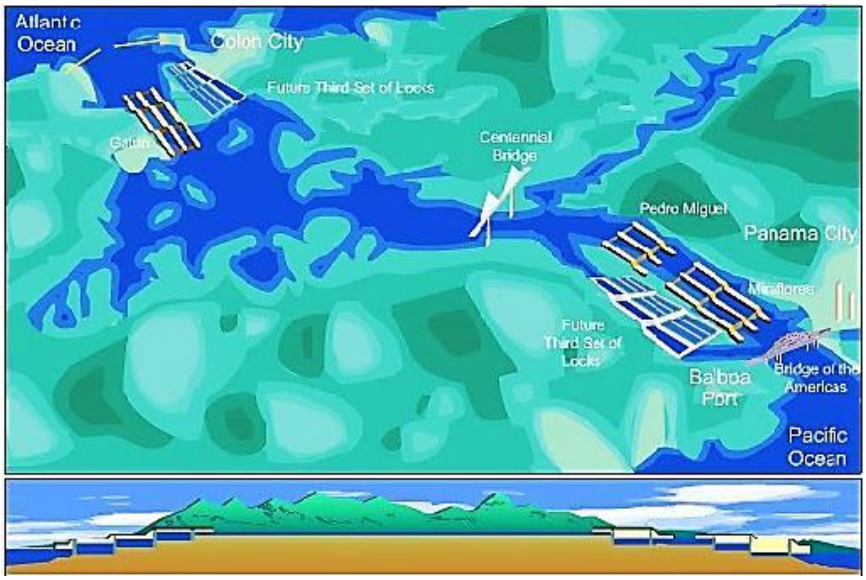

Figure 2: Third Set of Locks Project (Panama Canal Authority, 2006a)

There will be three consecutive chambers at each of the new lock facilities. These new chambers will be 427 m (1,400 ft) long, 55 m (180 ft) wide, and 18.3 (60 ft) deep. The chambers will move vessels from sea level to the level of Gatun Lake and back to sea level again. Each of the chambers will have three lateral water reutilization basins, which means each lock will have nine basins (see Figure 3). Three basins per chamber were selected based on a cost-benefit analysis of water yield in relation to construction costs. In addition, this number of chambers will have a low impact on lockage times and lockage capacity. Each water reutilization basin will be approximately 70 m wide, 430 m long and 5.50 m deep. With these basins, the third set of locks will reutilize 60% of the water in each transit. The existing locks use 55 million gallons of water per transit. The new locks, despite their bigger size, will use only 51 million gallons because of water reutilization from the lateral basins. The new locks will be filled and emptied by gravity without the help of pumps. The existing locks work the same way (Panama Canal Authority, 2006b).

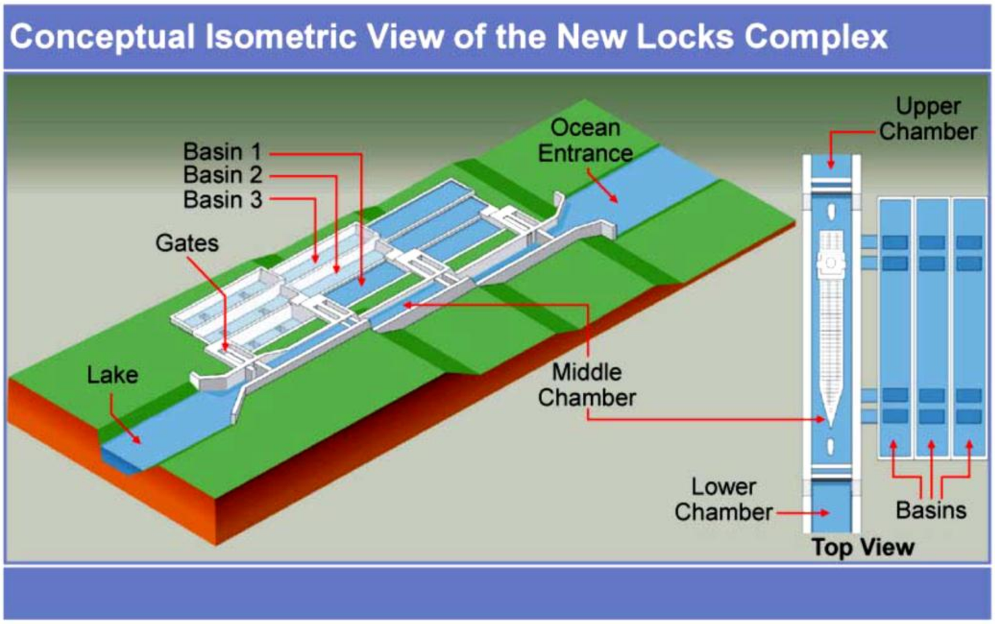

Figure 3: Conceptual Isometric View of the New Locks Complex
(Panama Canal Authority, 2006b)

The expansion project is planned to be completed by 2014 and consists of three main components. The first component is to construct the two lock facilities on the Atlantic side and the Pacific side, along with the water reutilization basins. The construction of access channels for the new locks, as well as the widening of existing channels, is the second component of the project. The third aspect is deepening existing navigation channels and the elevation of Gatun Lake's maximum operating level. The estimated cost for this project is $5,250 million (Panama Canal Authority, 2006a).

Currently the canal is operating approximately at 85% of its maximum sustainable capacity. Since 2004, the canal has not been able to accommodate every vessel that needed to pass through the canal, which led to approximately 20% of the requests being denied. In addition, half of the transiting vessels have the maximum width that fits in the locks and over 10% have the maximum length. The current size limit for ships travelling through the Panama Canal, termed "Panamax", is 289.6 m length, 32.31 m width, and 12 m depth (Panama Canal Authority, 2005). Adding a third set of locks will increase the maximum vessel size, because the new lock chambers will be able to transit post-Panamax containerships that are 366 m in length and 49 m in width, with a 15 m draft in tropical fresh water (Panama Canal Authority, 2006a).

2.1.4 La Autoridad del Canal de Panamá

The Panama Canal is operated by La Autoridad del Canal de Panamá, an autonomous entity of the Government of Panama. Established under Title XIV of the National Constitution, ACP has "exclusive charge of the operation, administration, management, preservation, maintenance, and modernization of the Canal, as well as its activities and related services, pursuant to legal and constitutional regulations in force, so that the Canal may operate in a safe, continuous, efficient, and profitable manner" (Panama Canal Authority, 2011a). On June 11, 1997, Organic Law provided legislation for ACP's organization and operation. ACP is financially autonomous, maintaining its own patrimony and right to administer its patrimony. The government entity is headed by an Administrator and a Deputy Administrator who are both under the supervision of an 11-member Board of Directors. The President of the Republic of Panama with the consent of the Cabinet Council and ratification by an absolute majority of the members of the Legislative Assembly appoints nine directors of the Board. The Legislative Branch designates one director, who may be freely appointed or removed by said branch. The Board's final director is appointed by the President of the Republic. This director assumes the role of the Board of Directors chair, having the rank of Minister of State for Canal Affairs. The director attends Cabinet Council meetings and has the right to voice and vote (Panama Canal Authority, 2011a). The members of the first Board of Directors were appointed for overlapping terms to ensure their independence from the country's administrations.

The Panama Canal constitutes an inalienable patrimony of the Republic of Panama; therefore, it may not be sold, assigned, mortgaged, or otherwise encumbered or transferred. The legal framework of the ACP has the fundamental objective of preserving the conditions for the canal to always remain an enterprise for the peaceful and uninterrupted service of the maritime community, international trade, and the Republic of Panama (Panama Canal Authority, 2011a).

2.2 Gatun Lake

The Panama Canal uses fresh water from Gatun Lake, at approximately 26 m above sea level, to operate the gravity locks system (Fernandez & Schattanek, 2010). The lake was formed by the construction of an earthen dam, the Gatun Dam, between 1907 and 1913 across the Rio Charges (or Chagres River*)* which runs northward toward the Caribbean Sea. The lake forms a major part of the Panama Canal, serving a dual purpose as a channel and a reservoir. Three sets of locks work as water elevators that lift the ships to the level of Gatun Lake and later lower them again to sea level on the other side of the Isthmus of Panama. Ocean-going vessels entering from the Atlantic Ocean are raised to Gatun Lake's level within the Gatun locks. Vessels then traverse the lake and continue south into the second set of locks, the Pedro Miguel Locks. This second set of locks commences the return of vessels back down to sea level. These locks are followed by Miraflores Lake and then the third and final set of locks, the Miraflores Locks. Following the Miraflores Locks, vessels are returned to sea level meeting the Pacific Ocean on the other side of the canal.

Gatun Lake is one of two artificial lakes (Lake Alhajuela being the other) comprising the Panama Canal Watershed. Within this two lake system, Gatun Lake serves several functions. First, it helps regulate runoff by distributing the flow of the watershed between the Caribbean and the Pacific spillways. The Panama Canal watershed extends over a surface of 336,650 hectares between the Caribbean and the Pacific spillways which flow into the Caribbean Sea (Atlantic Ocean) and the Pacific Ocean, respectively. The watershed contains three lakes (Gatun, Miraflores and Alhajuela) and six secondary watersheds (the rivers Chagres, Gatun, Boqueron, Pequeni, Trinidad, and Ciri). The second function of the lake is to provide drinking water (47 MGD) to the inhabitants of Colon, Panama City and its surrounding areas. Thirdly, Gatun Lake provides water for the generation of hydroelectric power. Lastly, Gatun Lake provides water to operate the lock system in the canal to allow ship transits. Over the period between 1994 and 2003, more than 4.2 billion cubic meters of water were used for the aforementioned purposes (URS Holdings, Inc., 2004). In its function as a reservoir, Gatun Lake stores water from rainfall for canal operations. During years of low rainfall, a shortage of freshwater is experienced which decreases the working capacity of the canal.

Currently, Gatun Lake contains roughly less than 0.05 ppt of salt. This concentration of salt does not pose a major threat to the quality of the water in the lake. Intruding salt is dispersed over the lake's area. Thus, salt intrusion does not necessarily imply poorer water quality since the overall salinity of the lake may remain unchanged. To this end, even though the expansion project may increase the amount of salt intrusion into Gatun Lake, the ACP reports that this augmented intrusion will raise no concern to the overall water quality as salinity levels may remain unchanged or change insignificantly throughout the lake (Panama Canal Authority, 2006b). The following section discusses salt intrusion in more detail.

2.3 Salt Intrusion

Salt intrusion is the migration of seawater into freshwater bodies. Because freshwater has a lower density than salt water, when mixed the freshwater will float to the top while the bottom layer is filled with saltwater. Salt intrusion most commonly occurs where freshwater and saltwater closely border each other such as Gatun Lake and the Caribbean Sea.

A method for measuring the amount of salt in water is salinity. Salinity is the amount of salt measured in 1000 grams of water and is typically expressed in parts per thousand (ppt). The average seawater salinity is 35 ppt or thirty five grams of salt in a thousand grams of water, while freshwater only has about 0.5 ppt salinity. The mixing of saltwater and freshwater creates moderate salinity water which is classified as brackish water. Brackish waters have between 0.5 and 17 ppt salinity (Office of Naval Research, 2011).

2.3.1 Salt Intrusion in Gatun Lake

Gatun Lake, bordered on nearly every side by land, is initially protected from salt intrusion. The primary cause of salt intake to Gatun Lake is the passage of ships through the locks. Vessels travelling to the Gatun locks from the Atlantic side first enter through Limon Bay then move into the Gatun lock compartments where gravity fed freshwater floods the lock, raising vessels from sea level to 26 meters above sea level; the approximate level of Gatun Lake (Panama Canal Authority, 2011b). Once the vessel is brought up to the level of Gatun Lake, the vessel then passes through Gatun Lake, the Gaillard Cut, Pedro Miguel locks, and Miraflores locks before making its way into the Pacific Ocean. This transit is illustrated by Figure 1.

Each lock is equipped with a floor filling system which equally distributes incoming water throughout the lock compartment. The side and center walls of the locks contain culverts running through the entire length of the locks; these culverts are the main culverts which supply and drain water into and out of the lock compartments. Side wall culverts are 5.5 meters in diameter and have a circular cross-section. The center wall culvert is shaped like a horseshoe and has a cross-sectional area of 23.7 m^2. These culverts connect the forebay (lock entrance) and the tailbay (lock exit). The designation of the forebay or tailbay is dependent upon whether or not a ship is on a down-lockage or up-lockage passage.

Water is drawn from the forebay through the center and side wall culverts through three rectangular openings which can be opened and closed by lifting valves located on the main culverts. Lateral culverts branch off from the main culverts into the floor of the lock compartments, each equidistant from one another and are in open connection with the main culverts to allow the inflow of water to fill the lock compartments. The culvert system within the lock walls is illustrated in Figure 4.

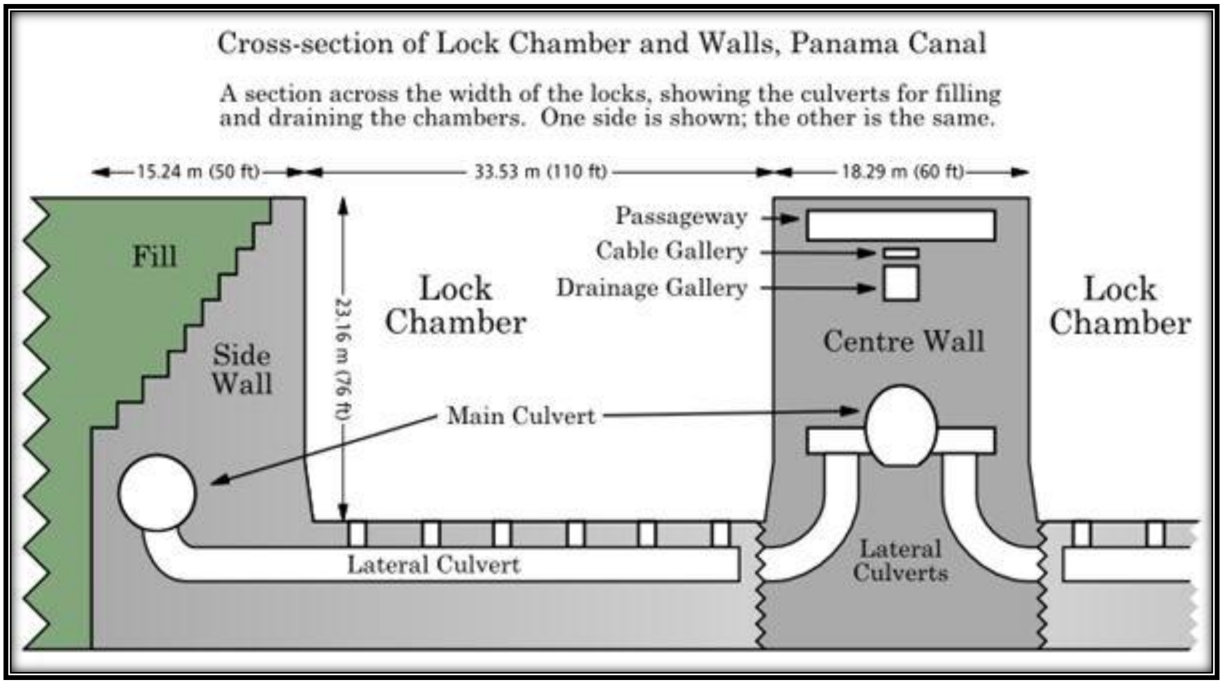

Figure 4: Cross-section of Lock Chamber and Walls, Panama Canal (Balu, 2010)

As vessels make their way into and out of the locks, salt is added to the lake while freshwater is lost to the sea. This occurs mainly because of density currents. Density currents are liquid currents in which heavier or denser fluid intrudes into a lighter environment (The National Center for Supercomputing Applications, 2006). A common misconception is that up-locking ships bring saltwater from the Atlantic Ocean into Gatun Lake. However, the majority of salt intrusion into Gatun Lake results from down-locking ships which displace brackish water into Gatun Lake as they exit the canal (Jongeling *et al.*, 2008). Down-locking ships transiting the canal on the Atlantic side enter the Gatun Locks from Gatun Lake and make their way through three lock compartments before exiting the canal into Limon Bay. Up-locking ships enter from Limon Bay and pass through three locks compartments into Gatun Lake. Similar lock operations occur on the Pacific side, the main difference being Miraflores Lake which is located between the Pedro Miguel Locks and Miraflores Locks. The Miraflores Lake acts as a buffer to counteract the saltwater displaced by transiting ships.

As a vessel sits in a lock compartment, the water on each side is separated by the lock gate. When the gate opens, brackish water can enter the lake under the fresher water. As the vessel travels down the three lock compartments, more and more brackish water can be displaced into Gatun Lake. However, the salt that gets into Gatun Lake is diluted, creating a low salinity in the lake (Jongeling *et al.*, 2008).

Some of the contributing factors to salt exchange between locks are ship size, number of daily passages of ships through locks, and variations in space and time of salt concentrations close to the locks (DHI Water & Environment, 2005). With the current shipping schedule, designated as the Gen3 shipping schedule, an average of 36 to 38 ships transits the canal every day. Because larger ships displace a greater volume of water, the expansion project could potentially increase salt intrusion into Gatun Lake. With the completion of the third set of locks, a new shipping schedule called the PP1 will be implemented, allowing 12 Post-Panamax ships to transit the canal per day.

Salt intrusion into and the loss of freshwater from Gatun Lake is of potential concern because Gatun Lake is a source of drinking water for the local population. Gatun Lake , which was formed nearly a century ago by the construction of the Gatun Dam, provides water for canal operations, hydropower generation, and drinking water for the cities of Colón and Panama metro area; the operational level of the lake is maintained to balance the water needs of these three components (Fernandez & Schattanek, 2010). Nearly seven percent of the total available water in Gatun Lake is used for public consumption, while 59% is used for canal operations and 34% of the total available water is used for hydroelectric generation (Fernandez & Schattanek, 2010). For use as drinking water, the lake supplies approximately 47 million gallons per day. The lake loses about five million more gallons a day due to ship transit than it does supplying drinking water to local communities (McAnally *et al*., 2000). The main focus is to keep the salinity of the water at low levels during and after expansion so that Gatun Lake may continue to provide drinking water to the populations of Panama metro area and Colón.

2.3.2 Impacts of Salt Intrusion

Although salt intrusion is not a current or foreseeable concern following the lock expansion, the potential impact of salinity increases has been researched. Studies of Gatun Lake have shown that increased salinity from salt intrusion, if it occurred, would adversely affect the flora and fauna. URS Holdings, Inc. (2004) inventoried flora and fauna in Gatun Lake. They then researched the impact increased salinity would have on the lake ecosystem and various species in the lake. Plant species were divided into three groups: algae, aquatic macrophytes and mangroves. A reported 147 species of six taxonomic groups were discovered for algae, 74 species of aquatic macrophytes, and 25 species of mangroves. 185 animal species were reported within Gatun Lake and the Gatun locks. With regard to salinity impacts, URS Holdings, Inc (2004) reported that only fifteen species may tolerate salinity levels of up to 1.32 ppt. Micro algae as well as various fish, their larva and eggs could disappear completely from Gatun Lake due to an increase in salt. This ultimately has an overall negative impact on the ecosystems in Gatun Lake.

However, the Panama Canal Authority reports that the addition of the third set of locks will not adversely affect the water quality in Gatun Lake:

> "…the project will not cause permanent or irreversible impacts on water or air quality…even when operating at maximum capacity, the third set of locks will not affect the water quality of Gatun lake…the lake will keep its tropical fresh water quality with stable ecosystems, and the water will be kept to well within appropriate quality levels and standards in order that they can be made potable and used by the population" (Panama Canal Authority, 2006b).

To confirm that salt levels are not increasing, the ACP monitors hydrometeorological parameters that affect intruding salt into the lake and the lake water quality. This is done through routine monitoring programs conducted by the ACP. The next chapter describes the ACP's monitoring programs.

3.0 Hydrometeorological and Water Quality Monitoring of Gatun Lake

ACP maintains many water quality and hydrometeorological measurement stations on the rivers and the lakes within the Panama Canal Hydrographic Water basin area (La Cuenca Hidrográfica del Canal de Panama or CHCP). The water quality measurement stations are sites of interest designated by the ACP where in-situ data can be taken to indicate the water quality at those particular locations. Data from these sites of interest are representative of the lake as a whole. Since water quality measurement stations are just designated locations within the water basin area, ACP personnel must travel to the sites in boats and acquire in-situ data using equipment that measures water quality parameters. On the contrary, the hydrometeorological measurement stations are equipped to measure hydrometeorological conditions in real-time. Most stations are equipped to monitor conditions at regular time intervals; real-time data are measured and archived every 15 seconds. In this way, data can be retrieved representing measurements for longer time intervals such as hourly, daily, and yearly measurements. The monitoring done by ACP at the measurement stations includes water quality parameters (physical parameters such as temperature, conductivity, water column depth, and salinity) and hydrometeorological conditions (such as air temperature, wind velocity, runoff, precipitation, and evaporation). Each year the measurement data gathered by the stations are published by ACP in hydrological and water quality year books (Jongeling *et al.*, 2009). The following sections describe the role of the water quality and hydrometeorological measurement stations in ACP's monitoring processes.

3.1 Water Quality Measurement Stations

There are 68 water quality measurement stations within the water basin area: 21 sites within the three reservoirs (Alhajuela, Gatun, and Miraflores); 8 sites within the main rivers; and 39 sites within other water bodies of the major sub-basins. Figure 5 shows the locations of the water quality monitoring stations.

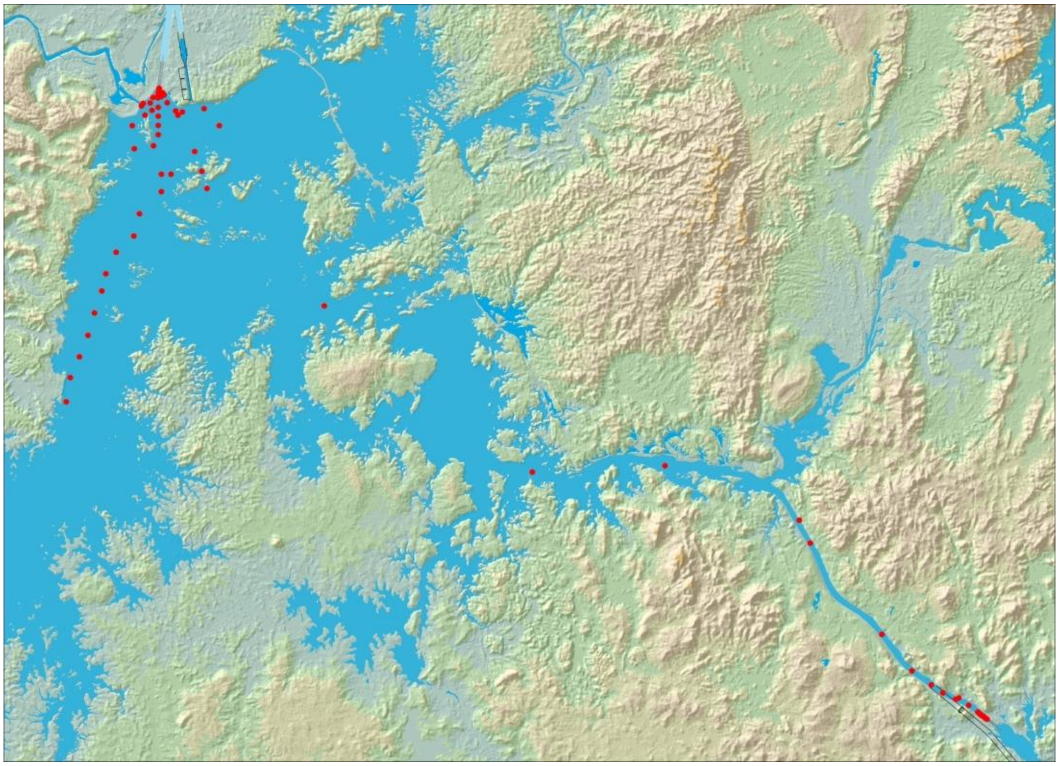

Figure 5: Water Quality Measurement Stations within Water Basin Area (Jongeling, 2008).

In-situ measurements are taken at the stations by ACP personnel during annual water quality campaigns. These measurements include water temperature, conductivity, dissolved oxygen, water column depth, turbidity, and salinity. In addition to in-situ measurements, ACP personnel collect water samples from each water quality measurement station during the campaign for analysis in ACP laboratories. These samples are analyzed for chloride levels. The laboratory personnel follow standard testing protocols per “Standard Methods for the Examination of Water and Wastewater” published by APHA *et al.* (2005) (ACP, 2010). The data obtained from each site during the water quality campaign are archived and published in an annual report on the water quality of the Canal Water Basin, el Informe de Calidad de Agua de La Cuenca del Canal.

3.2 Hydrometeorological Measurement Stations

There are 63 hydrometeorological measurement stations within the water basin area maintained by the ACP (Jongeling, 2008). Hydrometeorological measurements are collected by the stations's equipment every 15 seconds throughout each day of the year and are archived at the measurement stations. The ACP monitors the hydrometeorological parameters of air temperature, wind velocity, runoff, precipitation, and evaporation. Whereas most hydrometeorological measurement stations are equipped to monitor only one or several of these hydrometeorological parameters, some hydrometeorological stations, designated as "principal" stations, measure all hydrometeorological parameters at their sites (Jongeling, 2008). The ACP operates three principal hydrometeorological stations along the Panama Canal: Balboa Federal Aviation Administration (FAA) station at the southern entrance of the canal (Pacific side), Gamboa station at the mouth of Rio Chagres at the southern side of Gatun Lake, and Gatun station at the northern side of the lake close to the shipping locks of the same name (Jongeling *et al.*, 2009). Table 1 shows the location of these stations in Universal Transverse Mercator (UTM) coordinates as well as the elevation of each station given in Precise Level Datum (PLD) levels.

Table 1: ACP Hydrometeorological Stations

Station	**Latitude y [UTM Zone 17N]**	**Longitude x [UTM Zone 17N]**	**Elevation**
Balboa FAA	N 8.9689 ° 991664	W 79.5494 ° 659468	PLD + 10.1 m
Gamboa	N 9.1122 ° 1007455	W 79.6939 ° 643528	PLD + 31.4 m
Gatun	N 9.1122 ° 1024634	W 79.9206 ° 618565	PLD + 30.5 m

4.0 Salt Water Intrusion Modeling Software

Through its monitoring programs employed at the various water quality and hydrometeorological measurement stations, the ACP has the capacity to record real-time measurements and acquire information on the current conditions within the Panama Canal Water Basin area. As the canal's capacity and operations expand, it has become important for the ACP to predict future conditions within the water basin. In particular, predicting water quality within Gatun Lake is important to determine whether salinity levels may increase from increased canal activity. While historical data can identify trends over long periods of time, modeling software is used to predict future water quality in Gatun Lake and potentially avert any problems before they occur. ACP currently utilizes Delft3D software for predictive modeling.

Delft3D software was developed by Deltares, a Dutch institute known for its development of technology which analyzes delta processes and soft soil/sediment environments. There have been four versions of the Delft3D software; the fourth was released on July 8, 2011 and is the first version based on open source code. This version of the software simulates the hydrodynamics and inherent spatial characteristics of water systems.

As the name of the suite implies, Delft3D considers natural phenomena three-dimensionally. The modeling suite of Delft3D is based on software that is continuously being developed and approved through in-house research, development, and contributions by external users of the system. Since natural processes are often time dependent and interrelated, Delft3D simulates the interactions of water, sediment, and ecology in time and space to give an overall water quality assessment. The suite is primarily used for the modeling of natural environments such as coastal, river and estuarine areas. Delft3D has also been designed for integration into more artificial environments, such as harbors and locks. The suite consists of a number of well-tested and validated programs, which are linked to and are integrated with one another. Although the software handles complex interactions, it is user-friendly and thus can be used by domain experts and non-experts alike.

4.1 Delft3D-FLOW

Delft3D-FLOW is a multi-dimensional (2D or 3D) hydrodynamic simulation program. This program calculates non-steady flow and transport phenomena resulting from tidal and meteorological forcing on a rectilinear or curvilinear, boundary fitted grid. This program includes the effect of density differences due to a non-uniform temperature and salinity distribution (density-driven flow). The Delft3D-FLOW program has various areas of application such as stratified and density driven flows, river flow simulation, simulations in deep lakes and reservoirs, fresh-water river discharges in bays, and wave-driven currents. The area of application that the project team focused on was salt intrusion and dispersion, specifically in Gatun Lake.

Delft3D-FLOW can run simulations both in two-dimensional and three-dimensional modes. The two-dimensional mode of Delft3D-FLOW, which models horizontal flow, corresponds to solving depth-averaged equations. Tidal waves, storm surges, tsunamis, harbor oscillations and transport of pollutants in vertically well-mixed flow regimes can be simulated by Delft3D-FLOW in its two-dimensional mode using depth-averaged flow equations.

Transport problems where the horizontal flow significantly changes in the vertical direction can be solved by three-dimensional modeling of Delft3D-FLOW. Changes in horizontal flow may be caused by wind forcing, bed stress, Coriolis force, bed topography or density differences. Examples in which the three-dimensional mode can be applied are dispersion of waste or cooling water in lakes and coastal areas, salt intrusion in estuaries, fresh water discharges in bays, and thermal stratification in lakes and seas.

Delft3D-RGFGRID, a part of Delft3D modeling suite, generates a curvilinear grid. A curvilinear grid allows for a higher resolution in more important areas and lower resolution in less important areas, which saves computational time. Three types of equations are used in Delft3D-FLOW: horizontal equations of motion, the continuity equation, and transport equations for conservative constituents. These equations are expressed in orthogonal curvilinear coordinates or in spherical coordinates on the globe. The difference between curvilinear and spherical coordinates is their plane of reference. Curvilinear coordinates’ free surface level and bathymetry follow a flat horizontal plane of reference, whereas the spherical coordinates’ reference plane relates to the Earth’s curvature.

A special input file needs to be prepared to set up a Delft3D-FLOW model. Parameters that are used for the input file depend on the physical phenomena being modeled, and on the numerical techniques used for solving the equations that describe these phenomena. A Master Definition File (MDF) is the input file that is used for storing the selected data of the model.

MDF files contain all the necessary data required for defining a model and running the simulation program, such as temperature, discharges, wind, and evaporation data (Delft Hydraulics, 2010).

While ACP was conducting water quality modeling studies in 2003 – 2005, Delft Hydraulics was contracted by ACP to develop a simulation model tailored specifically to the Panama Canal region. The new simulation model SWINLOCKS simulates and calculates the salt load on Gatun Lake, Gaillard Cut and Miraflores Lake. The model can be used for the existing locks and for Post-Panamax Locks in the future. The simulation model SWINLOCKS provides an opportunity to compare the salt water load of different designs of Post-Panamax Locks. For example, the model can be run to predict salt water loads for Post-Panamax Locks with or without water saving basins, for the locks with or without salt water intrusion mitigation systems, for various water control scenarios of Gatun Lake, and for different Post-Panamax ship traffic intensities. Most importantly, a comparison of the salt load in the present situation to that of the future situation can be drawn using this model. It also incorporates generalized shipping schedules for the operation of the existing canal locks (Gen3) and for the operation of the future canal locks (PP1). However, the simulation model SWINLOCKS is not capable of predicting the time dependent salt water dispersion in Miraflores Lake, Gaillard Cut and Gatun Lake. For this reason, the simulation model SWINLOCKS is run in parallel with Delft3D-Flow, which has the capacity to analyze time-dependent variables (Jongeling *et al.*, 2008).

4.2 Mass Balance

Within the hydrodynamic model Delft3D–FLOW, Gatun Lake is presented as a hypothetical closed system with no open boundaries and the assumption that the total volume of water is conserved within the lake. This virtual assumption is checked by a mass balance of the real situation, considering all the relevant inflows and outflows of Gatun Lake. SWINLOCKS does not consider the sources and sinks of Gatun Lake and only simulates the operation of the locks and shipping schedules for lock transit; therefore, no mass balance is required to run the SWINLOCKS model. The Delft3D-FLOW model can only be run when the mass balance supports the assumption that the lake is a closed system. Understandably, it is expected that the mass balance of the real-world Gatun Lake would not represent a perfectly closed system where the difference between the lake inflows and outflows is zero. Namely, for the Gatun Lake system, a mass balance which yields a water level difference of 1 m is the maximum acceptable discrepancy for integration into the model. It is important that the lake system is closed when implemented into the model since an unclosed system can produce unrealistic differences in the water level of Gatun Lake. In addition, an unclosed lake system can imply that there are inflows or outflows that are missing in the mass balance consideration which could affect water quality. The mass balance indicates that the main sources of Gatun Lake's inflow are rivers and the main sources of outflow are both Gatun Dam and two locks systems (Gatun Locks and Pedro Miguel Locks) (Jongeling *et al.*, 2009).

4.3 Modeling Summary

The modeling capabilities of Delft3D software described in this chapter enable the ACP to predict the future conditions of the canal water basin area. The saltwater intrusion and dispersion calculation capacity of the SWINLOCKS simulation model was used by the project team to forecast future salinity levels within the water basin area and in particular, within Gatun Lake. The following chapter explains the methodology of the project team in determining how hydrometeorological conditions affect salinity levels within Gatun Lake, which includes the team's use of the modeling software.

5.0 Methodology

The goals of this project were to (1) gather historical data describing hydrometeorological characteristics of Gatun Lake, (2) model salt water intrusion through the Panama Canal and salt water dispersion into Gatun Lake using hydrometeorological data, and (3) monitor current water quality conditions through a water quality campaign. Historical hydrometeorological data from 2003 to 2005 and 2008 to 2009 were used as input for Delft3D hydrological modeling software to obtain saltwater intrusion predictions. The team conducted a comparative analysis of the model results from the two data sets. In a water quality campaign held by ACP, the team took samples and obtained measurements for different water quality parameters (conductivity, salinity, temperature and chlorides) at 68 locations in the lake. The model output from the hydrometeorological data and the water quality in-situ data were compared to determine if software simulations were representative of the current conditions in Gatun Lake. The following sections explain the methods in more detail.

5.1 Historical Hydrometeorological Characteristics

The hydrometeorological section of El Departamiento del Ambiente, Agua, y Energia (Environment, Water, & Energy Department) of the ACP provided the team with hydrometeorological data from 2003 to 2005 and from 2008 to 2009. These data were used as input data for salt intrusion modeling using Delft3D. Hydrometeorological data included the hourly inflow and outflow rates of the Gatun Lake Watershed for every day from January 1, 2003 to December 31, 2005 and from January 1, 2008 to December 31, 2009. The data also included hourly measurements for precipitation over the watershed, air temperature, wind velocity and direction, atmospheric pressure, solar radiation, relative humidity, evaporation, and elevations of Gatun and Madden Lake for every day over the two year period. ACP provided the data to the team in Microsoft Excel files, which were then converted to text files in a script recognizable by Delft3D.

5.2 Current Salt Intrusion Conditions

In order to assess current salt intrusion conditions in Gatun Lake, the team ran a saltwater intrusion and dispersion simulation using Delft3D software (Scenario 0 – Current Conditions).

The D-FLOW program of Delft3D was used with water quality data from 2003 to 2005, which was the most up-to-date data available to the team when Scenario 0 was run on November 14, 2011. Data from 2008 – 2009 were not obtained from ACP until the following day; this data still needed to be organized before its use within the software. Prior analysis by the ACP had shown that the conditions in Gatun Lake have remained consistent in recent history (ACP, 2010 & Jongeling, 2008), thus the 2003 – 2005 data were deemed adequate. Scenario 0 used the Gen3 shipping schedule, a generalized schedule for shipping in the existing locks which describes the current operation of the canal. It does not consider the future situation when the new set of locks will be operating and a different shipping schedule will exist.

The water quality data acquired by the team during the water quality campaign (see section 6.2) were compared to the results from Scenario 0 to demonstrate if the water quality in Gatun Lake had changed over time. This comparison between historical data and current in-situ data was completed to determine if factors other than operation of the new locks would potentially affect salt intrusion in Gatun Lake.

5.3 Salt Intrusion Modeling

The team ran salt water intrusion and dispersion simulations using the hydrometeorological data provided by the ACP for the two time periods of 2003 to 2005 and 2008 to 2009 using Delft 3D software. In particular, the D-FLOW program of Delft3D has the capacity to run 5 scenarios within ACP's contract with Deltares using the input hydrometeorological data. Due to time constraints, the team ran one of the five scenarios. Scenario 1 considered the operation of the canal after the expansion program is completed, using the general Gatun Lake operating conditions and the water saving basins for the new locks. This scenario utilizes general rules for operating the Gatun Dam and determines the yearly output from Gatun Lake for the operation of the locks. Generalized shipping schedules for shipping in the existing locks (shipping schedule Gen3) and for shipping in the future Post-Panamax Locks (shipping schedule PP1) were used to determine how much salt intrusion will occur as a result of the operation of the new locks. Since the existing locks will continue to be in use when the new Post-Panamax locks are in operation, Scenario 1 considers a general schedule for each lock system since the locks will be used concurrently. Thus, in each of the two simulation runs of Scenario 1 (one for 2003 to 2005 and one for 2008 to 2009), salinity levels of Gatun Lake are output considering the salt intrusion due to the operation of both series of locks (the existing locks and Post-Panamax Locks)

5.4 Water Quality in Gatun Lake

As mentioned in Chapter 3, in order to monitor the water quality of Gatun Lake, ACP conducts an annual water quality campaign in which it collects water samples from Gatun Lake for measurements of various water quality parameters. Water quality measurement stations are located at various sites throughout Gatun Lake. Over a 2-day period, the team visited 13 sites: 5 locations near Pedro Miguel Locks (PM14, PM15, PM17, PM20, and PM21) and 8 locations near the Gatun Dam and Gatun Locks (Buoy D, P13, GL17, GE-1, GE-2, GE-3, P6, and Buoy 11). Figures 6 and 7 depict the sites the team visited; the locations of the sites are indicated in each figure by blue dots and red dots, respectively.

Figure 6: Water Quality Measurement Sites near Pedro Miguel Locks

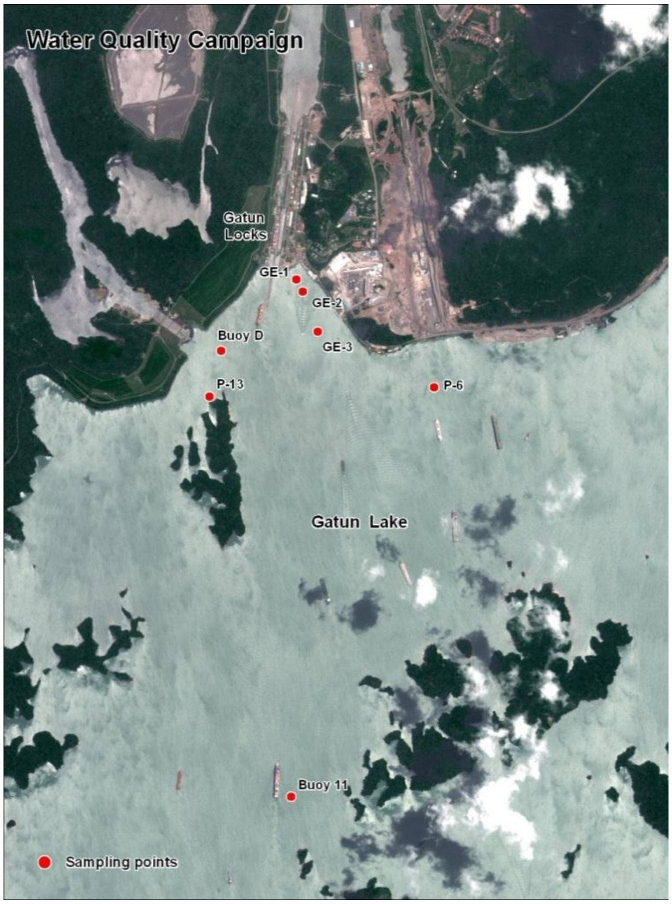

Figure 7: Water Quality Measurement Sites near Gatun Dam and Gatun Locks

At each site, the team collected water quality data via two methods. First, the team gathered in-situ data in real-time using the SBE *19plus* SEACAT Profiler (Sea-Bird Electronics, Inc., Bellevue, Washington), which measures conductivity, temperature, and pressure in marine or fresh-water environments at depths up to 7,000 meters. At each site, the SEACAT Profiler was submerged until it reached the water bed taking real-time data during submersion and upon its return to the surface. The SEACAT Profiler uses built-in software, Seaterm, to archive the real-time data in a text-file. Second, the team collected water samples using a Niskin bottle, which is designed to take water samples from below the surface of the lake (University of Wisconsin, Milwaukee, Wisconsin). Samples were transferred into 500 mL plastic containers, transported to the ACP laboratory and analyzed by ACP laboratory technicians for chloride concentration. The technicians used the potentiometric method, which is a titration method using standard silver nitrate ($AgNO_3$) solution and a glass and silver-silver chloride electrode system to measure the chloride concentration (APHA *et al.*, 2005). The water quality campaign took 2 days. Due to time constraints, the team used data obtained from 3 of the 8 monitoring sites near Gatun Dam and Gatun Locks for its analysis: Buoy D, GE-1, and P-6.

During this campaign, salinity levels at different depths of the water column for points Buoy D, GE-1, and P-6 were generated by the Seaterm software. Depths were converted to elevations by subtracting depths from the water surface elevation of Gatun Lake. For example, the water surface elevation for Gatun Lake is 27 m (PLD), so for a salinity reading taken at a depth of 5 m, the calculated elevation was 22 m (PLD).

6.0 Results and Analysis

The main goal of this project was to see how hydrometeorological conditions affect the salinity levels in Gatun Lake. To meet this goal, the project team used historical hydrometeorological data to predict salinity by software simulations and in-situ measurements taken during its water quality campaign. The following sections explain the results acquired by the team and the analysis of those results. Hydrometeorological input data for the software simulations (Scenario 0 & 1) run by the team are presented and discussed in the first section. In the following section, the salinity results from Scenario 0 run for 2003 to 2005 and the in-situ salinity measurements from the water quality campaign are presented and compared. The last section presents salinity results from Scenario 1 run for the two periods of 2003 to 2005 and 2008 to 2009. These results were analyzed to draw conclusions on how the operation of the future Post-Panamax lock system would affect salinity levels in Gatun Lake.

6.1 Hydrometeorological Parameter Input Data for Software Simulations

To reach the main goal of the project, the team studied the variation of the hydrometeorological parameters (air temperature, wind, precipitation, runoff, evaporation) in the period of 2003-2005 and the period of 2008-2010. The Hydrometeorological Section of the ACP provided data for each parameter. Each parameter represents a corresponding parameter built into the Delft3D software used by the project team since each parameter affects the salinity levels in Gatun Lake. As a result, the hydrometeorological data received from ACP by the project team served as the input data for the saltwater intrusion and dispersion simulations (Scenario 0 and Scenario 1) run by the software. The following sections present the input data for each hydrometeorological parameter, and thus, each parameter of the software. Data were monthly-averaged for each time period and compared to determine if hydrometeorological conditions within Gatun Lake have remained consistent historically and throughout each time period.

6.1.1 Air Temperature

Air temperature was one of the hydrometeorological parameters that was analyzed and compared. As shown in Figure 8, 2003 has higher air temperature values than 2008, with a difference of 0.5 – 1 degree. An exception can be observed from February to April of 2003, where the highest air temperature value is 27.8 degrees, which is more than 2 degrees higher than in 2008. Considering the second year of each data set, 2004 has significantly higher values in the first quarter of the year than in 2009. In mid-February 2004 the temperature reached 27.6 degrees, while in March 2009 the temperature dropped down to almost 25 degrees Celsius. From April to December, temperatures in 2004 and 2009 are similar. In 2010, the highest temperature occurs in mid-April (28 degrees), which is 1 degree higher than in 2005. Then, while the air temperature went up to 27.5 degrees from mid-May to mid-June in 2003, in 2005 the air temperature dropped to 26.7 degrees during the same month period in 2005.

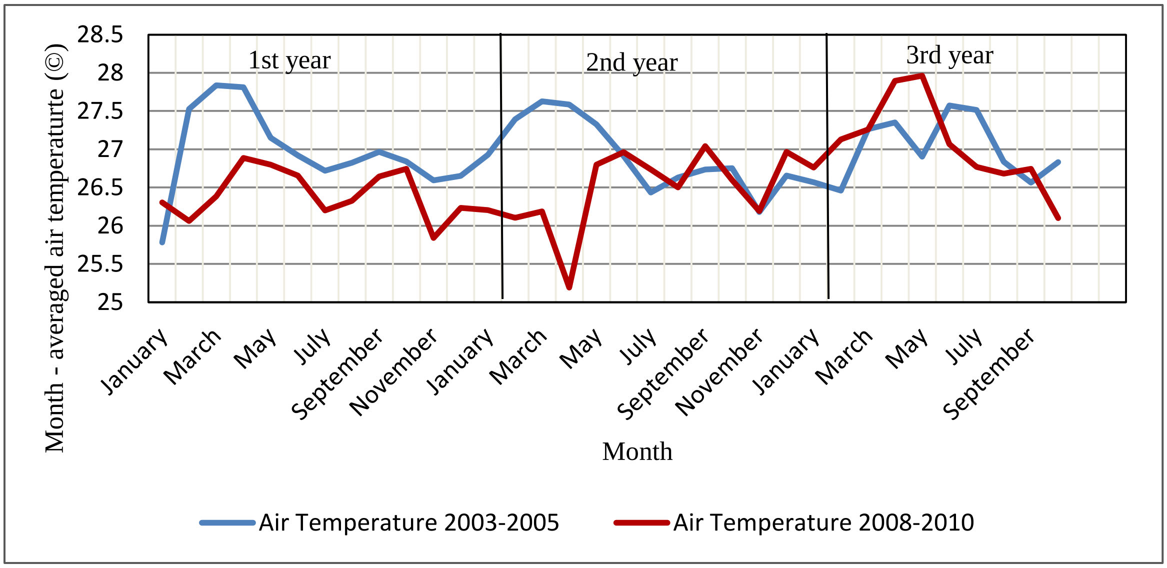

Figure 8: Air Temperature comparison 2003-2005, 2008-2010

6.1.2 Wind

As shown on Figure 9, there is a significant difference between the wind velocities of the two time periods. Wind speeds in 2003 to 2005 are more than double the recorded values in 2008 to 2010. The wind velocity values for the years of 2003 – 2005 are approximately 2 to 6 m/s, while the values for 2008 – 2010 are 0.7 – 4 m/s. The highest wind velocity values are observed during the dry season (January-May) for the both time periods, with the values reaching 6 m/s for 2003-2005 and 4 m/s for 2008-2010.

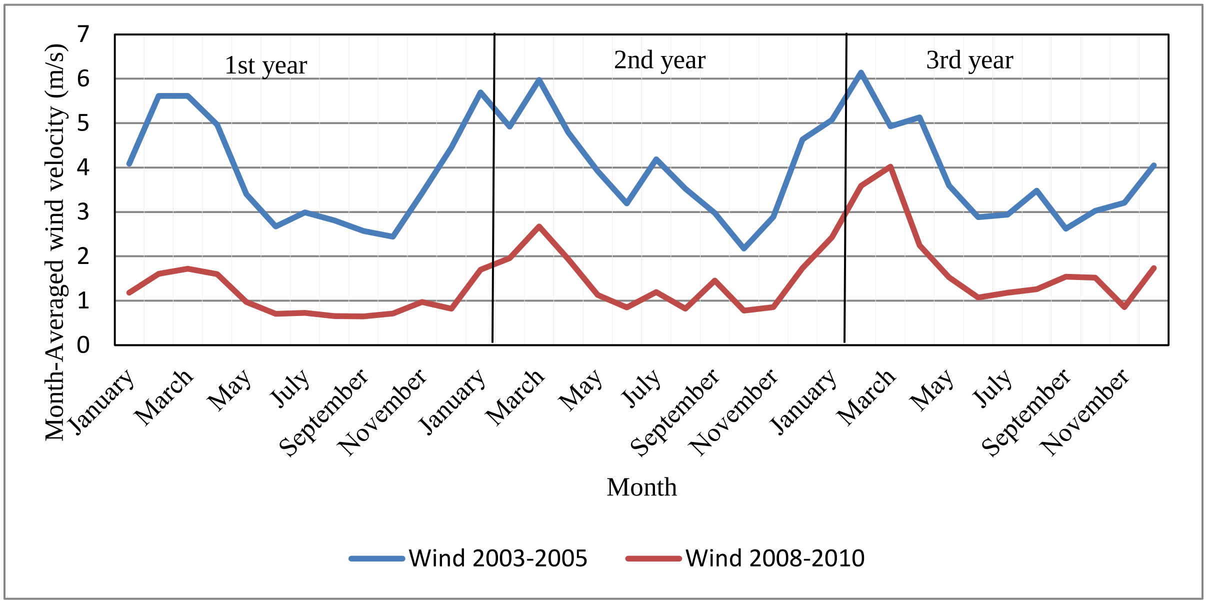

Figure 9: Wind velocity comparison 2003-2005, 2008-2010

6.1.3 Precipitation

Figure 10 shows monthly average precipitation for the two time periods. As seen on the graph, both time periods have similar overall trends with higher precipitation levels occurring during the wet season (May – December) and near zero precipitation levels during the dry season (January – April). The highest precipitation values are within the range of 300 – 350 mm for the years 2003 – 2005 and within a range of 300 – 500 mm for the years 2008 – 2010. As seen in Figure 10, there is a sudden rise of precipitation (~510 mm) in December 2010. This spike in precipitation can be explained by the event of “La Purisima,” a storm of heavy rainfall which occurred from December 7 – 10, 2010, causing more than 500 landslides in the upper reservoir of Lake Alajuela, in the Watershed of the Panama Canal (ACP, 2011). This graph is a good representation of hydrometeorological conditions staying consistent throughout a long time period in Gatun Lake.

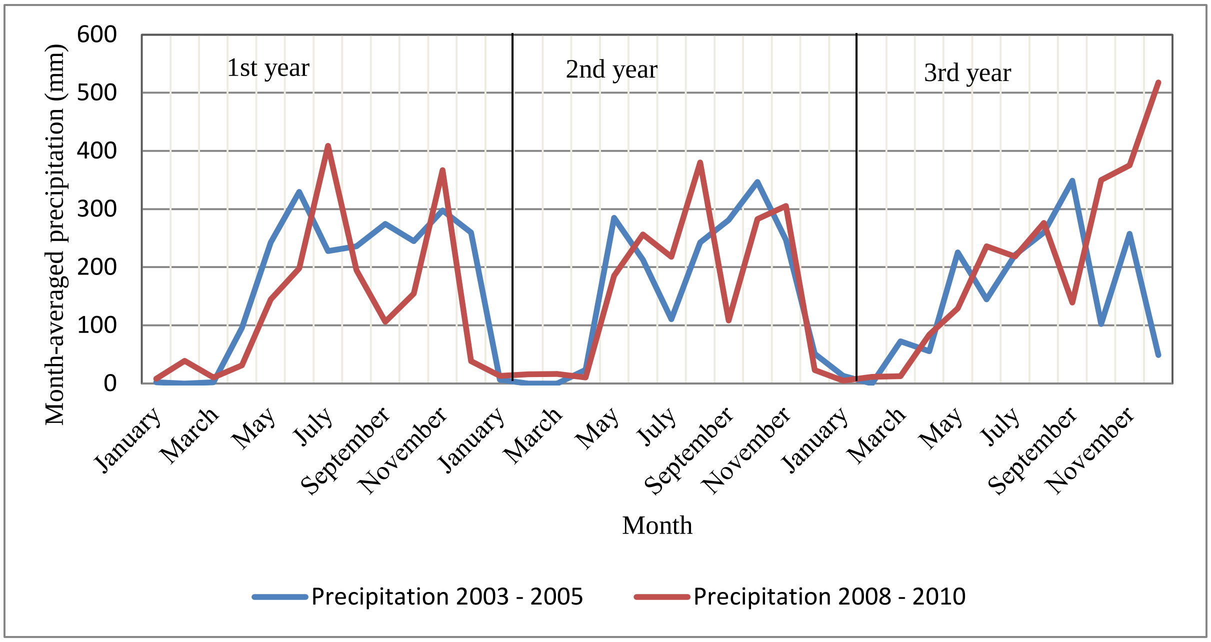

Figure 10: Precipitation comparison 2003-2005, 2008-2010

6.1.4 Runoff

For this parameter, discharges of three principal rivers were used. These principal rivers are Rio Ciri Grande, Rio Gatun, and Rio Trinidad. As shown in Figure 11, the patterns stay nearly consistent for each of the rivers. All three rivers have their highest peaks during the months of September to December which are the months of the rainy season. Precipitation is one of the conditions that directly affect the discharge values.

Rio Trinidad has a major difference in discharge of 10 m^3/s between mid-November values in 2003 and mid-November values in 2008. The river discharges in the years of 2004 and 2009 are similar. The year 2010 has a sudden peak of 27 m^3/s in mid-December as does Rio Ciri Grande, which is due to the storm “La Purisima” (ACP, 2011). This value is higher by 20 m^3/s than the mid-December value of 2005, which is a very significant difference throughout the overall trend.

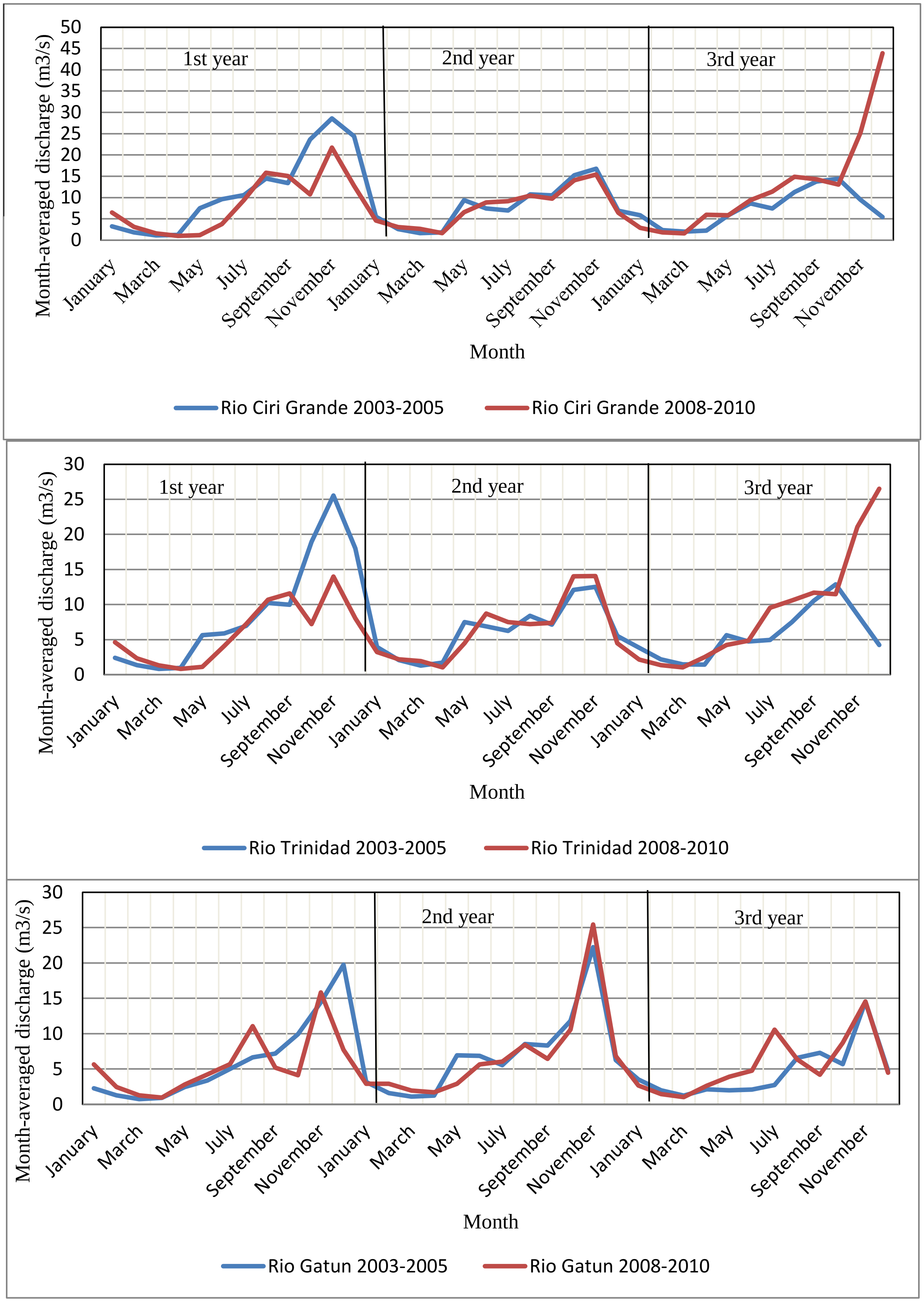

Figure 11: Runoff comparison for three principal rivers 2003-2005, 2008-2010

For Rio Gatun, similar patterns are observed from January to mid–June for 2003 and 2008. In 2008, the peak value of 12 m^3/s is observed in mid-July, which is 5 m^3/s higher than the discharge rate in 2003. Also, while the highest peak discharge occurred in mid-December in 2003, in 2008 it occurred in mid-November. The years 2004 and 2009 have very similar patterns except for a 4 m^3/s difference in the first half of April. Mid-June of 2010 has a peak discharge of approximately 10 m^3/s, which is almost 8 m^3/s higher than in the year 2005. However, both years have the same peak of 15 m^3/s in mid-November.

For Rio Ciri Grande, both time periods have very similar ranges of monthly averaged discharge. However, as shown in Figure 11, mid-October of 2003 has a peak discharge value of 28 m^3/s, which is approximately 5 m^3/s greater than in the year 2008. That is the most significant difference for Rio Ciri Grande, except for a sudden rise in December 2010 due to “La Purisima”.

6.1.5 Evaporation

Figure 12 shows that there is a significant difference in evaporation values for the two time periods. The evaporation values for 2003 to 2005 are within a range of 390 to 950 mm/day. For the 2008 to 2010 time frame, evaporation ranges from 190 to 400 mm/day. The decrease in evaporation values in recent years may be due to increased cloud coverage during the years of 2008 – 2010 or to increased solar radiation during the years of 2003 – 2005.

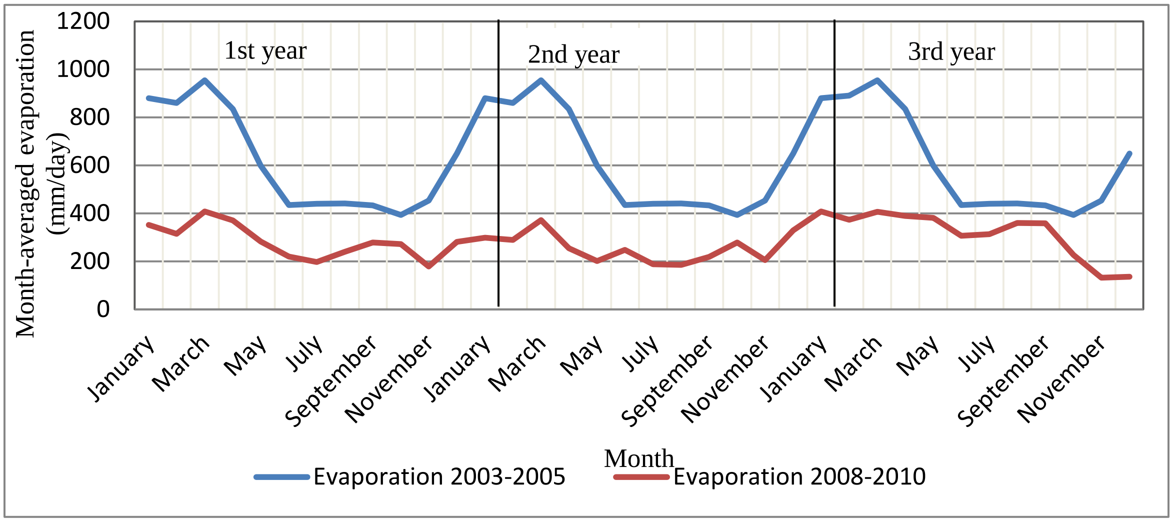

Figure 12: Evaporation comparison 2003-2005, 2008-2010

6.2 Water Quality Campaign Results and Simulation Results for Scenario 0

The hydrometeorological input data from the period 2003 to 2005, as presented in the previous section, were run within Scenario 0 of the software. As explained in Chapter 5, Scenario 0 was a simulation which used a generalized schedule (Gen3) for shipping in the existing lock system to describe the current operation of the canal. Consequently, the simulation does not consider the future situation when the new set of locks (Post-Panamax) will be operating and a different shipping schedule will exist. The purpose of running Scenario 0 was to determine if the software simulations were representative of the real conditions in Gatun Lake. To this end, the project team compared the simulation salinity results from Scenario 0 to real in-situ salinity measurements taken by the team during its water quality campaign. This section presents the in-situ salinity measurements taken at different water quality measurement stations during the water quality campaign and draws comparisons between these measurements and the salinity results from the software for Scenario 0.

During the water quality campaign, salinity measurements were collected at 13 sites near Pedro Miguel and Gatun Locks. Due to time constraints, the data from 3 stations near the Gatun Locks were analyzed by the team. Figure 13 displays the locations of the three measuring sites that were chosen: BuoyD, GE-1, and P-6.

Figure 13: Water Quality Measurement Stations near Gatun Dam and Gatun Locks

Salinity measurements taken at these sites were compared to the salinity results from Delft3D for the years 2003, 2004, and 2005. Delft3D generated salinity versus elevation quickplot graphs. As described in Chapter 5, depth data from the water quality campaign were converted to elevation for comparison purposes. A quickplot graph of salinity readings was generated by the software for the exact date and time salinity measurements were taken during the project team's water quality campaign. For the BuoyD site, quickplot graphs for December 2 at 11 am for the years of 2003, 2004, and 2005 were used. This was done to coincide with the in-situ measurements taken by the project team on December 2, 2011 at 11 am. The same date and years were used for GE-1 and P-6 with the exception of the time differences; GE-1 at 12 pm and P-6 at 1 pm. Comparisons between the quickplot graphs and the in-situ salinity measurements from the water quality campaign were drawn for each visited site and are included below.

6.2.1 BuoyD

Salinity measurements from the water quality campaign at BouyD are shown in Figure 14, while simulated salinity levels per the Delft3D software for 2003, 2004 and 2005 are shown in Figure 15. The model results show similar trends to the measured values.

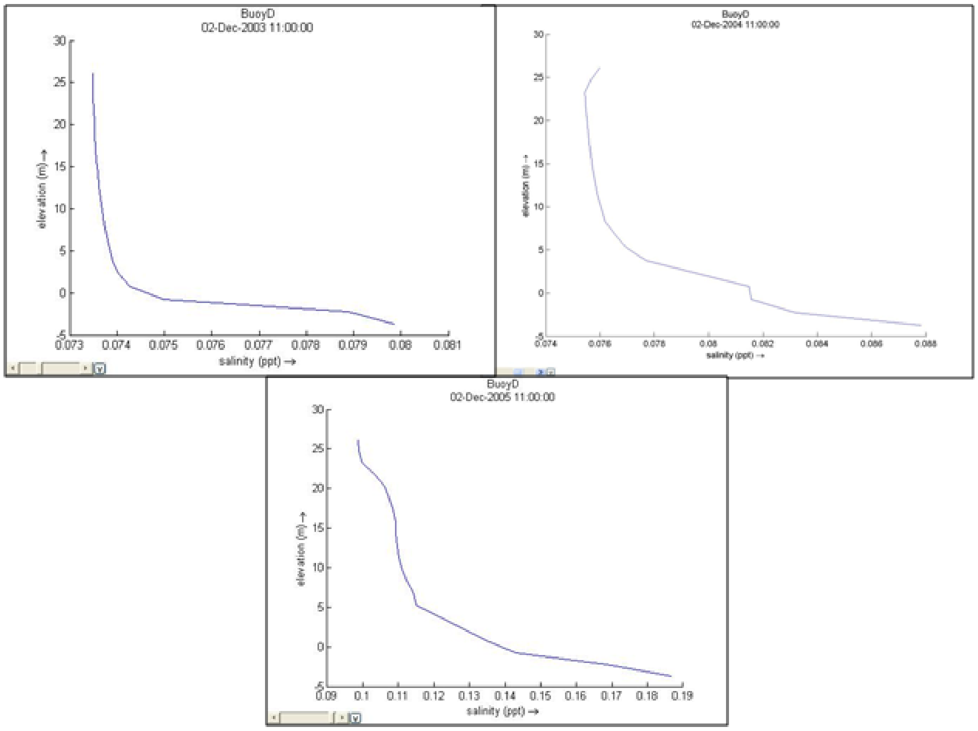

Figure 14: Delft3D Quickplot Salinity Modeling Results at BuoyD for 2003-2005

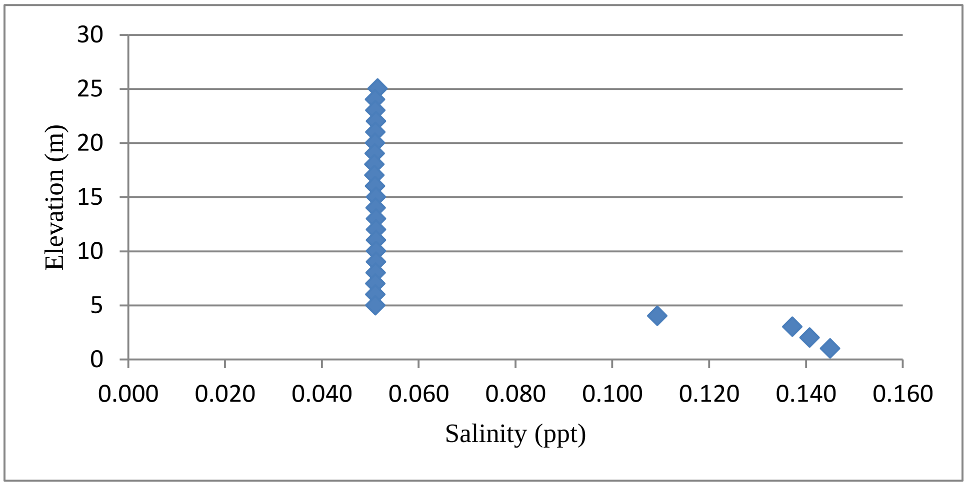

Figure 15: Salinity Measurements at BuoyD on December 2, 2011 at 11 am

The salinity values are reasonably consistent from the surface to an elevation of approximately 5 meters. Below 5 meters, the salinity levels increase. However, the salinity levels remain within the acceptable range for freshwater lakes (less than 0.5 ppt) at all elevations in the model and in the measurements. The salinity increase in the bottom layers of the lake is likely due to the location of BuoyD. As shown in Figure 13, the BuoyD station is located right in front of the Gatun Locks where incoming salt through the locks gets accumulated. High salinity currents from the locks cause the sudden increase in salinity in the bottom layers of the lake.

6.2.2 GE-1

Salinity measurements from the water quality campaign at GE-1 are shown in Figure 16, while simulated salinity levels per the Delft3D software for 2003, 2004 and 2005 are shown in Figure 17

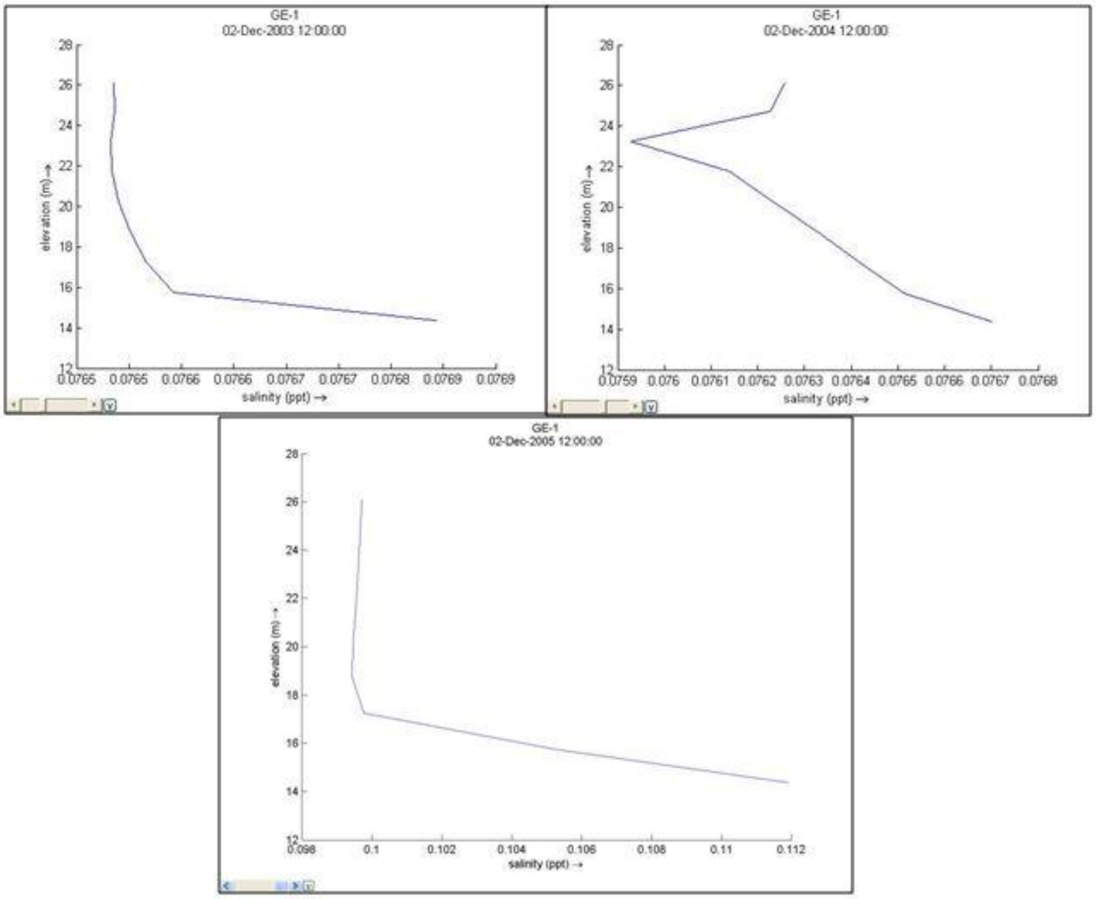

Figure 16: Quickplot Salinity Modeling Results at GE-1 for 2003-2005

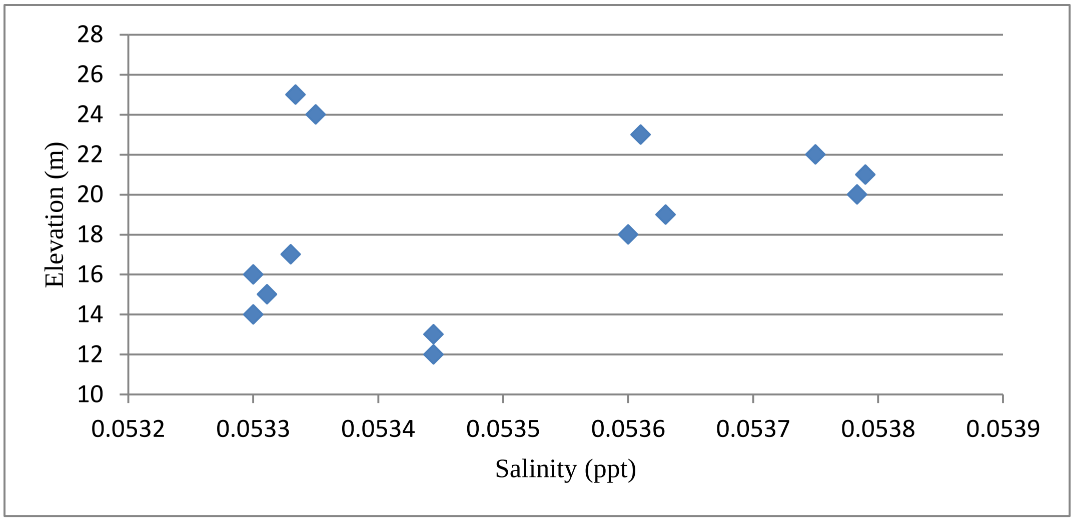

Figure 17: Salinity Measurements at GE-1 on December 2, 2011 at 12 pm

As seen in Figure 17, there is no consistent pattern for salinity at the different elevations of GE-1, which is likely due to the location of the station. As Figure 13 shows, the GE-1 measuring station is located to the right of the locks where there is high turbulence from the ships and boats going through the locks. The salinity values for the quickplot graphs of GE-1 are very close to the values of BuoyD since both stations are located close to the locks (Figure 14 & 16). There is a minor difference in salinity between the measured values from the water quality campaign and the quickplot graphs for the years of 2003 and 2004 (0.02-0.03ppt). The quickplot for the year 2005 has salinity values around 0.1 ppt, which is higher than the rest of the graphs. Still, these graphs are representative of salinity over a very short time period, whereas long-term patterns would be more consistent with the modeling results from the Delft3D.

6.2.3 P-6

Salinity measurements from the water quality campaign at P-6 are shown in Figure 18, while simulated salinity levels per the Delft3D software for 2003, 2004 and 2005 are shown in Figure 19. Measured values during the water quality campaign showed salinity at P-6 to be 0.05 – 0.06 that are within the acceptable range of salinity in fresh water (> 0.5 ppt). The salinity levels for the quickplot graphs are consistent during the years of 2003 and 2004 with salinity measurements ranging from 0.066 to 0.071 ppt. The values of 2005 are higher by 0.03 – 0.04 ppt than the values of the previous two years.

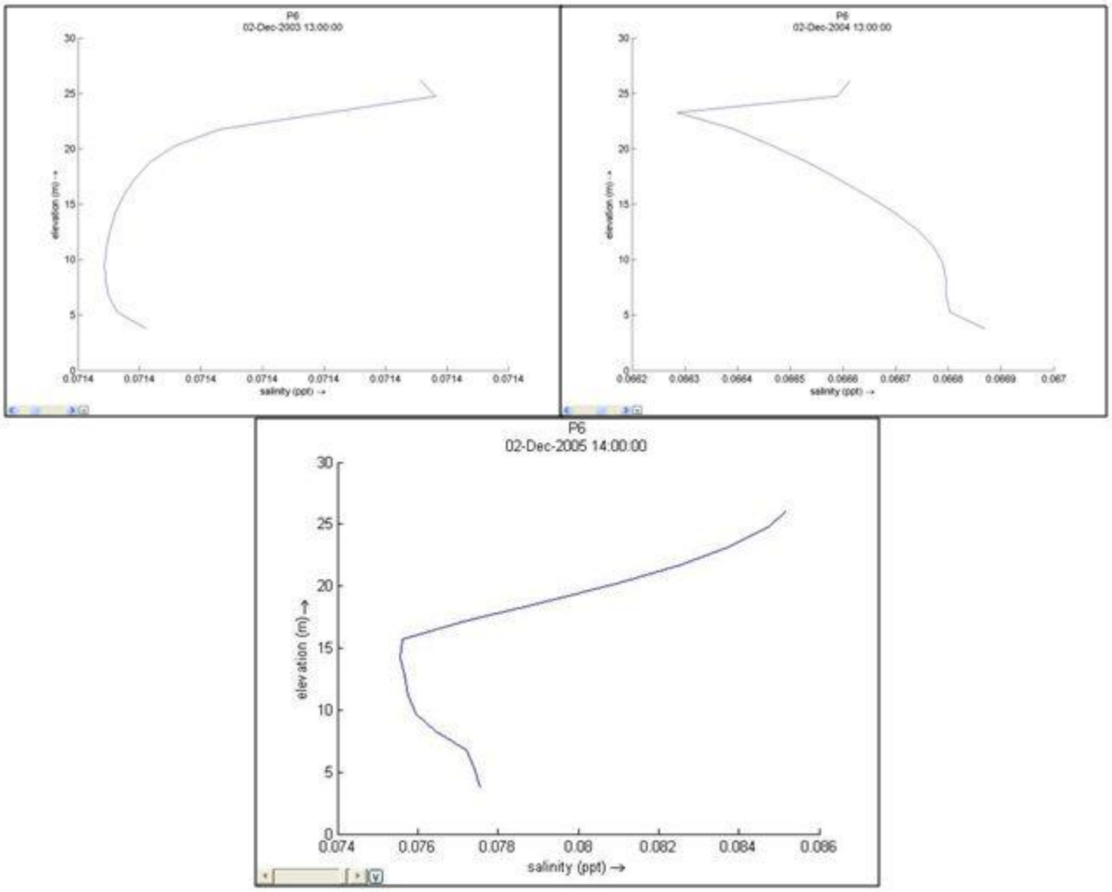

Figure 18: Quickplot Salinity Modeling Results at P-6 for 2003-2005

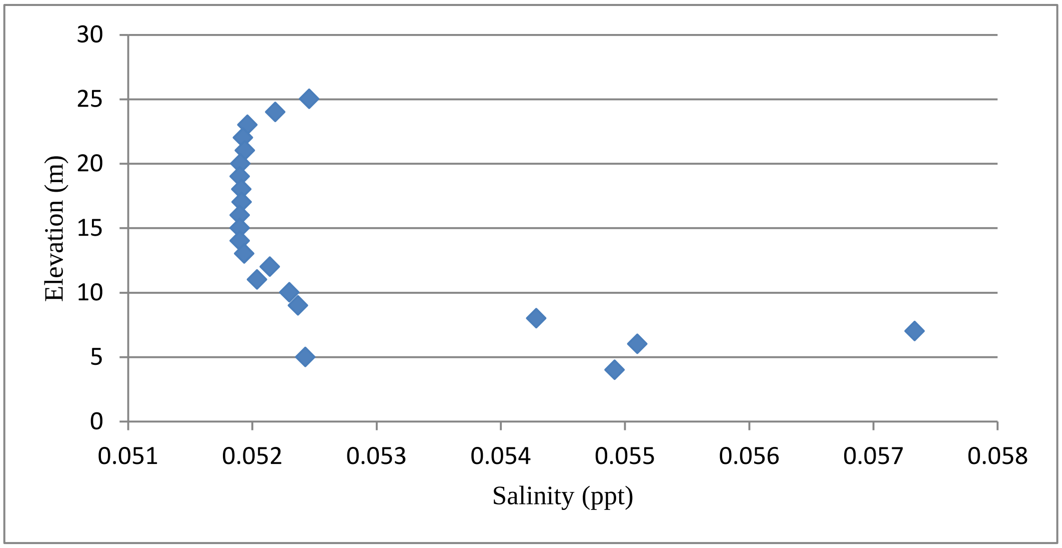

Figure 19: Salinity Measurements at P-6 on December 2, 2011 at 1 pm

The salinity results from the software simulation for Scenario 0 were consistent with the in-situ measurements of the water quality campaign. This demonstrates that the software is working correctly and is representative of the real conditions in the lake, and that the conditions of Gatun Lake have remained consistent over time, up to the present-day. In addition, since Scenario 0 only considers the operation of the current lock system, the consistency between the software results and the in-situ measurements implies that only the operation of the new locks would potentially affect salt intrusion in Gatun Lake and other factors will not affect predicted lake water quality.

6.3 Salinity Results for Scenario 1

The hydrometeorological input data from the periods 2003 to 2005 and 2008 to 2009, as presented in the Section 6.1, were run using the software for Scenario 1. As explained in Chapter 5, one run was done for each time period for a total of two runs. Scenario 1 includes both the the generalized schedule (Gen3) for shipping in the existing lock system and a generalized shipping schedule, PP1, for the future Post-Panamax locks. Thus, the salinity results generated by the software for Scenario 1 represent the future conditions in Gatun Lake when both series of locks are in operation. This section presents the salinity results for five freshwater intake stations, Sabanitas, Mt Hope, Escobal, Gamboa, and Paraiso, from the software for the each run of Scenario 1.

Although the five freshwater intake stations are far from the Gatun shipping locks (see Figure 20), special attention is given to them because these five points are freshwater intake stations for drinking water. Therefore, monitoring salinity levels at these locations is of high importance. Graphs were prepared for the bottom as well as the surface water elevations to illustrate salt concentrations at both extremes. Typically, the highest salt concentration at a specific point lies at the bottom of the lake while the lowest salt concentration occurs at the lake’s surface.

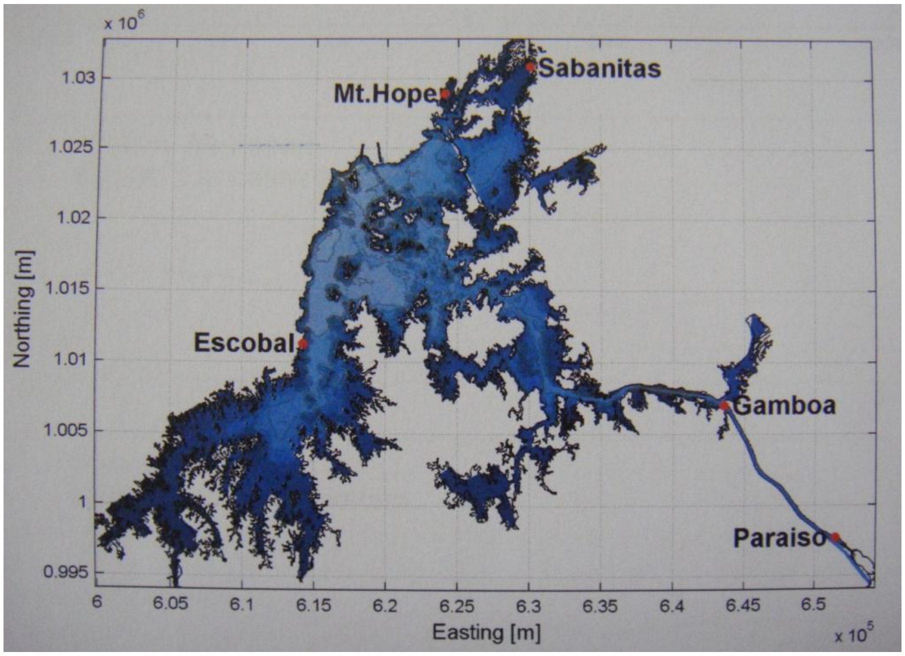

Figure 20: Freshwater Intake Stations in Gatun Lake

In addition, to gain a better understanding of the salt intrusion phenomena near the Gatun shipping locks, the team averaged the salinity levels for 23 hydrometeorological stations located throughout Gatun Lake. The team made a graph of the salinity level average from these 23 points as a representation of the overall salinity in Gatun Lake. The following sections display salinity graphs for various locations throughout Gatun Lake as well as a salinity graph for Gatun Lake as a whole (as the average of the salinity levels at the 23 sites). The salinity results displayed in these graphs are indicative of the future salinity levels at the five freshwater intake stations and in Gatun Lake in whole as a result of operating the current lock system with the future Post-Panamax lock system. Each graph was produced from simulation salinity results for Scenario 1.

6.3.1 Sabanitas

Figures 21 and 22 illustrate that the volume-averaged salinities at the bottom and surface of Sabanitas over the two time periods (2003-2005 and 2008-2009) are very similar and their differences in salt levels are insignificant. The volume-averaged salinities vary between about

0.1 ppt and 0.17 ppt. This range of salinity in the years 2008 and 2009 is very low and is consistent with the years 2003-2005.

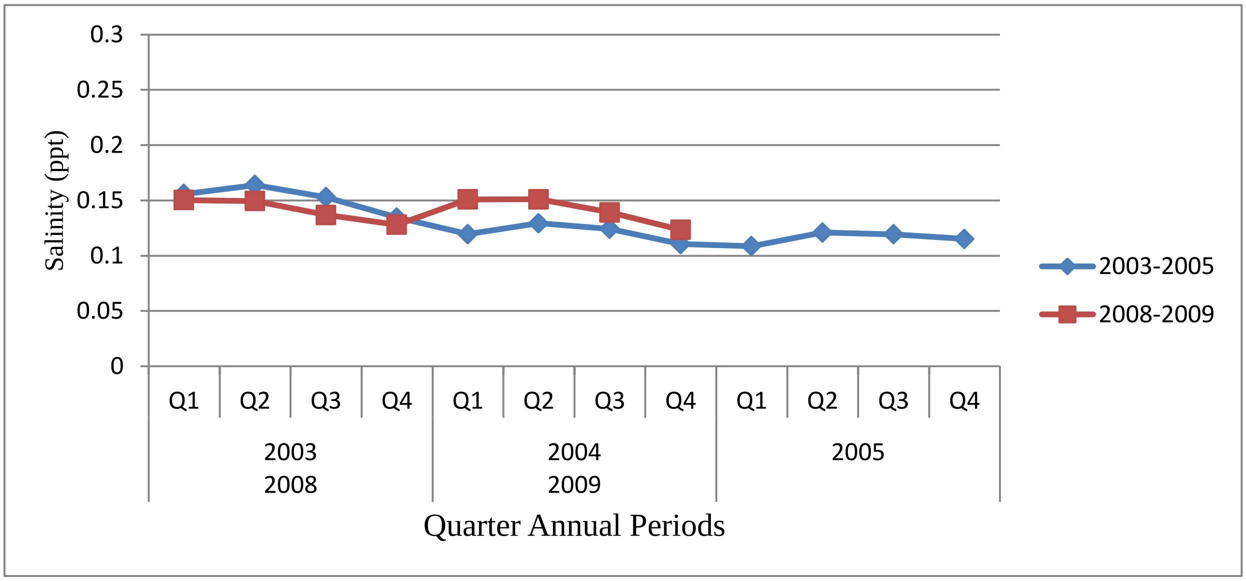

Figure 21: Sabanitas Salt Concentration at Depth 1 m above Bottom

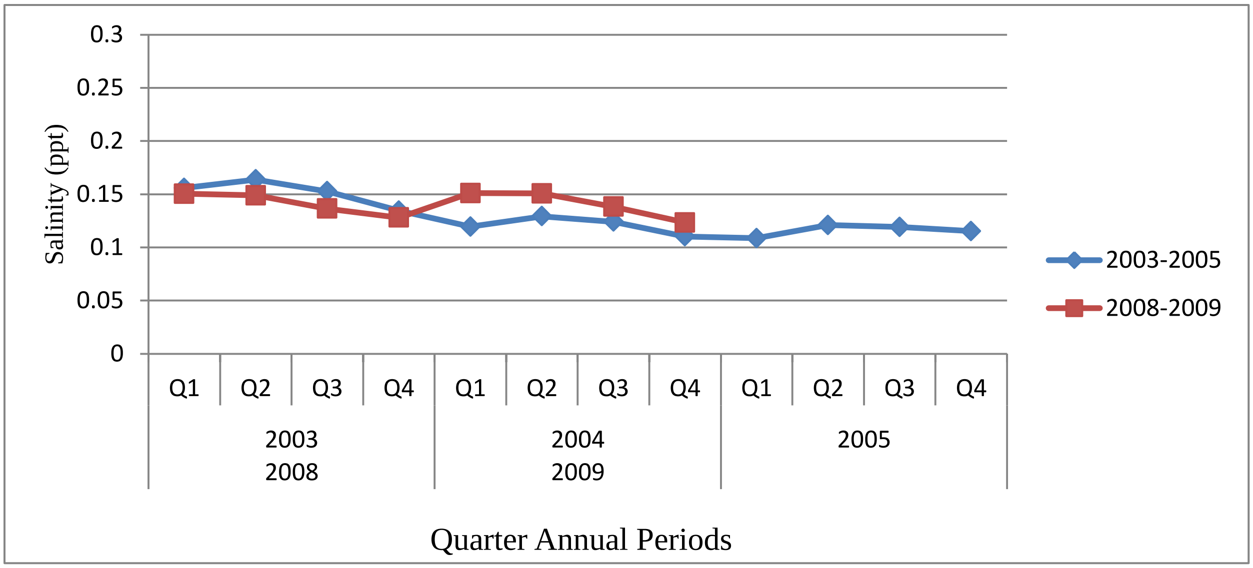

Figure 22: Sabanitas Salt Concentration at Depth 1 m below Surface

6.3.2 Mt Hope

Figures 23 and 24 illustrate that the volume-averaged salinities at the bottom and surface of Mt Hope over the two time periods (2003-2005 and 2008-2009) are very similar and their differences in salt levels are insignificant. The volume-averaged salinities vary between about 0.1 ppt and 0.16 ppt. This range of salinity in the years 2008 and 2009 is very low and is consistent with the years 2003-2005.

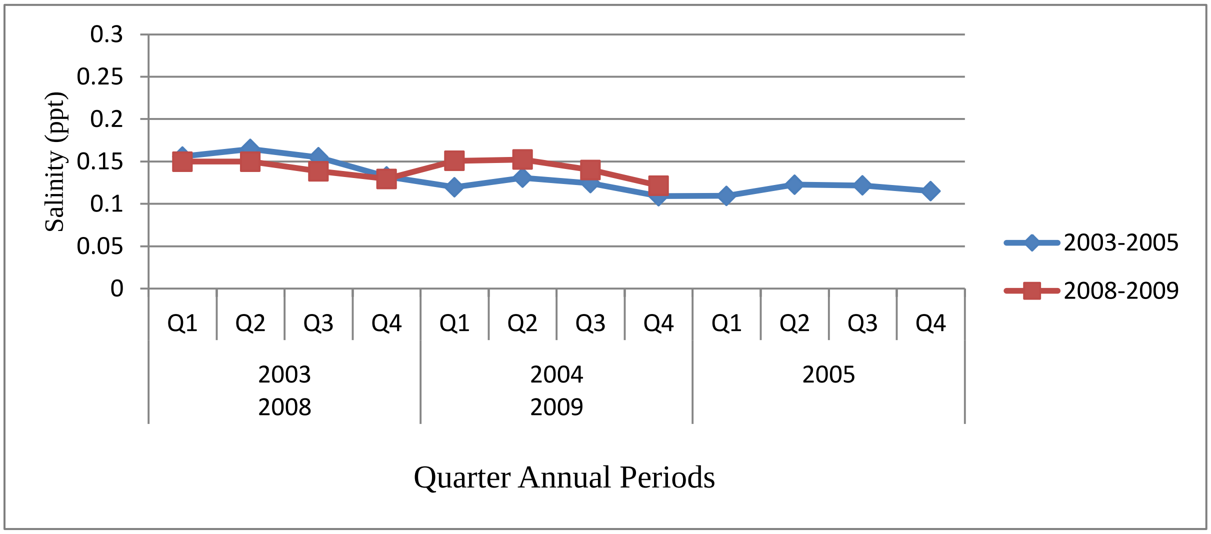

Figure 23: Mt Hope Salt Concentration at Depth 1 m above Bottom

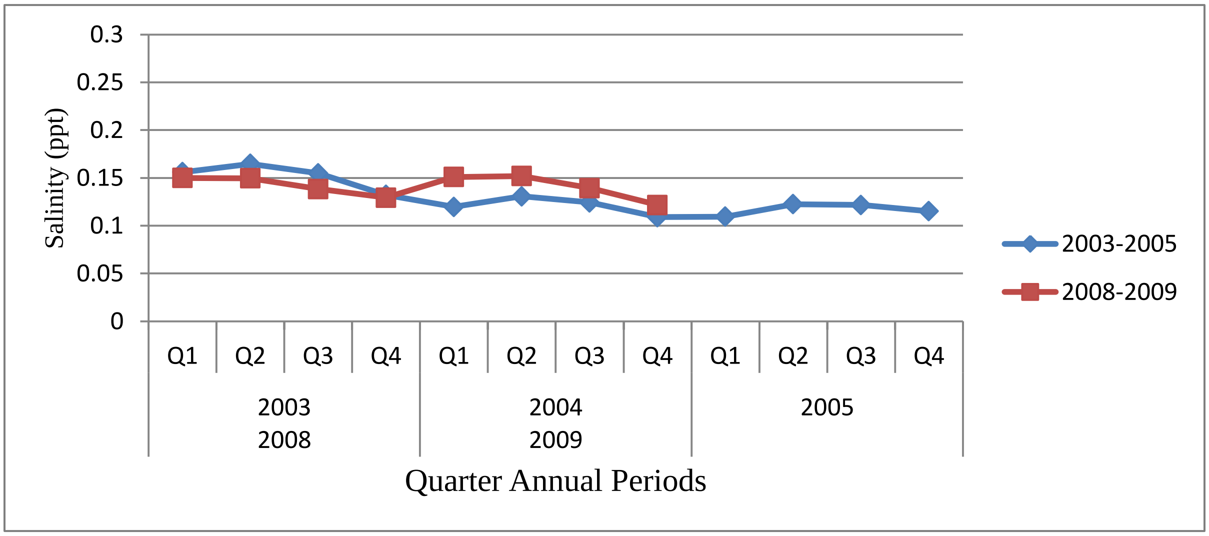

Figure 24: Mt Hope Salt Concentration at Depth 1 m below Surface

6.3.3 Escobal

Figures 25 and 26 illustrate that the volume-averaged salinities at the bottom and surface of Escobal over the two time periods (2003-2005 and 2008-2009) are very similar and their differences in salt levels are insignificant. The volume-averaged salinities vary between about 0.13 ppt and 0.2 ppt. This range of salinity in the years 2008 and 2009 is very low and is consistent with the years 2003-2005.

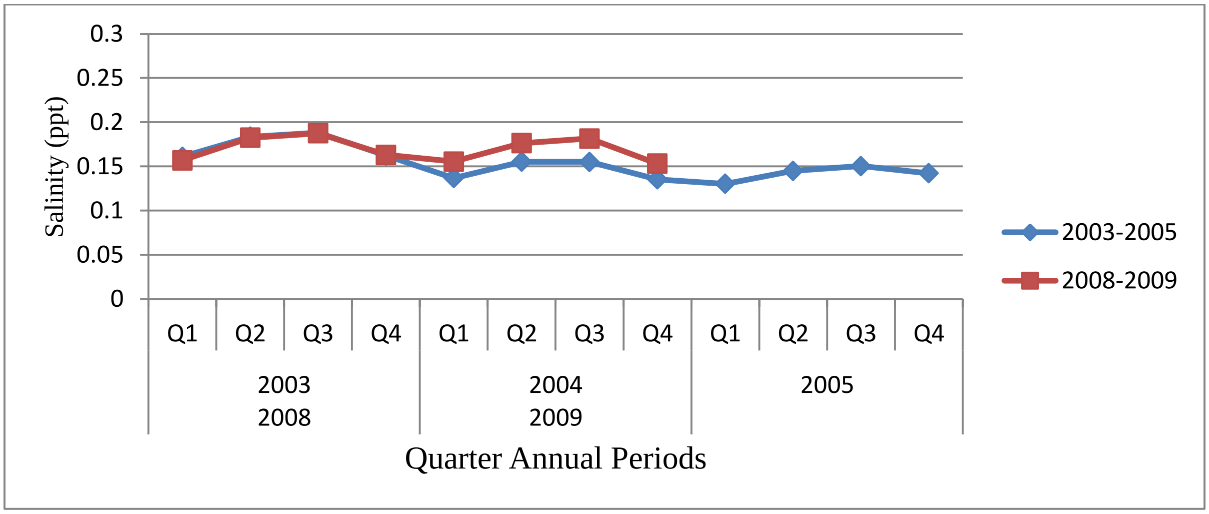

Figure 25: Escobal Salt Concentration at Depth 1m above Bottom

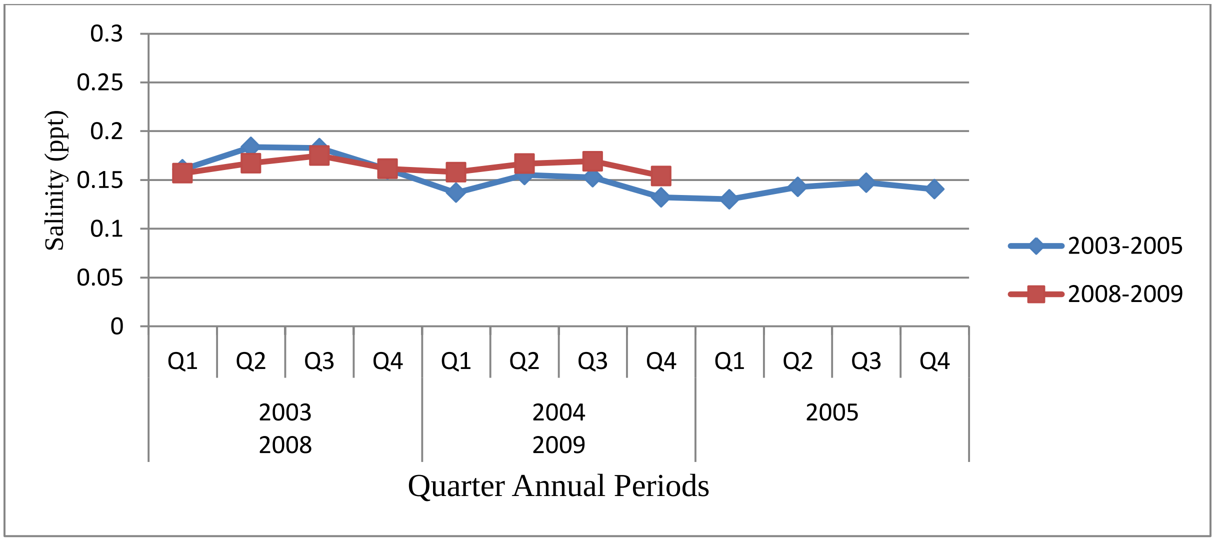

Figure 26: Escobal Salt Concentrations at Depth 1m below Surface

6.3.4 Gamboa

Figures 27 and 28 illustrate that the volume-averaged salinities at the bottom and surface of Gamboa over the two time periods (2003-2005 and 2008-2009) are very similar and their differences in salt levels are insignificant. Gamboa in particular has relatively low concentrations of salt of about 0.05 ppt. The maximum salt concentrations occur during the dry seasons in which there are long periods of dry heat and no precipitation. As a result more evaporation occurs in the lake leaving behind more salt as the salt does not evaporate with the water. Another reason this occurs is due to the lesser inflow of freshwater from the Madden Lake during these periods. The volume-averaged salinities vary between about 0.13 ppt and 0.2 ppt. This range of salinity in the years 2008 and 2009 is very low and is consistent with the years 2003-2005.

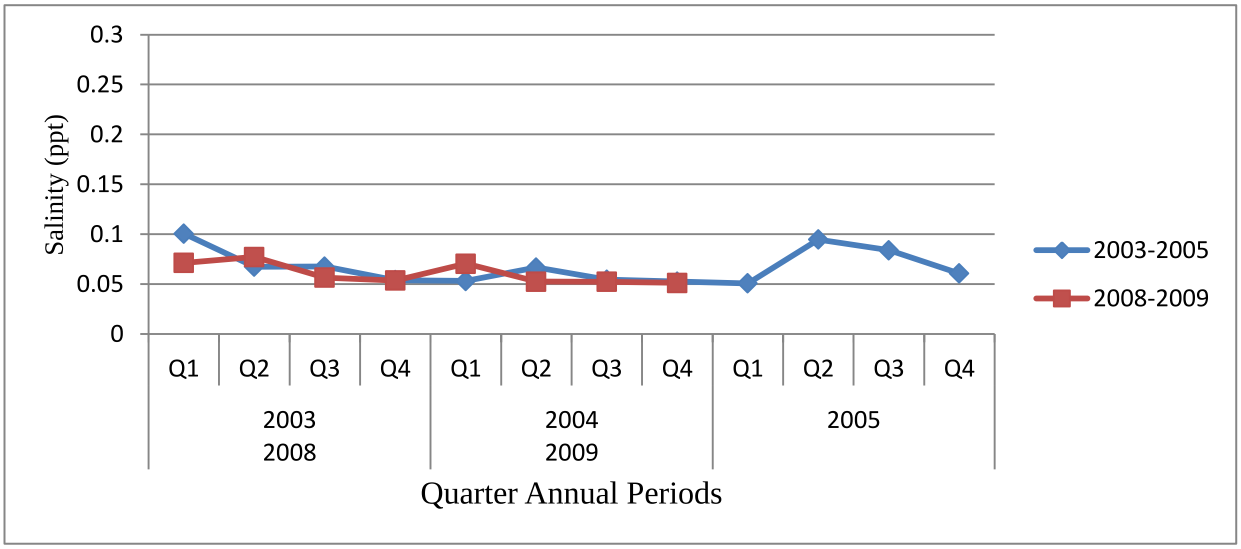

Figure 27: Gamboa Salt Concentration at Depth 1m above Bottom

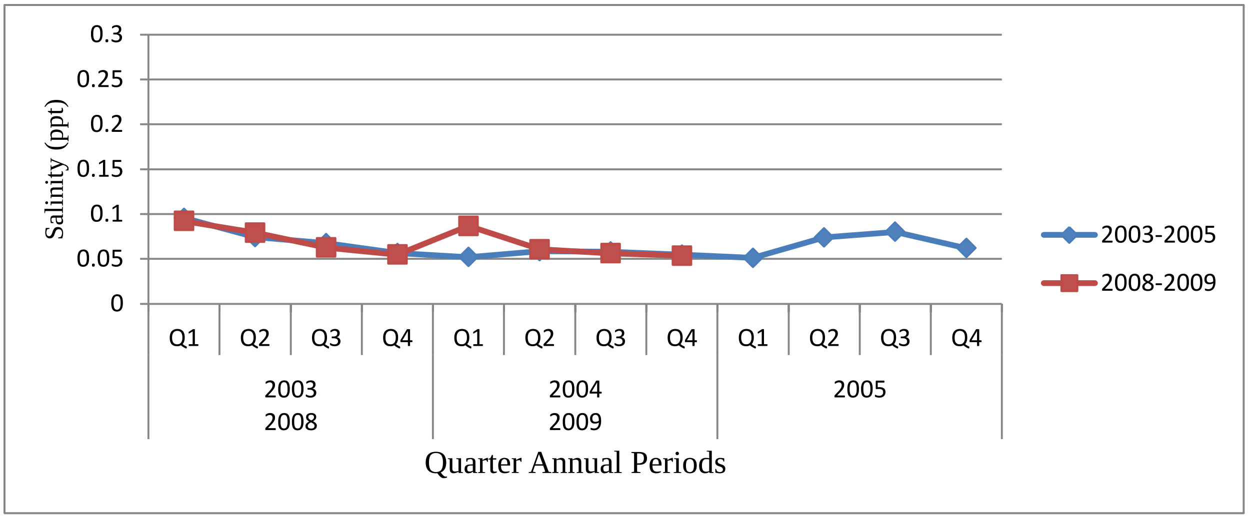

Figure 28: Gamboa Salt Concentration at Depth 1m below Surface

6.3.5 Paraiso

Figures 29 and 30 illustrate that the volume-averaged salinities at the bottom and surface of Paraiso over the two time periods (2003-2005 and 2008-2009). The volume-averaged salinities vary between about 0.15 ppt and 0.275 ppt and vary more significantly than at other freshwater intake stations. The salinity values presented here are also the highest of any station. This occurs mainly because the Paraiso water intake station is directly influenced by the Pacific Locks as it is located in close proximity to the Pedro Miguel Locks where the highest concentration of salt occurs. Although the results at this freshwater intake station vary more than others and are more elevated, the salinity levels present no concern as they are well below 0.5 ppt.

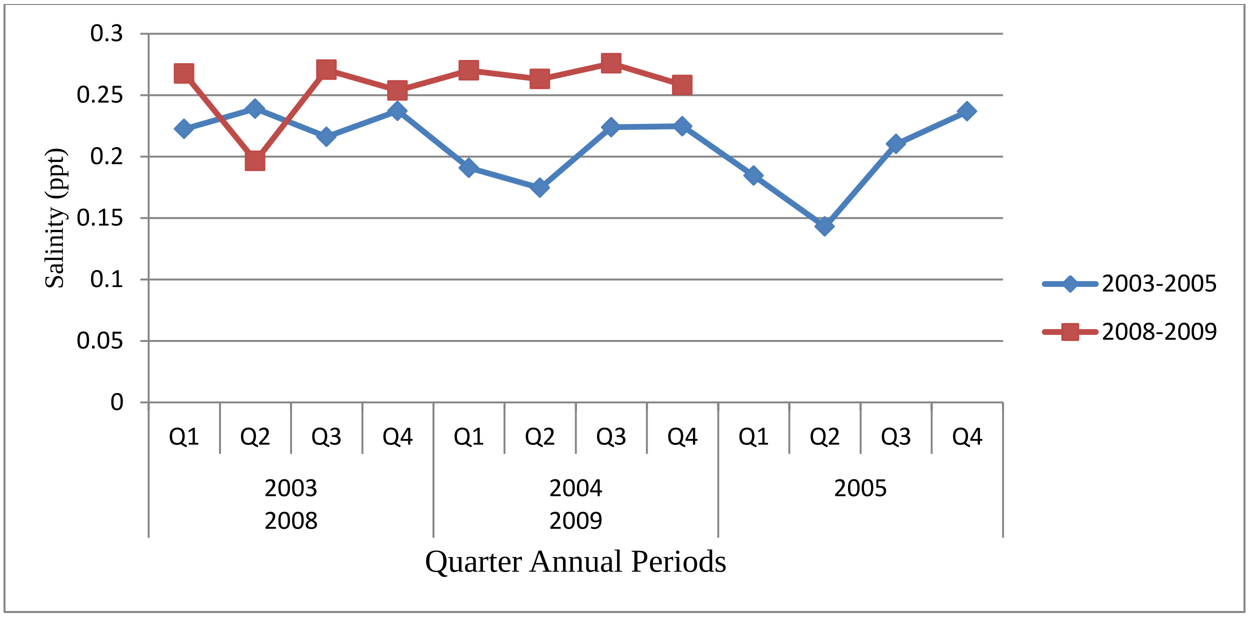

Figure 29: Paraiso Salt Concentration at Depth 1m above Bottom

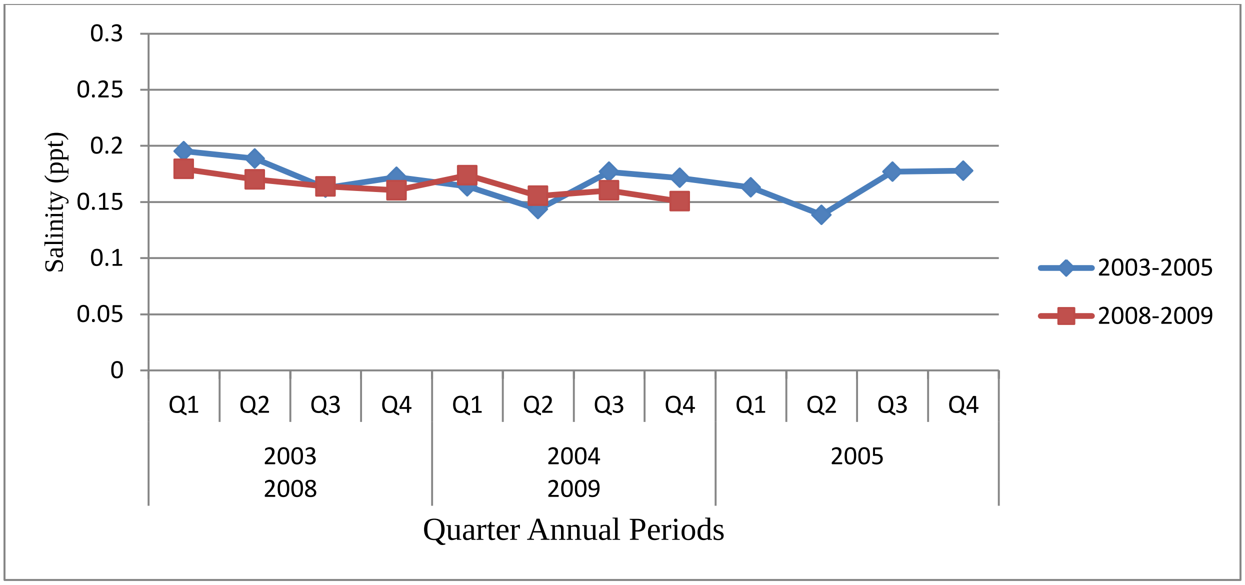

Figure 30: Paraiso Salt Concentration at Depth 1 m below Surface

6.3.6 Gatun Lake

As seen in Figure 31 the salt concentrations throughout the two time periods (2003-2005 and 2008-2009) are very consistent. The salinity ranges between 0.13 ppt and 0.2 ppt. The salinity values over the two studied time periods are within the acceptable freshwater range of 0.0 ppt – 0.5 ppt. These values coincide with what was anticipated looking at the historic data.

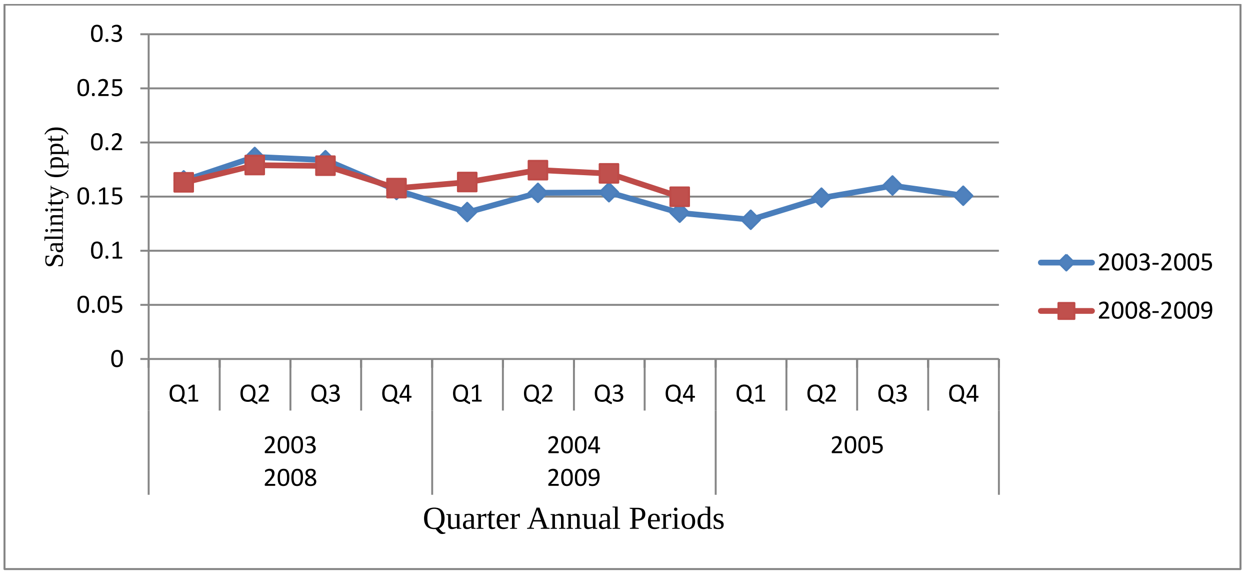

Figure 31: Volume-Averaged Salt Concentration in Gatun Lake

For all points and for Gatun Lake in whole, the project team observed that the salt levels are within the freshwater range (0 ppt - 0.5 ppt). Since Scenario 1 considers the operation of both the current and future lock system, the salinity results presented in this section demonstrate that salinity levels will remain consistent over time due to the operation of the current lock system (as demonstrated by Scenario 0 results) and will also remain consistent over time as a result of operating the future Post-Panamax lock system.

7.0 Water Treatment Plant

Delft3D modeling results showed that salt levels within Gatun Lake have remained consistent and are predicted to stay within the freshwater range, with salt levels less than 0.5 ppt. However, it is still possible that modeling efforts have not fully captured future water quality scenarios, or that changes in shipping schedules or operation of the locks could result in increased salt levels in Gatun Lake after the expansion project is completed. In order to prepare for these possible situations, the project team designed a water treatment facility that produces potable water for the city of Colon and the Panama City metro area considering brackish water conditions in Gatun Lake.

7.1 Plant Specifications

Gatun Lake supplies the populations of the Panama City metro area and the city of Colon with an estimated 115 MGD of water through three water treatment facilities. The Miraflores filtration plant is located on the Pacific side (45 MGD), and on the Atlantic side there is the Mount Hope filtration plant (42 MGD) and the Sabanitas filtration plant (28 MGD). The 2010 populations for the Panama City metro area and Colon are estimated at 1.207 million and 242,000, respectively (Hubbard, 2012). According to the CIA World Fact Book (2012), Panama experiences a population growth rate of 1.435% annually. Given the populations and annual growth rate, the 2032 populations of the Panama City metro area and Colon are an estimated 1.588 million and 318,000, respectively. Using a relative ratio of the 2010 populations and water demands to the projected 2032 populations, the water demand through 2032 is estimated to be 150 MGD.

Panamanian law requires that drinking water discharges comply with COPANIT 23-395-99 which states that treatment of surface waters requires some form of flocculation, coagulation, sedimentation, or filtration in addition to disinfection. Specific information on processes at the current water filtration plants was not available. A summary of important raw water quality conditions are listed in Table 2.

Table 2: Raw Water Quality in Gatun Lake (ACP, 2010)

Parameter	Average Value
Turbidity (NTU)	35.2
Dissolved Oxygen (mg/L)	6.06
pH	7.32
Conductivity (μS/cm)	148
Salinity (ppt)	0.5
Chlorine (mg/L)	8.3
Total Dissolved Solids (mg/L)	96
Total Suspended Solid (mg/L)	31
Alkalinity (mg/L $CaCO_3$)	52
$N\text{-}NO_2$ (mg/L)	0.001
$N\text{-}NO_3$ (mg/L)	0.198
$P\text{-}PO_4$ (mg/L)	0.010
SO_4 (mg/L)	3.2
Hardness (mg/L $CaCO_3$)	51.7
E. coli (MPN/100 mL)	64
Total Coliforms (MPN/100 mL)	2857

The project team assumed the same raw water quality as currently in the lake for the design of the plant, with the exception of increased salt. Brackish water is defined as water containing salt levels within the range of 0.5 ppt to 30 ppt. Any value above 30 ppt is considered salt water and any value below 0.5 ppt is considered freshwater. Due to the unlikelihood that the salt levels within Gatun Lake would reach 30 ppt, the team considered a lower value between 0.5 ppt and 15 ppt.

7.2 Design Alternatives

Treatment of brackish waters to drinking water standards (including a salt level less than 0.5 ppt) can be accomplished using membranes. The different types of membranes available are shown in Table 3. Microfiltration and ultrafiltration do not reject salt and are therefore not applicable for brackish waters. For this reason, microfiltration and ultrafiltration are not discussed further. While nanofiltration aids in the removal of salt by softening the water, the technology is not sufficient on its own to remove salt from water. Two technologies for salt removal that were examined are electrodialysis reversal and reverse osmosis.

Table 3: Membrane Types

Membrane	**Driving force**	**Membrane Structure**	**Applications**
Microfiltration	Pressure	Macropores	Pretreatment for NF and RO; particle, cyst, and bacterial removal
Ultrafiltration	Pressure	Mesopores	Pretreatment for NF and RO; macromolecule, cyst, bacteria, and virus removal
Nanofiltration	Pressure	Micropores	Softening; NOM removal
Reverse osmosis	Pressure	Dense, or thin film composite	Demineralization; TDS reduction, brackish and seawater desalinization
Electrodialysis Reversal	Electrical potential and pressure	Ion exchange	Brackish water desalinization

7.2.1 Electrodialysis and Electrodialysis Reversal

Electrodialysis (ED) is a membrane treatment processes that was developed in the 1950s. This process uses an electrical potential to remove salts and other ions through ion selective membranes to a concentrate collecting stream. The principal application of ED for water treatment is the desalination of brackish water.

Electrodialysis uses a configuration called an electrodialysis cell that consists of two compartments (dilute and brine) that are formed by an anion exchange membrane and a cation exchange membrane placed between two electrodes. Usually, multiple ED cells are arranged into a stack to provide a higher salt removal percentage. Anion and cation exchange membranes get arranged alternatively to form the multiple electrodialysis cell. ED cells separate the solution with anion exchange membranes, permeable only for anions and cation exchange membranes, permeable only for cations.

As shown in Figure 32, the stack of multiple ED cells has three different types of streams going through it. These streams are the dilute (D) feed stream, brine (C) stream, and electrode (E) stream. There are also an anode and cathode on two sides of the of ED stack. The anode and cathode are electrodes that have an electric current from a polarized electrical device flowing through them. Anions, negatively charged ions, migrate towards the positively charged anode because of an electrical potential difference. Anions pass through the positively charged ion exchange membrane, but they get stopped in the (C) stream when reaching the negatively charged ion exchange membrane, which results in (C) stream becoming highly concentrated with anions. The opposite happens to cations, which are positively charged ions. When they move towards the negatively charged cathode, they pass through the negatively charged ion exchange membrane and get stopped by the positively charged ion exchange membrane and also stay in the (C) stream. Electric current flows between the cathode and anode because of the anion and cation migration. As a result of the electrodialysis process, the (C) stream ends up highly concentrated with ions, while the ion concentration in the (D) stream dramatically decreases. The (E) stream flows past each electrode in the stack and it can have the same or different species as the feed stream passing through it.

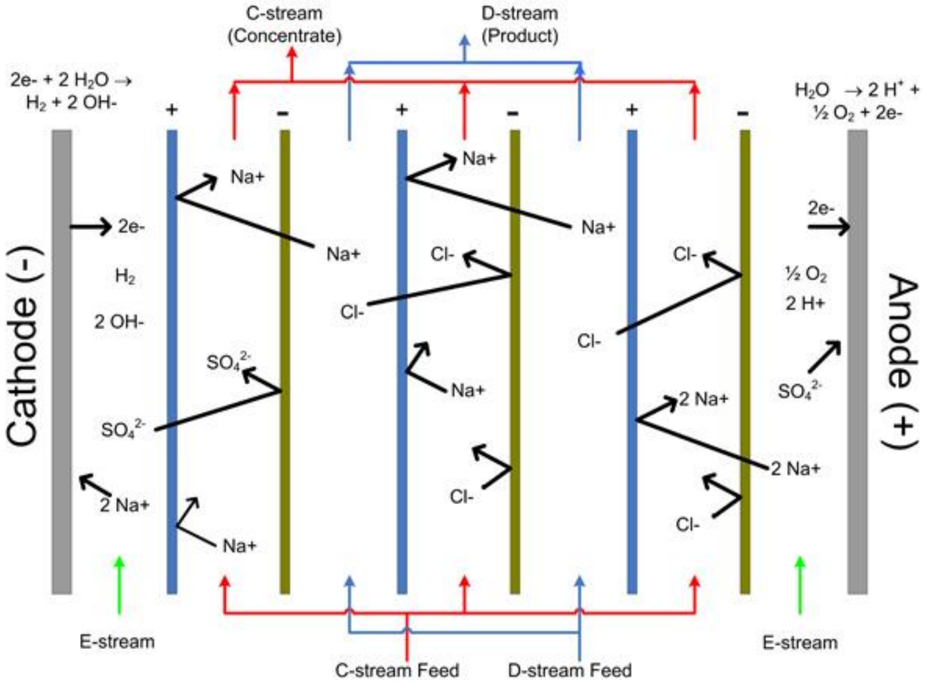

Figure 32: Electrodialysis Process (EET Corporation, 2009)

Electrodialysis reversal (EDR) uses the same concept as electrodialysis, except the polarity charges on the membrane get periodically changed, which causes the flow to reverse. It is done to reduce fouling and to extend the membrane life.

Typical removal of salt from brackish water ranges from 25 to 40 percent of dissolved solids per stage of treatment. Therefore, efficient removal of salt by ED requires multiple stage treatment systems. With every additional stage the salt percent removal increases by 25 – 30 percent. Figure 33 shows a schematic of a three-stage EDR process with four treatment trains, which has 90% overall recovery and 87.5% solute removal (Trussell Technologies, 2008).

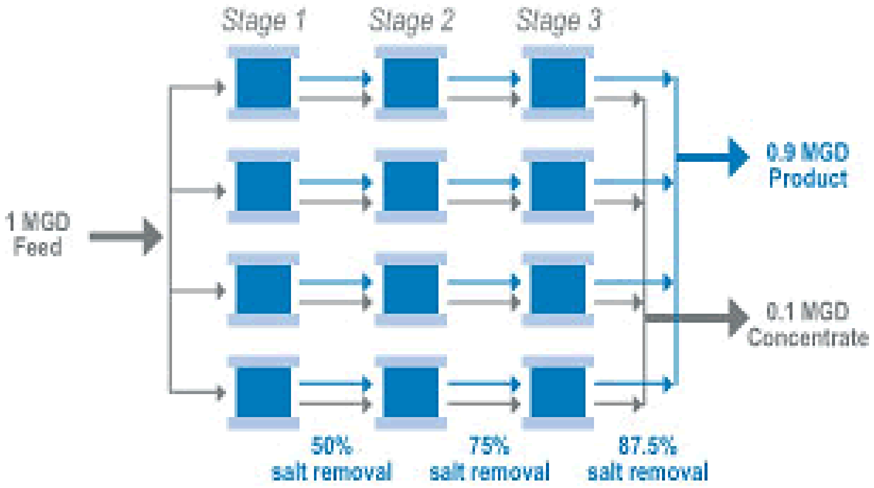

Figure 33: EDR configuration (Trussell Technologies, 2008)

The energy requirement for ED systems is 2.6 – 4.2 kWh/1,000 gallons of product water for removal of 300 mg/L of dissolved solids. In addition to salt, ED can also remove various contaminants such as potassium, zinc, acetate, TDS and others.

Electrodialysis membranes are very resilient, and can be used under a wide range of pH conditions (pH 2 – 11). These membranes can endure high temperatures during cleaning, and can be scrubbed if necessary. If maintained properly, membranes can be used up to 15 years. Various solids left in the system can be flushed out by turning the power off and letting water circulate through the stack. Each stack has to be disassembled, mechanically cleaned, and put back together on a regular basis (TSC Water Treatment Engineering Team, 2010).

7.2.2 Reverse Osmosis

Reverse osmosis (RO) is a widely used process for the desalination of brackish and seawater. In RO, water is forced from a stronger saline solution to a weaker one through a semi-permeable membrane. The semi-permeable membrane blocks the passage of salt particles through the system and only allows water molecules to pass because the salt particles are larger than the water molecules (Figure 34). The result of the process is desalinized, purified water on one side and a solution of concentrated salt, known as brine, on the other side. The brine is removed from the system and disposed of.

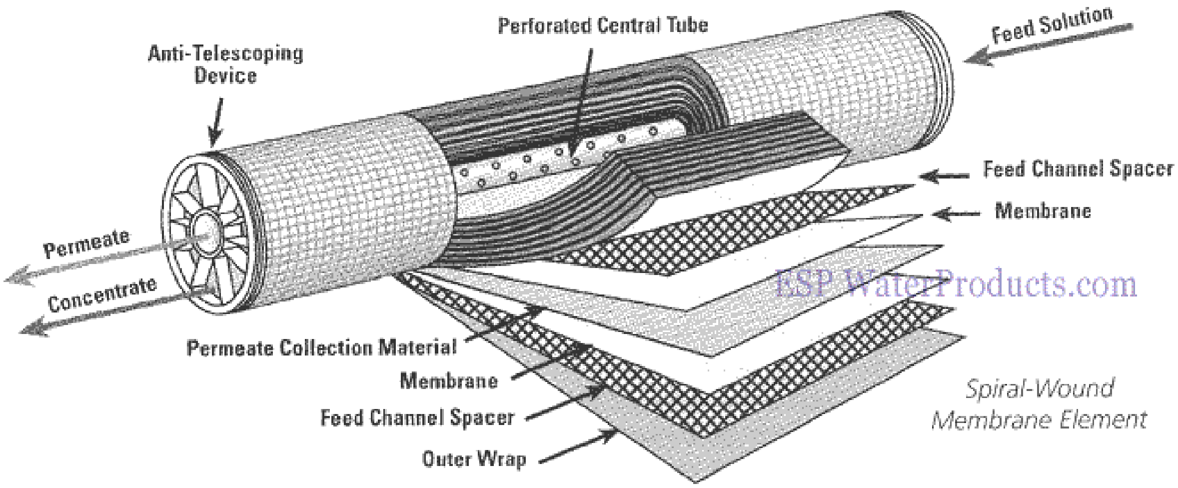

Figure 34: Reverse Osmosis Process (E.S.P. Water Products, 2009)

A pretreatment system is typically required prior to RO in order to reduce scaling, plugging, and membrane fouling. Options for pretreatment include microfiltration, ultrafiltration, cartridge filtration, coagulation/flocculation, and sedimentation. Properly designed RO systems reject 90 to 99% of the salt. In addition to salt, RO systems remove lead, manganese, iron, calcium, and fluoride. However, RO will not remove contaminants such as chlorine and volatile organic chemicals (VOCs). VOCs are synthetic chemicals such as insecticides and herbicides. Due to their small size, chlorine and VOCs pass through the semi-permeable membrane and remain in the drinking water.

Due to membrane fouling, the membrane within the system should be replaced every 5 to 7 years depending on the quality of water flowing through the system. To enhance the performance and life of RO systems, it is necessary to complete regular flushing of the system using treated water as well as intervals of chemical cleaning of the semi-permeable membrane when necessary.

7.2.3 Membrane Process Selection

Electrodialysis reversal and reverse osmosis were compared for treating brackish water based on operation conditions recovery and cost as shown in Table 4. RO systems require extensive pretreatment with large amounts of chemicals involved. RO also requires a higher operating pressure than EDR. RO systems have a process recovery of 65 – 75% in comparison with EDR systems that have a process recovery of 80 – 90%. This means that an EDR system has a lower feed water usage and wastewater discharge cost. As mentioned previously, EDR systems are resistant to bacteria and are not affected by high temperatures, which means that they do not require special storage space. EDR systems have an average membrane life of 7-10 years and can be cleaned with acid (Valero *et al.*, 2011). RO systems require specific storage conditions with controlled temperatures. When being cleaned, RO systems require the addition of acid and a sequestering agent; the resulting waste then has to be additionally treated when being discharged to the environment. RO systems have a membrane life of 5-7 years, which is lower than EDR systems. For these reasons, the project team recommends a treatment plant with electrodialysis reversal for treating brackish water from Gatun Lake.

Table 4: Comparison of Electrodialysis Reversal and Reverse Osmosis

Comparison criteria	**Electrodialysis Reversal**	**Reverse Osmosis**
Operating pressures	60 – 100 psi	150 – 400 psi
Process recovery	80 – 90%	65 – 75%
Reject water percentage	10 – 20%	25 – 35%
Costs/energy requirement	Cost effective	Only more cost effective than ED/EDR when TDS is > 3000 mg/L
Pretreatment requirement	Required	Recommended
Driving force	Electric potential and pressure	Pressure
Mechanism of separation	Ion exchange, dialysis	Solution/diffusion + exclusion
Durability	7 – 10 years	5 – 7 years

7.3 Disinfection

In addition to the membrane system, which satisfies treatment requirements for filtration, Panamanian law requires water treatment plants treating surface water to have a disinfection system. Disinfection is used in water treatment plants to prevent waterborne diseases from entering the water distribution system by inactivating or killing pathogens. Disinfectants also oxidize organic compounds in water supplies. Primarily, water treatment facilities use chemical oxidants for disinfection, including chlorine, chlorine dioxide, and ozone. More recently, drinking water treatment facilities have also implemented ultraviolet (UV) disinfection in which UV light propagating from a source, usually a mercury lamp, interacts with materials in the water through absorption, reflection, refraction, and scattering (AWWA, 2005). Absorption is the most important mechanism for disinfection, in which UV light is absorbed by the DNA of microorganisms. Whether a water treatment plant utilizes chemical disinfection or UV disinfection, each disinfection system has its own advantages and disadvantages. Table 5 presents a summary of disinfection options, which are further discussed in the following sections.

Table 5: Characteristics of Disinfectants (adapted from MWH, 2005)

Characteristic	**Disinfectant**			
	Chlorine	**Chlorine Dioxide**	**Ozone**	**Ultraviolet light**
Inactivation of:				
Bacteria	Excellent	Excellent	Excellent	Good
Viruses	Excellent	Excellent	Excellent	Fair
Protozoa	Fair to poor	Good	Good	Excellent
Endospores	Good to poor	Fair	Excellent	Fair
Frequency of use as Primary Disinfectant	Most Common	Occasional	Common	Emerging Use
Regulatory limit on Residuals	4 mg/L	0.8 mg/L	Not Applicable	Not Applicable
Formation of Regulated Byproducts	4 THMs; 5 HAAs	Chlorite	Bromate	None
Formation of Other Byproducts	Cyanogen halides, NDMA	Chlorate	Biodegradable organic carbon	None Known
Typical Dose, mg/L (kg/ML)	1 – 6	0.2 – 1.5	1 – 5	20 – 100 mJ/cm^2
Typical Dose, lb/MG	8 – 50	2 – 13	8 – 42	Not Applicable

7.3.1 Chlorine

Chlorine disinfection is widely used in the drinking water industry as a disinfectant. Chlorine effectively inactivates a wide range of waterborne pathogens, produces a free chlorine residual in the system that ensures the drinking water is properly disinfected, and has the lowest relative costs to other disinfectant chemicals. In addition, chlorine serves as an oxidizing agent to oxidize naturally occurring organic and inorganic compounds found in water. Chlorine disinfection prevents algal growth in treatment systems, removes potential scale-forming metals like iron and manganese, oxidizes hydrogen sulfide, and bleaches organic dyes which compromise the aesthetics of the drinking water. However, chlorine produces disinfection by-products when it reacts with organic matter. Some of these byproducts are known or suspected carcinogens. Also, there is a health and safety concern when chlorine gas is administered into a treatment system since the gas is classified by the U.S. Department of Transportation as poisonous (HDR Engineering, Inc., 2001). Chlorine can be applied as a gas, liquid or solid. Chlorine is delivered as liquid gas in tank cars, 1 ton and 150 lb cylinders, or as liquid bleach which can be generated onsite from salt and water using electrolysis. In very small applications, calcium hypochlorite powder is also used as a source for chlorine disinfection. In the past, chlorine was added at the beginning of the plant and residual was carried through. Increasingly, engineered contactors are used (MWH, 2005).

7.3.2 Chlorine Dioxide

Not as widely used as chlorine, another disinfectant used in drinking water treatment is chlorine dioxide. This disinfectant is effective in destroying phenols and other organics in water without the formation of the byproducts trihalomethanes (TTHs) and haloacetic acids (HAAs), which are formed during chlorine disinfection. Chlorine dioxide does not dissociate or disproportionate as chlorine does at normal drinking water pH levels (~ 6 to 10) and as a result is a faster acting disinfectant than chlorine at higher pH levels. It exerts a demand when it is first added to a water supply, which must be overcome if a persistent residual is to be maintained throughout the system. Like chlorine, chlorine dioxide is photosensitive, and because it is a gas at temperatures above 11°C, its residuals are easily removed by aeration. It is unsafe to store chlorine dioxide once it is generated because it is a gas that readily reacts with multiple stimuli. An increase in temperature, exposure to light, changes in pressure, and exposure to organic contaminants in the water may cause the pure gas to explode. As a result, chlorine dioxide is usually generated through a two-chemical oxidative process, in which chlorine, either as a gas or in solution, is mixed with a 25 percent sodium chlorite ($NaClO_2$) solution. It can also be generated by direct electrolysis of sodium chlorite as powder or stabilized liquid solution. In the past, chlorine dioxide was typically added at the beginning of the plant and residual was carried through. Increasingly, engineered contactors are used. Chlorine dioxide has gained popularity throughout Western Europe and the United States because the disinfectant does not form the undesirable byproducts formed by chlorine disinfection. Still, there is concern that there are other organic byproducts of chlorine dioxide that are not yet well understood, and it may have other undesirable reaction products (AWWA, 2005).

7.3.3 Ozone

An allotrope of oxygen with three oxygen atoms, ozone (O_3) is a strong oxidative gas. As a result, extended exposure to ozone-containing air is harmful. At high concentrations (>23 percent) ozone is unstable (explosive) and under ambient conditions it undergoes rapid decay. Therefore, unlike chlorine gas, it cannot be stored inside pressurized vessels and transported to the water treatment plant (HDR Engineering, Inc., 2001). Consequently, like chlorine dioxide, ozone must be generated onsite. Ozone is manufactured onsite using a corona discharge in dry air or pure oxygen. Oxygen is usually delivered as a liquid. In some large plants, oxygen is also manufactured onsite (MWH, 2005).

Once dissolved in water, ozone begins a process of decay that results in the formation of the hydroxyl radical. For the inactivation of microorganisms and chemical breakdown of organics in water, ozone reacts in two ways: (1) by direct oxidation and (2) through the action of hydroxyl radicals (HO•) generated during its decomposition. Treatment plants using ozone disinfection require two components: (1) a mass transfer device for dissolving the ozone into the water and (2) a contact chamber in which the disinfection reaction takes place. In practice these two components have been combined by the introduction of the ozone into the water in large, deep basins using porous diffusers. When designing an ozonation system there are many challenges that must be addressed including: determining a means for estimating mass transfer of ozone into the water, having an understanding of the kinetics of ozone decay, having an understanding of the disinfection kinetics, and determining a means for estimating dispersion in the reactor. For a full-scale water treatment design addressing all of these issues with a variety of approaches can be difficult. In addition, since ozone is sparingly soluble, the facilities that are required to introduce it into water are usually expensive (HDR Engineering, Inc., 2001). Ozone has always been added in specially engineered contactors. Currently, these contactors are using more compartments and other techniques are being experimented with (MWH, 2005).

7.3.4 Ultraviolet Disinfection

Disinfection by ultraviolet (UV) radiation inactivates microorganisms by absorption of light, which causes a photochemical reaction that alters molecular components essential to cell function. UV radiation is excellent when disinfecting microorganisms such as bacteria and viruses. Higher dosages of UV energy are required for the inactivation of protozoa such as *Giardia* and *Cryptosporidium*. In addition, no undesired by-products or residual remain as a result of UV disinfection; UV radiation [via electromagnetic waves] quickly dissipates into water, to be absorbed or reflected off material within the water. For germicidal purposes the optimal UV range is between 245 and 285 nm. Within a disinfection system low-pressure lamps emit maximum energy output at a wavelength of 253.7 nm, and medium-pressure lamps emit energy at wavelengths from 180 to 1370 nm. Lamps that emit at other wavelengths in a high-intensity “pulsed” manner can also be utilized (HDR Engineering, Inc., 2001). Ultraviolet light lamps are placed in gravity channels or in specially manufactured UV reactors. Because the contact time is so short, reactors must be tested for short circuiting (MWH, 2005).

7.3.5 Disinfection Process Selection

Since the water treatment plant was designed for treating water in Panama, the team considered the suitability of each disinfectant and its accompanying system to its application in the country of Panama which is undergoing aggressive infrastructure development (CIA, 2012). Although an excellent oxidative chemical, chlorine produces undesirable byproducts that would require an additional removal process, increasing costs and complexity to the system by the introduction of another system. Chlorine dioxide is suited for more sophisticated and equipped facilities as it requires mixing tanks and chlorine dioxide is a highly reactive and dangerous gas. Since ozone is sparingly soluble, an additional system is needed to facilitate the mass transfer of ozone into water and a contact tank is needed for chemical reaction. In contrast, UV disinfection is cost-effective and does not produce unwanted byproducts. In addition, UV lamps can be installed with minimal maintenance or health concerns.

7.4 Water Treatment Plant Design

In the EDR process, polarity reversal is used to dissolve and flush precipitated salts from the brine out of the system without involving any chemical pretreatment (HDR Engineering, Inc., 2001). Still, some form of pretreatment is necessary. For this application, a 5-micron cartridge filter was chosen as a means of pretreatment. Cartridge filters are typically used for point-of-use systems and for pretreatment in advance of membrane treatment systems. These filters can be made out of membrane, fabric, or string filter mediums, which are supported by a filter element and placed in a pressure vessel. In the design of a water treatment plant for Gatun Lake, the team has referred to the drinking water treatment plant (DWTP) built in Abrera (Barcelona), Spain. This plant was designed by General Electric and was put into operation in April 2009 (Valero *et al.*, 2011).

The DWTP in Abrera has a total flow of 58 MGD. The plant uses cartridge filters for pretreatment and electrodialisys reversal units for treatment. Details of the process design are shown in Table 6. The plant has 18 cartridge filters followed by 9 EDR modules. These numbers include both processes in operation and those off-line for cleaning and maintenance. The design was scaled up to a design for a 150 MGD plant for Panama City. As shown in Table 6, the Panama City plant is designed with 48 cartridge filters and 24 EDR modules.

Table 6: The Main Characteristics of Abrera and Panama City Water Treatment Plants

Process	**Abrera Plant (58 MGD)**	**Panama City Plant (150 MGD)**
Number	18	48
Pore Size	5 µm	5 µm
Flow per cartridge	3.2 MGD	3.125 MGD
Number of off-line filters	4	8
Modules	9	24
Stacks per module	64	64
Stacks (total)	576	1536
Number of off-line EDR stacks	1 module = 64 stacks	3 modules = 192 stacks

A total of 18 cartridge filters with a pore size of 5 µm are used during the pretreatment for the water flow of 58 MGD (Valero el al., 2011). Scaling up to 150 MGD, a total of 48 cartridge filters with a pore size of 5 µm will be needed.

Electrodialisys reversal was chosen for the desalination of the brackish water. The DWTP of Abrera uses 9 modules with 576 stacks in double stage (Valero el al., 2011). Scaling up to a water demand of 150 MGD will require 1536 EDR stacks in double stage as well.

The disinfection system designed for the Panama water treatment plant is based off of the Orange County water district's ground water replenishment system located in California. While the Orange County plant design is not focused on treating brackish water, it is still applicable because the design has the capability to desalinate water and incorporates some of the same design components as the plant for Panama: microfiltration, reverse osmosis, and ultraviolet disinfection. The treatment plant has a capacity to treat 70 million gallons of water per day. Trojan UV Phox equipment is used for the UV disinfection system. The design incorporated 9 ultraviolet trains with three stainless steel vessels installed in a vertical row as well as 39 low pressure, high output UV lamps in each of the two chambers within in the vessels (Chalmers *et* *al.*, 2008). For the Panama City plant, the design includes 20 trains with 7 stainless steel vessels installed in a vertical row as well as 84 UV lamps in order to treat a flow of 150 MGD. All preceding values were obtained using a relative ratio to the referenced Orange County water district's ground water replenishment system. The contact time will be within the range of 20 to 30 seconds which is the typical contact time reported by the Environmental Protection Agency (EPA, 1999).

Figure 35 provides a schematic of the Gatun Lake water treatment plant design. Untreated brackish water is stored in the storage tank. The water from the storage tank is pumped into 48 cartridge filters for pretreatment. After being filtered, pretreated water is pumped into 24 modulus of electrodialysis stacks, with each modulus containing 64 stacks where brackish water is desalinated. After the EDR stacks, water is transferred into 20 trains of the UV disinfection system.

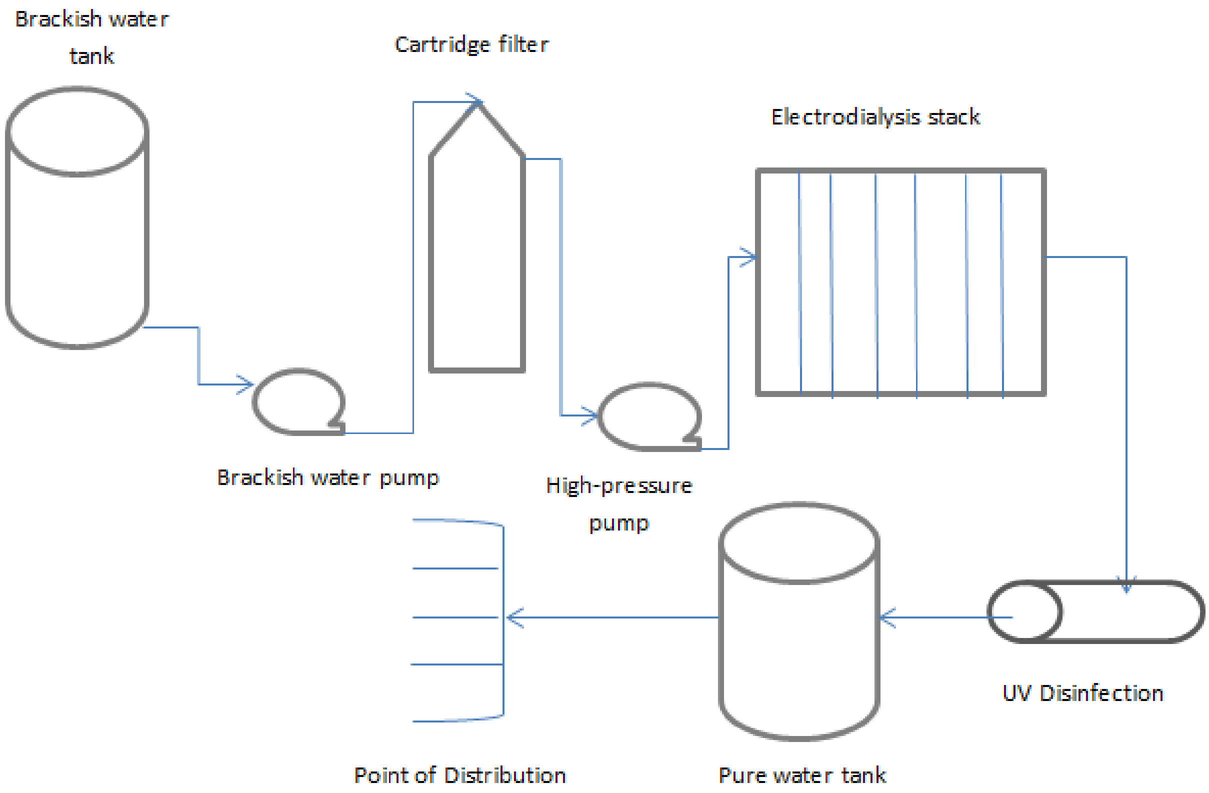

Figure 35: Water Treatment Plant Flowchart

8.0 Conclusion

Current salinity levels in Gatun Lake were determined from water quality sampling campaign conducted in 2011, which showed that the lake water is of freshwater quality. Then, a modeling program was used to model salinity in the lake under current canal conditions (Scenario 0) and future Post-Panamax conditions (Scenario 1). Modeling results showed that salinity levels in Gatun Lake are expected to remain low after the expansion project is complete. Namely, the results show that with the current lock system in operation the conditions of Gatun Lake have remained consistent over time, up to the present-day. Furthermore, the results indicate that salinity levels will remain consistent even with the operation of the Post-Panamax lock system in the future. However, it is possible that the modeling efforts of Delft3D did not fully capture the future water quality of Gatun Lake or that changes in canal operation could cause future changes to the salinity in Gatun Lake. Based on these potential issues, a drinking water treatment plant was designed to treat water from Gatun Lake assuming it was brackish. Based on treatment process research and requirements in Panamanian for the treatment of surface waters, the final design incorporated an EDR system for salt removal and UV light for disinfection.

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