Panama Canal Extension: A review on salt intrusion into Gatun Lake

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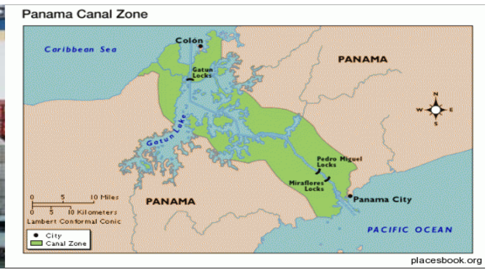

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Summary

The Panama Canal consists of two sets of lock systems. One on the Pacific side and one on the Caribbean side. The lock systems are separated by the freshwater Gatun Lake. The lock systems elevate the ships to a height of 26 meters above sea level in order to navigate Gatun Lake. The freshwater from Gatun Lake is used to operate the locks by gravitational forces. With the migration of the ships through the locks, salt water is transported upward and penetrates Gatun Lake. More salt is transported in upward direction during downlockage than during uplockage of the vessels.

The Panama Canal will be extended with additional larger locks that can transport the larger Post-Panamax vessels. With the completion of the expansion, more freshwater is needed to operate the locks and more salt water will penetrate Gatun Lake, especially during the dry season. It is expected that the increased salt concentration in Gatun Lake will impact biodiversity and effects drinking water supply to Panama city.

This report gives a review of various studies focussing on salt water penetration into Gatun Lake. Modelling studies show that salinity concentrations in Gatun Lake will remain below 0.5 ppt. Locally, in the near vicinity of the locks the bottom water could increase up to 0.7 ppt during the dry season. In general those salinity concentrations are too low for marine and brackish species to survive. Therefore, it is not feasible that Gatun Lake could be a stepping stone for marine exotic species to migrate between the Pacific ocean and the Caribbean sea. Some freshwater species in Gatun Lake, in the near vicinity of the locks could be impacted by the increased salt concentrations. Further study on the species composition, the sensitivity to salt water and the expected salt concentrations is needed.

Various potential mitigating measures to prevent the increase of salt concentration in Gatun Lake have been discussed. Measures range from the increase of the freshwater supply to the reduction of water use and physical methods to prevent the mixing of fresh water and salt water.

1 Introduction

1.1 Background

The Panama Canal was constructed in 1881-1914 to allow ships to sail from the Atlantic Ocean to the Pacific Ocean and vice versa. Ships are transferred through a three-step lock waterway at both sides. The Panama Canal needs to be extended to ascertain the envisioned traffic demand and to allow the transit of the larger Post-Panamax vessels. Therefore, a third lane will be added with larger locks that are suited for those Post-Panamax vessels. One of the potential effects of the Expansion of the Panama Canal is that Gatun Lake, which is a freshwater lake that is used for drinking water, will increase in salt concentration. The present freshwater conditions in Gatun Lake preserve the biological separation of the oceans while safekeeping biodiversity and water quality for human use. Increasing salt concentrations could potentially have an impact on these functions of Gatun Lake.

The European Investment Bank (EIB), which is one of the investors in the Panama Canal Expansion project, has received complaints from various stakeholders concerning the effects of salt intrusion in Gatun Lake due to the Panama Canal Expansion. The Complaint Mechanism of the EIB has requested IMARES to review the existing reports concerning salt intrusion into Gatun Lake. The main issues are:

- Penetration of salt water into Gatun Lake.
- Loss of biodiversity due to the increased salinity.
- Water management in the area, especially during the dry season.
- Migration of exotic species between Pacific and Caribbean.
- Potential mitigating measures.

1.2 Reports provided by client

The Complaint Mechanism of the EIB has provided IMARES with PDF files of 14 reports (Table 1). The present report consists of a thorough review of these reports with special attention to the issues mentioned above. Where needed, additional literature and information was used.

Table 1 Overview of literature provided by client

Nr.	Description	Reference
1	Jongeling, T. H. G. (2003) Salt water intrusion analysis Panama canal Locks. Existing situation. Report A: Field data collection, development and validation of simulation model, analysis of salt water intrusion.	(Jongeling, 2003c)
2	Jongeling, T. H. G. (2003) Executive summary: Salt water intrusion analysis Panama canal Locks. Existing situation. Report A: Field data collection, development and validation of simulation model, analysis of salt water intrusion.	(Jongeling, 2003b)
3	Jongeling, T. H. G. (2003) Salt water intrusion analysis Panama canal Locks. Existing situation. Report A: Field data collection, development and validation of simulation model, analysis of salt water intrusion. Annex A: Salinity measurements wet season	(Jongeling, 2003d)
4	Jongeling, T. H. G. (2003) Salt water intrusion analysis Panama canal Locks. Existing situation. Report A: Field data collection, development and validation of simulation model, analysis of salt water intrusion. Annex B: Salinity measurements dry season	(Jongeling, 2003e)
5	Jongeling, T. H. G. (2003) Salt water intrusion analysis Panama canal Locks. Future situation: Post-Panamax Locks. Report B: single-lift locks, Report C: three-lift locks, report D: two-lift lock	(Jongeling, 2003f)
6	Roux, S., F. Storck en J. Gouverneur (2004) Conceptual design to recycle water in Post Panamax locks. Hydraulic part.	(Roux et al., 2004)

Nr.	Description	Reference
7	Jongeling, T. H. G. (2005) Salt water intrusion analysis Panama canal Locks. Future situation: Post-Panamax Lock. Report F: Study, modeling and analysis of salt water intrusion mitigation systems for revised 3-lift lock configurations	(Jongeling, 2005)
8	URS Holdings, I. (2005) Tropical lake ecology assessment with emphasis on changes in salinity of lakes. Project No. SAA-140714. Final technical memorandum #5. Water quality sampling plan,	(URS Holdings, 2005)
9	Vested, H. J., E. A. Hansen, O. Petersen en H. Nasner (2005) Review of saltwater intrusion and mitigation studies and models for proposed Post-Panamax locks. Final report.	(Vested et al., 2005)
10	Vested, H. J. (2005) DHI project quality plan. Review of possible saltwater intrusion and mitigation studies and models for proposed Post-Panamax locks.	(Vested, 2005)
11	Jongeling, T. H. G., D. Schwanenberg en R. Hulsbergen (2009) Water Quality Model of Gatun Lake for Expanded Panama Canal. Part I Modelling of the present situation. WL | Delft Hydraulics, Rapport nummer: Q3959, 224 pagina's.	(Jongeling et al., 2008)
12	Jongeling, T. H. G., F. Zijl en R. Hulsbergen (2009) Water Quality Model of Gatun Lake for Expanded Panama Canal. Part II Modelling of the future situation.	(Jongeling et al., 2009)
13	Jongeling, T. H. G. (2008) Water Quality Model of Gatun Lake for Expanded Panama Canal. Water Quality Monitoring. Final report part III	(Jongeling, 2008)
14	Louis Berger Group Inc (2008) Technical consulting services for the Panama Canal expansion program	(Louis Berger Group Inc, 2008)

1.3 Set-up of report

This report starts with a general overview including the water balance of the present situation (chapter 2). In chapter 3, an overview is given on the Post-Panamax extpasion of the Panama Canal. Chapter 4 focuses on the modelling of salt water within the locks and in Gatun Lake. Finally, in chapter 5 conclusions are presented of this review study, focusing on the effect of salt intrusion into Gatun Lake.

2 Present situation

2.1 Overview

The Panama Canal was constructed in 1881-1914 to allow ships to navigate from the Atlantic Ocean to the Pacific Ocean and vice versa. The total length of the route is 77 km. The transport route crosses Gatun Lake (26 meter above sea level), which was created in 1913 by damming the Chagres river, to reduce the amount of excavation work. The water from Gatun Lake is used to operate the Panama Canal locks and provides drinking water for Panama City.

Figure 1 Overview of the Panama Canal

2.2 Shipping locks

Ships are elevated to the Gatun Lake by a set of 3 locks at both sides. The Gatun Locks are located at the northern, Caribbean side. At the southern side, the Miraflores Locks are separated from the Pedro Miquel Locks by the Miraflores Lake. The Lock chambers are 304.8 meters in length and 33.53 meters in width. Vessels with maximum dimensions of 32.3 meters in beam, 294.1 meters in length and 12 meters of draft can be transported through the locks.

No pumps are used at the Panama Canal. The water does its work by force of gravity alone. Water is admitted or released through giant tunnels, or culverts, eighteen feet in diameter, running lengthwise within the center and side walls of the locks. A large number of holes distributes the water evenly over the full floor area to control turbulence.

2.3 Navigation

Between Gatun and Pedro Miguel Locks the vessels need to navigate through Gatun Lake (30 km) and Culebra Cut (13 km). Gatun Lake is a shallow lake. Continuous dredging takes place in order to deepen the channel of the lake. The Gaillard Cut is an excavated channel with a very complex geology and is the narrowest section of the navigational track. Large ships cannot navigate both directions the same time. Restrictions are in effect for vessels with beams greater than 27.8 meters. To cope with this limitation, convoy transit methods are employed daily, with northbound vessels transiting in the morning and southbound in the afternoon. This transit mode tends to create idle time at the Pacific Locks, whose effect is reduced by mooring vessels at tie-up stations north and south of Pedro Miguel Locks (Louis Berger Group Inc, 2008).

2.4 Hydrology

2.4.1 Water storage lakes

The Panama region has two predominant seasons: a dry season that begins in mid-December and extends through April; and a wet season that extends through the rest of the year, with heavy rainstorms frequently occurring from September to November. The Panama Canal watershed has two artificial lakes for the storage of freshwater: Gatun Lake and Alhajuela Lake (Madden Lake) (Figure 2). The watershed that feeds these two lakes covers an area of 339,649 hectares. Within the Canal, there exist also a terminal lake between Pedro Miguel and Miraflores Locks, which is called the Miraflores Lake.

Gatun Lake has a surface area of 436 km^2 and an average elevation of 26 meters. Its active storage range is limited to less than 2 meters (26.67 – 24.84 meters Precise Level Datum, PLD) due to the need to maintain a water depth of 13.6 meters with a channel bottom elevation at 11.3 meters PLD. This is needed to allow the transfer of Panamax vessels at maximum permissible draft of 12 meters. The storage capacity of Gatun Lake under the existing configuration has been estimated at 766 x10^6 m^3. Alhajuela Lake is located midway down the Chagres River, west of Gatun Lake. Alhajuela has a surface area of about 50 km^2, an active storage range of 18.9 meters (76.81 – 57.91 meters PLD), and a storage volume of 651x10^6 m^3 (Louis Berger Group Inc, 2008).

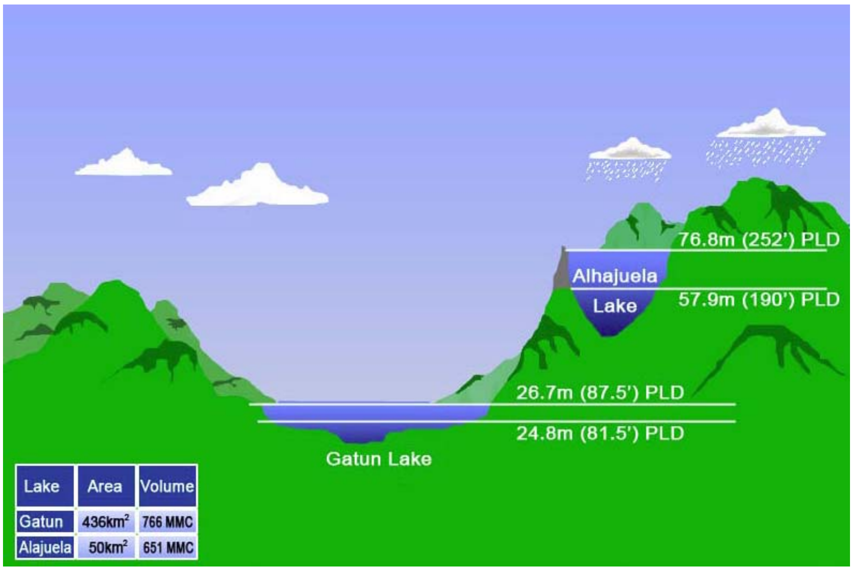

Figure 2 Elevation and water level variation of Alhajuela Lake and Gatun Lake (Louis Berger Group Inc, 2008).

Gatun Lake is filled with rainwater that accumulates in the lake during wet months. During the dry season, and especially during El Niño, there is a shortage of water. The spillway in Gatun Dam is designed for a maximum discharge of 4955 m^3 s^{-1}. The spillway is combined with a hydropower plant. The water level in Miraflores Lake is controlled by the Miraflores spillway with a maximum discharge of 2600 m^3 s^{-1}. Alhajuela Lake is used to compensate the water loss in Gatun Lake.

2.4.2 Water budget

The water from Gatun Lake and Alhajuela Lake is used for the operation of the Locks, hydropower generation and drinking water. The Panama Canal has three spillways—one at each lake and hydroelectric plants at Alhajuela with 36 megawatts of capacity and at Gatun with 24 megawatts of capacity. Both the hydroelectric power dams and spillways are used to regulate the water levels in Gatun and Alhajuela lakes. The Miraflores spillway is used to regulate the water level upstream of Miraflores Locks. During the period 1993 to 2004, the water input to these lakes from precipitation was estimated at 5.3×10^9 m^3 $year^{-1}$. Nine percent of this volume was lost due to direct surface lake evaporation, leaving the net runoff at 4.8×10^9 m^3 $year^{-1}$. When Gatun Lake is at its maximum operating level or when the water levels of the lakes are rising faster than normal, the water is released to avert flooding conditions (0.6×10^9 m^3 $year^{-1}$), leaving the net usable runoff at 4.2×10^9 m^3 $year^{-1}$. This net runoff is used for drinking water, industrial uses, transit operations and for generating electricity at the Madden and Gatun hydropower facilities. For the period 1993-2004, net usable runoff was allocated at 7% (0.3×10^9 m^3 $year^{-1}$) for potable water, 59% (2.5×10^9 m^3 $year^{-1}$) for transit operations and 34% (1.4×10^9 m^3 $year^{-1}$) for hydropower (Louis Berger Group Inc, 2008).

Historical runoff data and the existing configuration of the watershed showed that it is capable of producing enough water for 99.6% of the time, while supplying 38.7 lockages/day, with only the most severe droughts, e.g. El Niño phenomena of 1982-83 and 1997-98, forcing the Canal to reduce maximum draft below the 12 meters (critical depth) for a few weeks on each occasion.

Due to the dredging of the navigational channel of Gatun Lake to 10.4 meter elevation PLD, the active storage range of Gatun Lake has increased proportionally. The maximum freshwater supply for the watershed at 50 lockages/day, is more than adequate to meet the demand from the population and the existing Canal operating at its maximum capacity, while maintaining extremely high levels of reliability for guaranteeing maximum ship draft.

2.4.3 Alternative water management

During dry periods, especially during El Niño, supply of freshwater from Gatun Lake could become limiting. Nine alternatives have been studied to save water during those dry periods (Louis Berger Group Inc, 2008). Four of them involved the construction of new reservoirs (Coclé del Norte/Cano Sucio, Toabre, Rio Indio and Alto Chagres). One increased the storage of Gatun Lake by using pump storage (Lower Trinidad). One option was to recycle spilled water from the locks. Two options increased the active storage volume of Lake Gatun by deepening its navigational channel and by raising its maximum operating level. The last option was the re-use of the water within the locks using water saving basins (Figure 3). Based on investment costs, water supply and social and environmental impact, the last option, the use of water saving basins, was selected as the most favourable alternative.

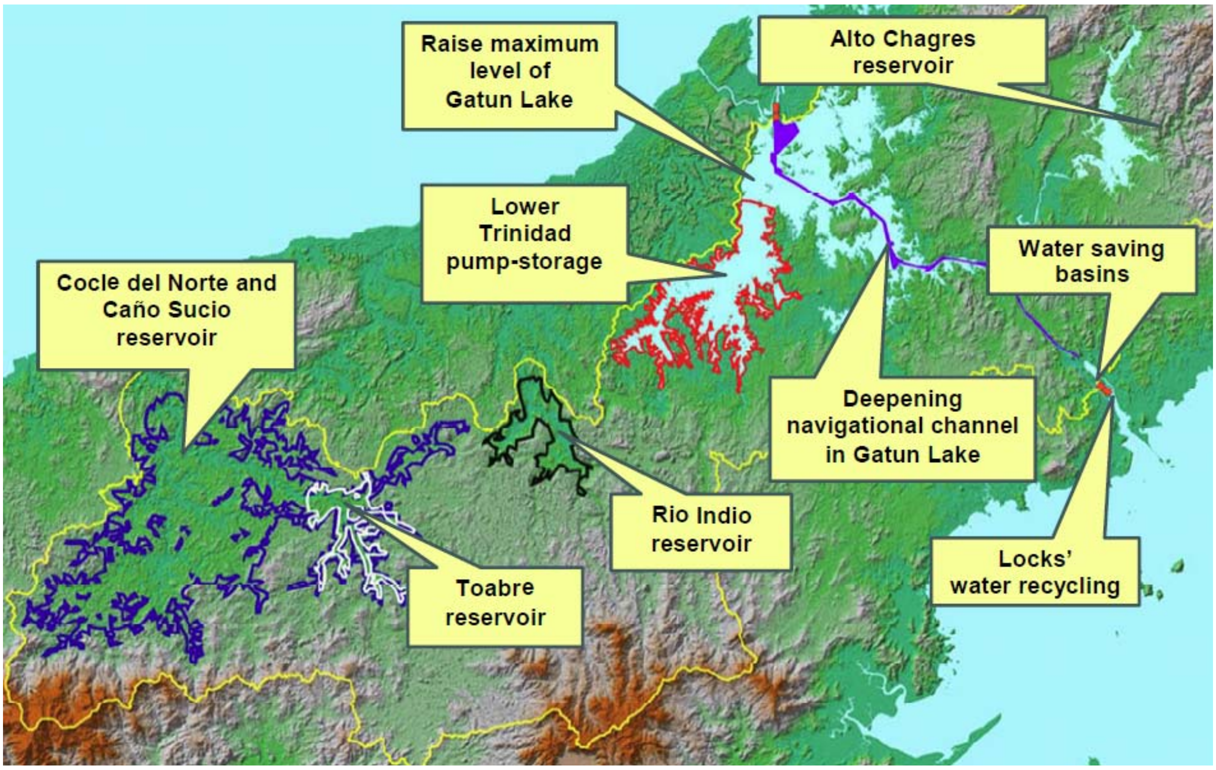

Figure 3 Overview of options studied to increase water supply or reduce water consumption (Louis Berger Group Inc, 2008)

Water saving basins (WSB) have successfully been used in German locks for over a century, providing savings on upstream water extraction of 40%, 60% and over 70% depending on the number of water saving basins used. All the German locks with water saving basins, however, have a single lift and are basically meant for raising and lowering relatively small barges. This technology has never been tried for large Post-Panamax locks with multiple lifts, but the concept seemed straight-forward and scalable (Louis Berger Group Inc, 2008).

3 Panama Canal expansion

3.1 Configuration

The present canal has two lanes both with their own set of locks. The expansion project will add a third lane at each end of the canal. The new locks in the third lane will be larger than the locks of the existing lanes and will be able to transport the larger Post-Panamax vessels. The Panama Canal expansion will double the capacity of the Panama Canal. The project is expected to create a demand for ports that handle the larger Post-Panamax ships.

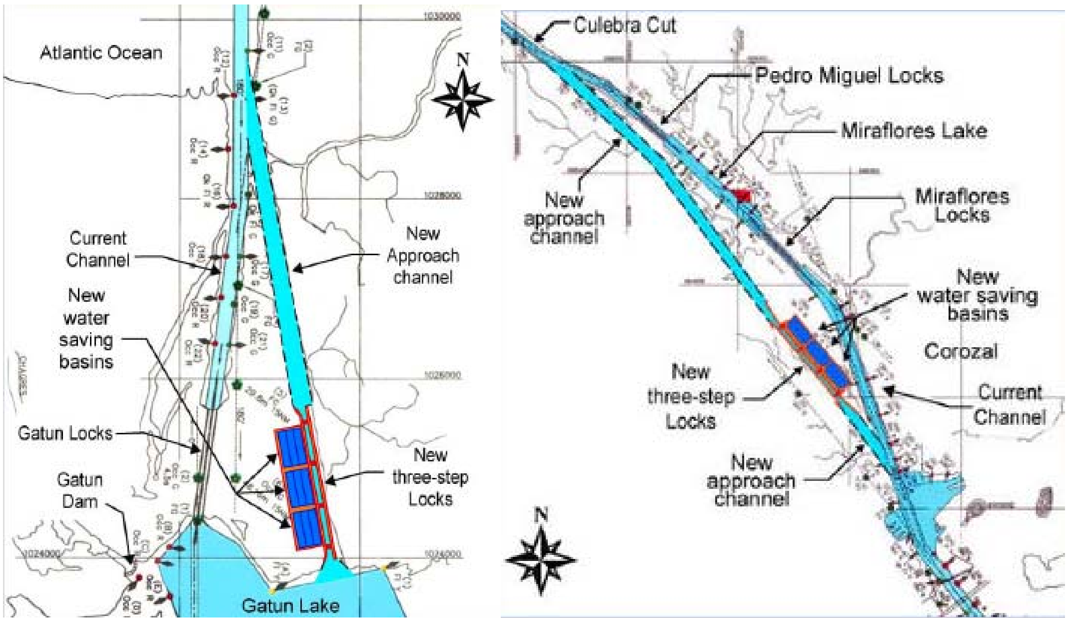

Figure 4 Overview of the expansion of the Panama Canal at the Atlantic Ocean (left hand side) and the Pacific Ocean (right hand side). (www.pancanal.com)

3.2 Shipping locks

The existing lock chambers are 304.8 meters in length and 33.53 meters in width and permit the transit of vessels with maximum dimensions of 32.3 meters in beam, 294.1 meters in length and 12 meters of draft. The new locks have a width of 55 meters, a minimum depth of 18.3 meters and a length of 427 meters. With this increase in lock volume, the amount of water that is lost to the oceans will increase. In order to reduce the amount of water that will be lost to the ocean, water saving basins (WSB) have been designed (Figure 5). The idea of these basins is that less freshwater is needed to fill the locks. The freshwater is re-used and because of that the salinity in the water saving basins increases.

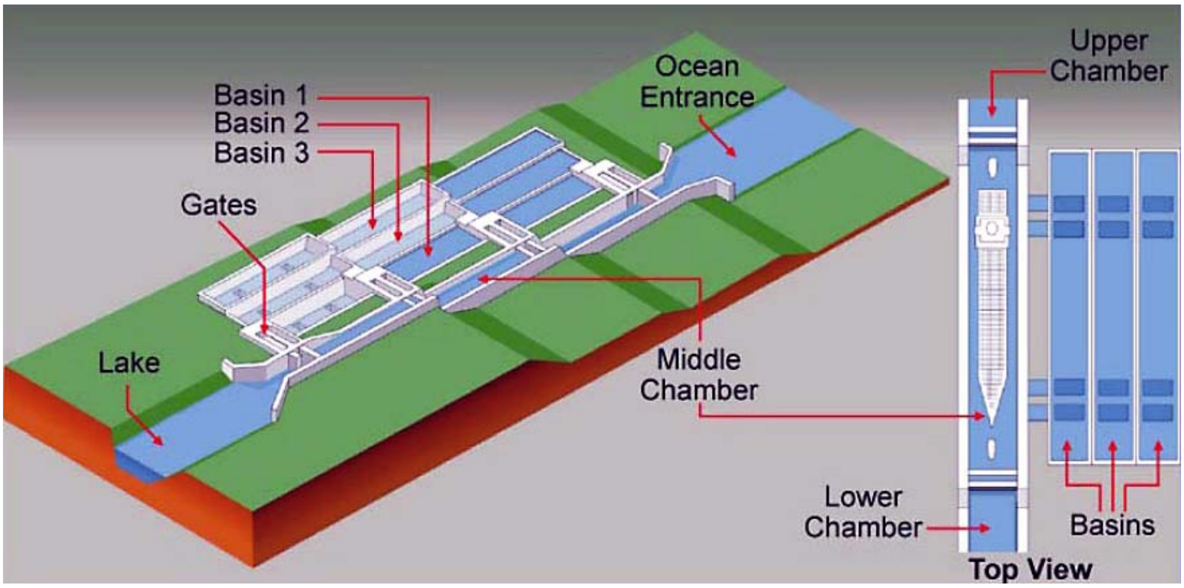

Figure 5 Overview of the locks and the water saving basins for the Panama Canal extension (Louis Berger Group Inc, 2008).

A lot of freshwater is spilled into the oceans due to locking of the ships. In a detailed study different scenarios for recycling water using pumping stations instead of water saving basins were explored (Roux et al., 2004):

- Direct pumping station from tailwater (Pacific Ocean) into Gatun Lake;
- Semi-direct pumping with a new constructed lower pond to capture spilled water from the locks. Water is pumped from the lower pond to the forebay of the locks;
- Semi-direct pumping with two ponds, a lower and an upper pond.

All three scenarios were studied for a 2-lift and a 3-lift lock system with and without water saving basins at different daily traffic levels of Post-Panamax vessels.

The first option was the worst case in terms of salt intrusion into Gatun lake. The last option is most favourable for preventing salt intrusion into Gatun Lake. However, all three pumping scenario's would create unacceptable salinity levels in Gatun Lake and therefore water saving basins are a better alternative.

The water saving basins make it possible to re-use the water within the locks and reduce the amount of water that is spilled into the ocean. Locks and their basins are filled and emptied by gravity. However, the water-saving basins of the new locks will also allow more salt water to penetrate into Gatun Lake. The salt concentration of the water in the water saving basins is, generally, also higher than the water in the adjacent higher lock, causing less dilution of the water in the receiving lock chamber. Therefore, the effect of using water saving basins is a greater inflow of salt water into Gatun Lake

4 Modelling salt water intrusion

Salt water intrusion into the fresh water of Gatun Lake is a major factor of concern for the Post-Panamax expansion. Increased salt concentration could impact the biodiversity of the lake and could be a threat to the drinking water supply of the region

Water from Gatun Lake goes stepwise down to the oceans during uplockage and downlockage of the ships, by mixing with the water in the lower locks. When the ship moves to the next lock, the ship's volume of water is exchanged and density flows occur between basins with different water densities (due to salinity difference). This allows salt water to move from the lower basins to the higher basins, and finally into Gatun Lake. Average salinity levels decrease considerable in each higher lock chamber. Spillage of water from the locks causes a reduced salinity in the near surface waters in the oceans.

More salt is transported in upstream direction during downlockage than during uplockage. Important factors are mixing of the waters during filling of the locks and the replacement of the water (submerged volume of the ship) when the ship leaves a lock. The upward step at the entrance of a higher lock, together with the return current along the ship are effective means to limit salt water intrusion during uplockage. Moreover, fill water from the higher adjacent lock during uplocking is drawn from the bottom layer, which has highest salinity.

In 2003, WL | Delft Hydraulics conducted a study on the salt intrusion of the Panama Canal locks for the existing situation (Jongeling, 2003b, c, d, f) and the future situation (Jongeling, 2003e). In these studies, field data on salinity concentrations were collected in a wet season (Jongeling, 2003c) and a dry season (Jongeling, 2003f). Also a simulation model (SWINLOCKS) was developed and calibrated with field observations (Jongeling, 2003b, d). With the calibrated model simulations have been executed for three future scenarios (Jongeling, 2003e).

The reports of the study of WL | Delft Hydraulics (Jongeling, 2003a, b, c, d, e, f) have extensively been reviewed by DHI (Vested, 2005; Vested et al., 2005). The focus of the review was on the following aspects:

- Salt water intrusion in Locks with SWINLOCK model;
- Critical factors in the model;
- Mitigation systems;
- Simulation of mitigation.

4.1.1 Salinity measurements

Salinity measurements were carried out in a wet season (November-December 2001) (Jongeling, 2003d) and in a dry season (April 2002) (Jongeling, 2003e). The wet season in Panama is from mid-May to the end of December. The dry season is from January to mid-May. Due to this seasonality, the water level in Gatun Lake varies. Other processes that may cause seasonal variation are upwellings at the Pacific coast during the dry season and variation of water release from the lakes.

The purpose of the salinity measurements was to determine exchange coefficients of the water within the Locks and to calibrate and validate the numerical model. Measurements were carried out in Locks, but also in Gatun Lake and Miraflores Lake in the vicinity of the locks. The measurements have been done with two, fast response CTD (Conductivity, Temperature and Depth below water surface) instruments. With those instruments, vertical profiles over the water column have been measured. From the measurements, salinity and density can be derived as a function of water depth.

The applied CTD's have a lower measurement limit of 0.1 ppt. Since many of the measurements in Gatun Lake are in the order of 0.1 ppt, the relative error of these measurements is quite high. However, the main reason for these measurements were to calibrate the SWINLOCKS model, a model to simulate the water balance within the locks. The measurements within the lock system, where salinity is higher than 0.1 ppt were sufficient for that.

4.1.2 Results salinity measurements

The salinity in Miraflores Lake, which is within the lock system on the Pacific Ocean side, is higher than in Gatun Lake. The average salinity concentration in Miraflores Lake during the wet season is about 0.7 ppt. In the dry season, the average salinity increases up to 1.5 ppt. The Miraflores Lake acts as a buffer against salt penetration into Gatun Lake from the Pacific Ocean side. Measurements of salinity in the shipping channel between Gatun Locks and Pedro Miguel Locks are close to 0.0.

Historical salinity measurements (1916 – 2000) in Gatun Lake and Miraflores Lake show that the salt concentrations in Gatun Lake are generally low (<0.2 ppt). In Miraflores Lake, the salinity levels have increased after the completion of the Panama Canal. As a result, Miraflores Lake was abandoned in the past as a source of drinking water. At present, salinity levels in Miraflores Lake can increase up to 3.0 ppt locally.

4.1.3 Model set-up and calibration

The salt and water balance within the lock systems is calculated with the SWINLOCKS model. The SWINLOCKS model consists of a series of mutually connected basins. Variables are water volume and volume-averaged salt concentrations within each basin. Exchange of water and salt is calculated by water flow and salt exchange coefficients. With the model the effect of up- and down-lockage, and flushing events on salt transport can be modelled. The model is not aimed to predict the time dependent dissemination of salt water in Miraflores Lake and Gatun Lake. The model was calibrated with the salinity measurements during a dry and wet season in Miraflores Lake and Gatun Lake.

Upward leakage of salt from the Ocean to Gatun Lake is depending on mixing processes of water of different salinities within the locks during uplockage and downlockage of the ships. The mixing processes cannot be simulated in three dimensional numerical flow models. Therefore, a simplified model (SWINLOCKS) is used. The results confirm that salinity within the locks is higher during downlockage than during uplockage and that salt intrusion into Gatun Lake is higher during down-lockage than during up-lockage.

4.1.4 Model predictions

The model, that is calibrated for the existing situation (Jongeling, 2003d) is used to predict salinity intrusion for different configurations of the Post-Panamax Locks (Jongeling, 2003f, 2005), with a third shipping lane. In the first report (Jongeling, 2003f), three different scenarios were simulated with different configurations of the Post-Panamax locks: A: Single lift, B: two-lift and C: three lift. In the baseline scenario the water releases remain as they were in the existing situation and in the second scenario the water release at the Gatun Dam is reduced with the water losses caused by the shipping in the new lane. The ship transit prospects for the 50 years of simulation were derived from Autoridad del Canal de Panama (ACP). A sensitivity analysis showed that the model is sensitive to the calibrated exchange coefficients, but this sensitivity is relatively small compared to the effect of configuration. From the study, it was concluded that the three lift system is the best alternative, both from the point of view of salt water intrusion into Gatun Lake and the water management of Gatun Lake.

From the model simulations it was concluded that from the point of salt water intrusion and extra water supply into Gatun Lake, a 3-lift Post-Panamax Lock is the best alternative. The application of water saving basins helps to save water, but increases salt water intrusion into Gatun Lake. Especially in Gaillard Cut, the shipping lane and the north-eastern area of the salinity will.

In the study of 2005 (Jongeling, 2005), the favourable 3-lift lock system is studied in more detail and various mitigations against salt-water intrusion have been analysed. Most of the mitigating measures consisted of flushing different locks with fresh water. Also specific options such as catchment of salt water in a deep pit, pneumatic barriers and desalination of intruded salt water were studied. A total of ten mitigating measures was studied:

1. Stepwise flushing of all lock chambers (dummy lockage);
2. Flushing the middle and upper lock chamber;
3. Flushing the upper and lower lock chamber;
4. Enhanced flushing of the upper and lower lock chamber;
5. Intensive flushing of upper lock chamber;
6. Exchange of salt water with fresh water in lower lock chamber;
7. Drainage of salt tongue through silt in forebay bottom;
8. Flushing of salt water from pit in forebay;
9. Flushing of salt water from pit perforated floor in forebay;
10. Pneumatic barrier at entrance of the lower lock.

The mitigating measures are evaluated against following criteria:

- Expected effectiveness;
- Corresponding total water loss per lockage;
- Delay for shipping;
- Hindrance of shipping;
- Complexity of the system and ease of operation;
- Construction cost.

Calculations have been done for 15 Post-Panamax ships per day in the new third channel. The capacity of the third channel, however, is larger than 15 ships per day and therefore the calculations probably do not reflect a worst-case situation. Regarding the reduction of salt water intrusion, it was concluded that a situation without water saving basins and stepwise flushing of the lock chambers after each downlockage operation is the best option. However, this costs large amounts of freshwater from Gatun Lake and it is questionable if this quantity of water is available during the whole year.

In the report, it is advised to choose the option of three water saving basins per lift in combination with a stepwise flushing of all lock chambers after each downlockage operation. Also it is advised to make provisions in the locks for easy construction of bubble screen devices. However, the flushing of the locks will reduce the shipping capacity. If this reduction is not acceptable, a salt collecting pit in Gatun Lake could be an alternative. Bubble screens at the entrance of the locks reduce mixing of the water. However, ship-bound exchange of water is not prevented by bubble screens. Monitoring of salt intrusion during operation of the locks is important.

The SWINLOCKS model is an appropriate model to calculate the water and salt budget within the locks (Vested, 2005; Vested et al., 2005). The model is extensively calibrated for the present configuration of the Panama Canal. An important and critical factor is the exchange coefficients. Although it is not clear if the estimated exchange coefficients are valid for the Post-Panamax configuration it is assumed that the estimations are sufficient to predict the salt exchange in the future situation. The field measurements to estimate the exchange coefficients were adequate for the SWINLOCKS model.

With the SWINLOCKS model, it is not possible to calculate the salt concentrations in Gatun Lake. Therefore, a full-3D model is required. However, the SWINLOCKS model can be used to calculate the salt intrusion into Gatun Lake, which can be used as input to the 3D model of Gatun Lake.

The 3-box model cannot be used to describe the salinity conditions in the lakes. This has to be done with a 3-D hydrodynamic simulation model. SWINLOCKS can be used to calculate salt exchange between the locks. In their review, simple calculations have been done for the vicinity of the Gatun locks and forebay with the DHI modelling tool MIKE-3 (Vested, 2005; Vested et al., 2005). The model shows that salinity gradients occur in the vicinity of the locks. In the SWINLOCK model the 5.17 km^3 Gatun Lake is modelled as one completely mixed box, which is an important simplification of the system. Due to this simplification, the 0-D SWINLOCKS model overpredicts the salt intrusion into the lake and underpredicts the flushing of salt out of the lake.

Vested et al. (2005) advise in their review that salinity gradients near the existing locks should be studied by a combination of detailed measurements and 3D simulation models (Vested, 2005; Vested et al., 2005). For the Post-Panamax situation a 3D simulation model should be combined with a lock model (SWINLOCKS). Also it is advised to establish a long-term monitoring programme for salinity and biological parameters. The biological monitoring could give information on the biological sensitivity of the system with respect to salinity changes, which can be combined with the predictions of salinity with the 3D model. Also a literature review is recommended aiming at summarising the known tolerances of freshwater organisms for salinity. Based on that, sensitive key species can be identified for on-going monitoring over several years {Vested, 2005 #2290}.

4.2 Water quality Gatun Lake

4.2.1 Model set-up

In a more recent study of WL | Delft Hydraulics, the water quality of Gatun Lake for the present (Jongeling et al., 2008) and future (Jongeling et al., 2009) situation has been modelled with a 3-D numerical model. Also detailed measurement campaigns were organised in 2007 and 2008 (Jongeling, 2008). The salt load in the present situation was calculated from measurements (Figure 6). The salt loads for the future situation was calculated using a recalibrated version of the SWINLOCKS model. The salt loads are input to the 3D overall flow model of Gatun Lake.

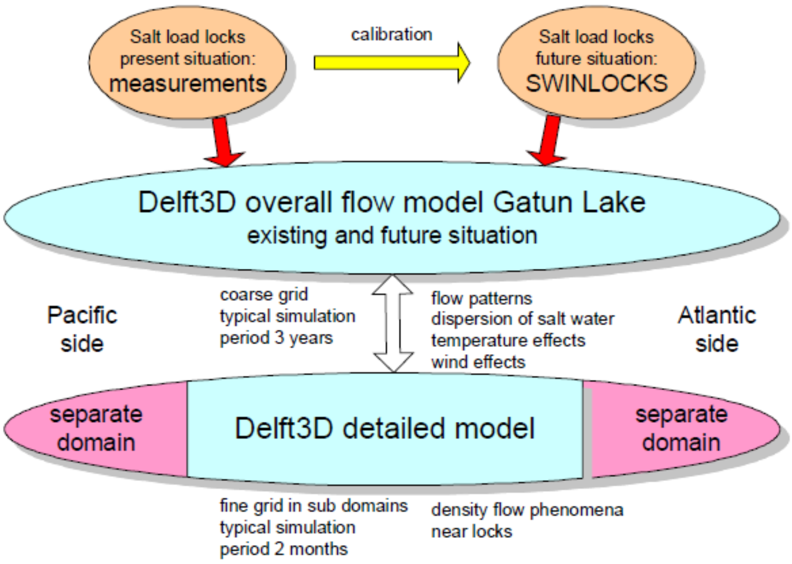

Figure 6 Schematic overview of the water quality model (Jongeling et al., 2008).

The hydrodynamics within Gatun Lake are described by a course-grid overall flow model and a detailed flow model, with a fine grid near the Gatun Locks and the area near Pedro Miguel Locks. In these areas, the model grid is detailed for a further analysis of density flows and mixing processes. After adjustment, the water balance was well modelled by the 3D model. There was a good agreement between model predictions of the water level in Gatun Lake and the measurements.

4.2.2 Monitoring

During three monitoring campaigns (July 2007, November 2007 and March-August 2008) water quality parameters were measured in the Gatun and Pedro Miguel Locks and in the Gatun Lake, in the close vicinity of the Locks. The measurements in 2008 were part of a long-duration monitoring campaign in Gatun Locks and corresponding forebay (March-July), followed by salt concentrations measurements in the deep area, near Gatun Locks in August 2008. Also data of salinity measurement in Gatun Lake from published yearbooks of the ACP were used. In a previous study, a detailed sampling plan and sampling protocols have been developed for Gatun Lake and Miraflores Lake to monitor the water quality (salinity, temperature, dissolved oxygen, total suspended solids) in these lakes (URS Holdings, 2005).

The monitoring program is focused on the salt intrusion into the forebays and Gatun Lake area, but also on salt transport and salt concentrations within Gatun Lake. Salinity measurements in Gatun Lake, away from the locks, in the period 2003 - 2005 indicate a very low salinity in the range of 0.06 to 0.08 ppt. In Miraflores Lake, the average concentration was 0.8 ppt near the bottom and 0.6 ppt at the surface.

The quantity of salt water that intruded thought the locks at the Pacific side is smaller than at the Atlantic side. This is caused by the presence of the intermediate Miraflores lake, which dampens the upward movement of salt. The dampening effect of Miraflores Lake will not be present in the case of the new Post-Panamax Locks.

From continuous salinity measurements near the bottom and at the surface in Gatun Lake, close (1 km) to the Gatun Locks it is shown that relatively salt water (0.9 ppt) travels from Gatun Locks towards the deeper areas of Gatun lake. Further away from the Gatun Locks, none of the measurements indicated an increased salt concentration level. The salt load is estimated from measurements of salt concentration in the upper lock chambers. For the “present situation” a gross salt load of 512 000 kg day^{-1} is estimated from Gatun Locks. From the Pedro Miguel Lock a salt load of 71 000 kg day^{-1} is estimated. This gross salt load is input for the purpose of the numerical simulations. A large part of this gross salt load is immediately withdrawn during lock operations. The average loss of water from Gatun Lake due to the up- and downlocking is estimated at 82 m^3 sec^{-1}.

4.2.3 Model results present situation

With the Delft-3D model salinity concentrations in Gatun Lake are calculated for the present situation. Volume-averaged salinity varied between 0.06 ppt in the wet season and 0.07 ppt in the dry season. The model has been validated with measurements near Isla Guarapo, in the vicinity of Gatun locks. The measurements near the bottom show somewhat higher peaks (up to 0.7 ppt) than the model calculations (up to 0.4 ppt).

4.2.4 Model results Post-Panamax extension

With the model, different scenarios for the future situation are modelled (Table 2). All simulations were run with the hydrological conditions for the period 2003 to 2005. These conditions were representative for a “normal” situation. The scenario’s varied in the operation of the water saving basins (wsb’s) and operation of dummy lockages. One scenario was run for a dry El Niño event. During an extreme dry season, the salinity concentrations in Gatun Lake could become higher. The freshwater inflow in this event was reduced by 40% compared to the normal hydrological conditions. Finally, the 5th scenario consisted of different simulations with different combinations of Post-Panamax ships. The simulations were run for a shipping schedule with 12 ship transits per day in the new locks and 36 ship transits in the existing locks. According to the prognosis of ACP the number of 12 Post-Panamax ship transits will be reached by 2030.

Table 2 Scenarios for simulation of the future situation; locks running at maximum capacity

Scenario	Description	Details
1	Base line scenario	General rules for operation of Gatun Dam, full operation of wsb's
2a	Reduced operation of wsb's	Wsb's are not used if the date is between August and December AND the water level is above PLD +26.7 m
2b	further reduced operation of wsb's	Wsb's are not used if the date is between May and December AND the water level is above PLD +25.0 m
2c	WSB's not used	This scenario seems not realistic considering the low water but was applied to study the effects of extreme conditions
3a	One dummy lockage at downlockage	Full operation of wsb's. Dummy lockage, not using the wsb's, between the 3rd and 4th ship
3b	Two dummy lockages at downlockage	Full operation of wsb's. Dummy lockage, not using the wsb's, between the 3rd and 4th ship and the 4th and 5th ship
4	El Niño year	Full operation of wsb's. Inflow from rivers and rainfall is reduced with 40% from July 2003 through March 2004
5	Variation of PP-shipping schedule	Full operation of wsb's with different combinations of Post-Panamax ships

The Post-Panamax canal will result in an increase of the average salinity in Gatun Lake to 0.11 ppt in the wet season and about 0.15 ppt in the dry season. The volume-averaged salt concentrations will remain beneath the freshwater limit of 0.4-0.5 ppt. Highest salinity concentrations will be observed in the vicinity of the locks (Figure 7 and Figure 8). At one of the freshwater intakes in Gatun Lake, Paraiso, the maximum salt concentration becomes almost 0.5 ppt, which makes it unsuitable for drinking water.

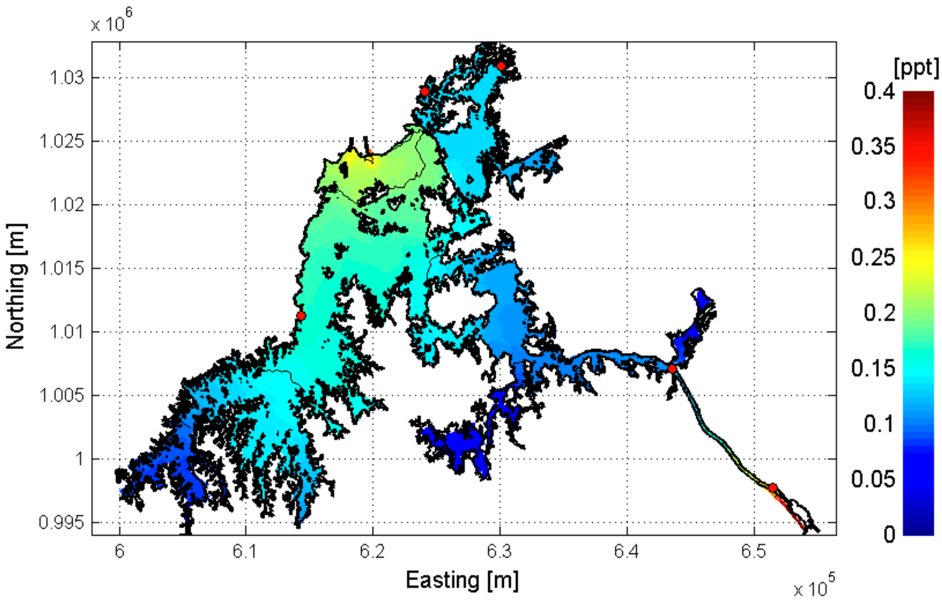

Figure 7 Predicted time and depth-averaged salinity concentration in Lake Gatun in Post-Panamax locks for scenario 1 (2004-2005). Dots indicate drinking water intake locations (Jongeling et al., 2009).

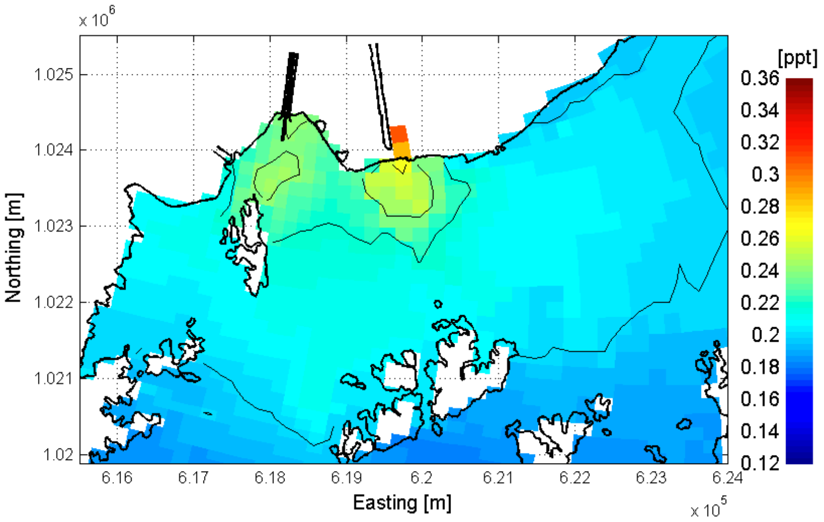

Figure 8 Detail of predicted depth-averaged salinity concentration near Gatun Locks in Post-Panamax locks for scenario 1 (Jongeling et al., 2009).

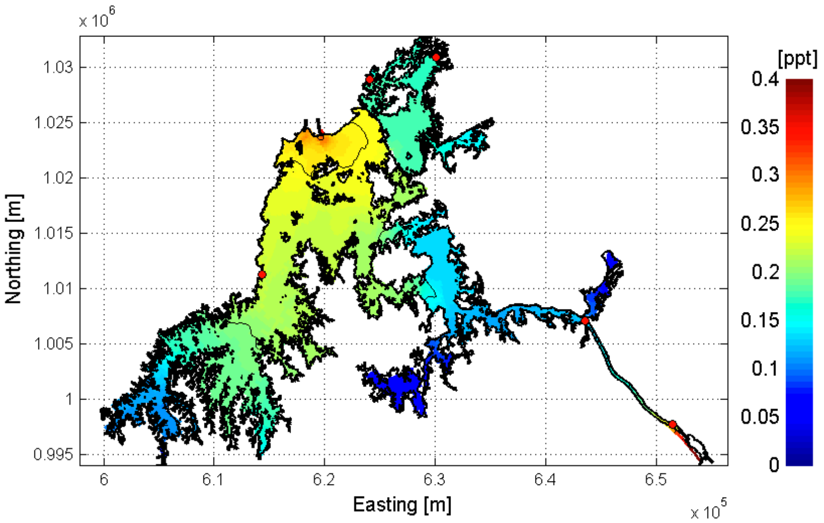

Figure 9 Predicted time and depth-averaged salinity concentration in Lake Gatun in Post-Panamax locks for scenario 4 (El Niño) (2004-2005). Dots indicate drinking water intake locations (Jongeling et al., 2009).

One of the most extreme conditions is in during El Niño. Figure 9 presents the predicted time and depth averaged salinity concentrations in Gatun Lake during a dry El Niño event. In the scenario with the dry El Niño event, the salinity in the vicinity of the Atlantic Post-Panamax locks increased to maximum values of 0.35 ppt and to 0.55 ppt in the vicinity of the Pacific Post-Panamax locks.

The total daily water loss from Gatun Lake caused by the Pacific and Atlantic locks amounts 5.98×10^6 m^3. The water saving basins can reduce this quantity to 2.392×10^6 m^3. The additional water loss for the Post Panamax locks will be at the expense of the water that can be used for hydropower generation. The Post-Panamax locks will lead to an increase of the salt load into Gatun Lake. Depending on the time of the year, the use of water saving basins and the amount of vessels, the total gross salt input into Gatun Lake is estimated between 500 000 kg day^{-1} (wet season without using the water saving basins) to more than 1.5 million kg day^{-1}.

4.3 Evaluation model studies

In the studies of WL | Delft Hydraulics, state of the art modelling tools are used. SWINLOCKS model gives good estimate on salt intrusion into Gatun Lake. The Delft-3D model is able to calculat the temporal and spatial variation of salt within Gatun Lake. Current velocities in Gatun Lake are low. Currents are mainly wind driven and therefore, very much depending on meteorological conditions (wind, rain, evaporation). The model is forced with meteorological conditions of (2003-2005), which can be characterised as average years. Extreme years might be more interesting. One of the scenario's is an El Niño year which can be seen as an extreme situation. For the present situation, the water balance is well modelled for Gatun Lake. Water (and salt) transport is only calibrated for a single location near Gatun Locks. Measurements in Gatun Lake, further from the locks are not used for validation. The model for the present situation is forced (salt intrusion) with actual measurements, while the predicted future situation is forced with SWINLOCKS. For a proper comparison both present and future situation should be forced with SWINLOCKS.

It is recommended that het salt water intrusion into the Gatun Lake will be monitored after the completion of the new Post-Panamax locks. Changes should be analysed using trend analysis. Data can also be used for further calibration and validation of the model and checking the effectiveness of salt intrusion control measures.

5 Conclusions

5.1 Penetration of salt water into Gatun Lake

With the movement of ships through the Panama Canal, salt water will penetrate into the freshwater Gatun Lake. During downlocking of ships, there is more leakage of salt than during uplocking. This is mainly caused by the replacement of water when the ship leaves a lock. With the new Post-Panamax locks and the increasing shipping intensity, the salt flux into Gatun Lake will increase. The water saving basins, that will be constructed with the Post-Panamax locks, will reduce the amount of freshwater that is needed to operate the locks. However, they will also increase the salt penetration into Gatun Lake. For the Post-Panamax expansion, the gross salt loss into Gatun lake is estimated between 0.5 million kg day^{-1} to more than 1.5 million kg day^{-1}, depending on the season and the use of the water saving basins.

During the wet season, the salt water will be flushed from Gatun Lake. Also there is enough water to flush the salt water out of the locks. However, during the dry season, and especially during El Niño, there is not enough water to flush the salt water from Gatun Lake, and salinity concentration of the water near the locks will increase, especially near the bottom.

Model studies for the Post-Panamax expansion show that the average salinity in Gatun Lake could increase to 0.11 ppt in a wet season and 0.15 ppt in a dry season. However, locally in the vicinity of the locks, the salinity could become higher, up to 0.5 ppt in the forebay. Increased salinity concentrations in Gatun Lake could have an impact on drinking water intake and biodiversity within Gatun Lake. Gatun Lake serves as drinking water basin for Panama city.

5.2 Loss of biodiversity due to the increased salinity

Although salinity in Gatun Lake will increase due to salt penetration from locks, the concentrations remain below 0.5 ppt and are occurring very locally in the close vicinity of the locks. A concentration of 0.5 ppt is regarded as a biological threshold between freshwater and brackish waters {Ysebaert, 2013 #2305}. Therefore, also with the Post-Panamax expansion, Gatun Lake will remain a freshwater lake with fresh water aquatic organisms. However, some organisms are more sensitive to very low salt concentrations than others. Those organisms might locally be impacted at locations with increased salt concentrations. It is, however, not easy to predict which species could be impacted by increased salt concentrations in Gatun Lake. Detailed information of species composition and distribution within Gatun Lake is needed for that.

It is recommended to establish a detailed and long-term monitoring programme for salinity and biological parameters in Gatun Lake. The salinity measurement could be used to validate the model results and as an early warning tool for increased salinity concentrations. Based on these measurements, management actions could be taken. The biological monitoring programme could be used to evaluate the impact of the Post-Panamaxs locks on biodiversity. Moreover, the biological monitoring could give information on the ecological sensitivity of the system to increased salt concentrations. This information can be combined with the salinity predictions of the 3D model. Sensitive key species can be identified for on-going monitoring.

The species composition in Gatun Lake can be compared with the species composition of Miraflores Lake. The latter is supposed to be already impacted by salinity increase caused by the Panama Canal. Also within Gatun Lake the Delft-3Dmodel indicates regions with relatively low and relatively high salinity. Comparison of biodiversity and community composition between locations with relatively high and relatively low salinity will likely give more insight in the potential impact of salt penetration to the biodiversity of Gatun Lake.

5.3 Potential mitigating measures

Various mitigating measures to reduce salt intrusion into Gatun Lake have already been studied in the past. The mitigating measures can be subdivided into three categories:

1. Increase of water supply;
2. Reduction of water use;
3. Reduction of water exchange.

5.3.1 Increase of water supply

Salt intrusion can be prevented by flushing the locks with freshwater from Gatun Lake. However, this requires large amounts of freshwater, which is not available during the whole year, in particular during the dry season.

Water supply can be increased by increasing the volume of Gatun Lake or Alhajuela Lake by increasing the water level in (part of) these basins. This requires expensive infrastructural investments. Also the volume can be increased by deepening the channels. However, since the active volume of Gatun Lake is about 800 million m^3, large amounts of sediment need to be dredged and deposited on land to have some effect on the water storage capacity. New water storage basins can also be created by damming rivers. This will have an impact on the terrestrial ecosystem. Some options have already been studies in the past (see Louis Berger Group Inc, 2008).

5.3.2 Reduction of water use

The operation of the locks require large amounts of freshwater. Re-using the freshwater could reduce the requirement of freshwater. Water saving basins reduce the water consumption of the locks significantly. However, the increased salinity within the locks will increase the salt penetration into Gatun Lake. Also more freshwater is needed for an effective flushing with freshwater.

5.3.3 Reduction of water exchange

The mixing of freshwater with salt water is an important factor causing the penetration of salt water into Gatun Lake. Mixing of water masses can be effectively prevented using bubble screens. However, a bubble screen between the locks is not very effective since large amounts of water are exchanged between the locks when a large ship moves from one lock to another. If it is possible to pump the volume of the exchanged water actively into the water saving basins during the movement of the ship, a bubble screen could be effective.

It might also be interesting to investigate if the vertical stratification of water within the locks could be explored better. Salt water has a higher density than freshwater. Therefore, freshwater tends to float on salt water. If the stratification could be maintained by reducing vertical mixing in the locks, the upper , more fresh layer could be used to fill the water saving basins.

5.4 Water management in the area during the dry season

The canal expansion project using locks equipped with water-saving basins might produce a "shortage" in municipal and industrial water production, especially during dry periods. With the recommended flushing of the locks, fresh water from Gatun Lake would be run through the locks and the brackish water from the basins would be dumped to get the salt water out of the locks system. Although this is an effective mitigating measure against salt intrusion into Gatun Lake, it increases the loss of water from the Gatun Lake.
The criteria for flushing of the locks during a dry season should be set clearly. This can be based on online salinity measurement in Gatun Lake and forecast calculations on water supply and traffic.

5.5 Migration of exotic species between Pacific and Caribbean.

Connections of oceans by human made channels are an important vector for introduction of marine exotic species. A good example is the Suez Canal that was constructed in 1869 and connected the Mediterranean sea with the Red Sea. Currently about 300 species from the Red Sea have been identified in the Mediterranean Sea, and there are probably others yet unidentified (Zenetos et al., 2012).

The Panama Canal is another situation. Migrating marine species between the Pacific ocean and the Caribbean sea have to pass the freshwater Gatun Lake. The salinity concentrations in Gatun Lake are so low (<0.5 ppt) that marine organisms will not be able to settle within the Lake. These species need much higher salt concentrations to settle in the Lake. Even the worst case salt concentrations that could be reached during the season (e.g.) are too low for those marine species to settle permanently in the lake. Most of the marine organisms, attached to the hull of the ships will not survive the transport within the freshwater of Gatun Lake. A complete transit between ocean and ocean takes 8 to 12 hours (Louis Berger Group Inc, 2008). Some organisms, for example mussels (and barnacles) could be able to survive by closing their valves. This is also the case in the present configuration of the Panama canal. The Post-Panamax expansion will not increase the chance for those organisms to migrate between the two oceans. Therefore, it is not likely that the Post-Panamax expansion will increase the migration potential of exotic marine species between the Pacific and the Caribbean.

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Quality Assurance

IMARES utilises an ISO 9001:2008 certified quality management system (certificate number: 124296-2012-AQ-NLD-RvA). This certificate is valid until 15 December 2015. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Fish Division has NEN-EN-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 1st of April 2017 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.

Justification

Report number: C215/13
Project number: 4303105601

The scientific quality of this report has been peer reviewed by the a colleague scientist and the head of the department of IMARES.

Approved: Dr. Karin Troost
Scientific researcher

Signature:

Date: December 2013

Approved: Dr. B.D. Dauwe
Head of department Delta

Signature:

Date: December 2013