Saltwater intrusion analysis for Post Panamax Locks - Water recycling at Pacific side of Canal and salt water intrusion mitigation

Análisis de la intromisión de agua salada en esclusas Pospanamax - Reciclaje de agua en el lado Pacífico y mitigación de la intromisión de agua salada

WL Delft Hydraulics

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Salt Water Intrusion Analysis
Panama Canal Locks

Future situation: Post-Panamax Locks

Report E
part I: Effect of water recycling at Pacific side of canal
part II: Alternative methods to mitigate salt water intrusion

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Salt Water Intrusion Analysis Panama Canal Locks
Future situation: Post-Panamax Locks

Report E, summary

Effect of Water Recycling at the Pacific Side of the Canal
Alternative Methods to Mitigate Salt Water Intrusion

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1 Introduction

The Panama Canal Authority (ACP) is developing a long-range master plan to augment the capacity of the Panama Canal and it's capability to transit vessels. To that purpose ACP has undertaken a study to evaluate the feasibility of constructing facilities and features to provide additional sources of water supply and associated hydropower generation, new sets of locks, alternate systems for raising / lowering vessels, channel improvements and maritime infrastructure. The study is designed to help the Canal meet future traffic demands and customer service needs and to continue providing efficient and competitive service for the next fifty years and beyond.

The available water resources for Canal operations have been analysed by the Canal Capacity Projects Division and several new water supply projects with potential for providing water for long-term Canal operation demands (including new locks) and for increased municipal and industrial needs have been identified. The Canal Capacity Projects Division has subsequently initiated the conceptual development of new locks that would service Post-Panamax vessels. The tentative size of proposed Post-Panamax locks is 61 m wide by 457 m long by 18.3 m deep, which is significantly larger than the existing Panamax-size locks that measure 33.5 m wide by 305 m long by 13 m deep.

The proposed Post-Panamax locks could have several design configurations, ranging from a single-lift system to a three-lift system. It is expected that the new lock configuration and the number of lifts effect the transmission of salt sea water through the lock system to Gatun Lake and Miraflores Lake, and that the new locks will require a greater quantity of fresh water for Canal operation. In view of the latter the use of lateral water saving basins is considered.

The issue of possible salt water intrusion into Gatun Lake caused by the operation of the existing locks and proposed Post-Panamax locks is a very important environmental concern and will play a serious role in the evaluation of proposed Post-Panamax locks. The evaluation requires a comprehensive understanding of salt water intrusion through the lock operations and use of water saving basins. New tools are needed to perform an analysis of the physical and operational processes involved.

Autoridad del Canal de Panamá (ACP) has awarded WL | Delft Hydraulics the contract for 'Salt Water Intrusion Analysis of the Panama Canal Locks, Water Recycling System for Post-Panamax Locks' (contract No SAA-110830, dated 3 June 2003, with extension of February 2004).
The objective of this Consultancy is to provide services to the ACP on the subject of salt water intrusion through the shipping locks of the Panama Canal. The services are focused on the future situation with Post-Panamax Locks in a third shipping lane and comprise:

- Analysis of the effects of water recycling at the Pacific side of the canal on salt concentration levels of Gatun Lake and Miraflores Lake.
- Identification of alternative methods to mitigate the salt water intrusion through the locks of the Panama Canal.

The study on water recycling is presented in Part I of this Report E and the study on mitigation measures in Part II; these two parts can independently be read. The studies have been executed in the period September 2003 – February 2004. The present part of the report gives an outline of the studies and summarizes the main findings, conclusions and recommendations.

Throughout the report reference is made to previous reports in this series on salt water intrusion:

- Report A, June 2003 (WL | Delft Hydraulics project number Q3039): presents the results of the salt water intrusion analysis for the existing situation.
- Reports B, C and D, September 2003 (WL | Delft Hydraulics project number Q3039): present the results of the salt water intrusion analysis for the future situation with third shipping lane and 3-lift, 2-lift and 1-lift Post-Panamax Locks.

2 Effect of water recycling at Pacific side of canal

2.1 Background and purpose of study

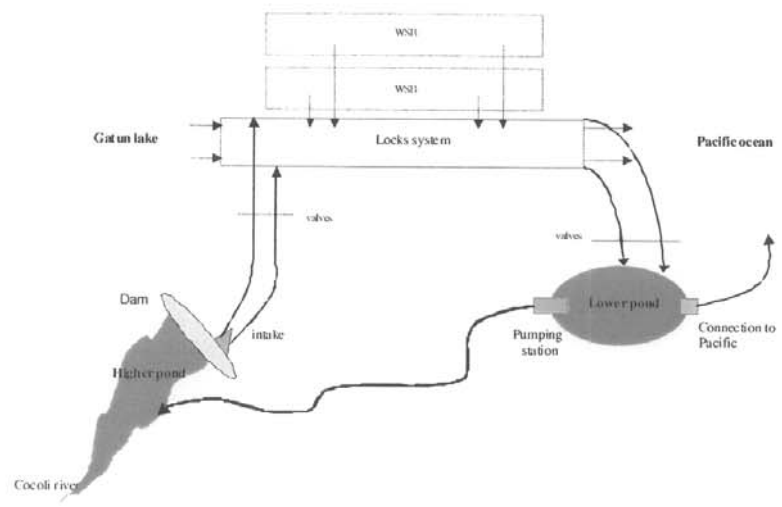
ACP is considering the installation of a water recycling system in the Post-Panamax Locks at the Pacific side of the canal. This system is aimed to compensate for the loss of water caused by the lock operations in the third shipping lane, and is used in dry periods, when there is a shortage of fresh water. In this way, water recycling may be an alternative for the supply of fresh water to Gatun Lake from new water sources. However, the system may at the same time cause an extra salt water load on Gatun Lake, and – indirectly – Miraflores Lake.

Three options for recycling of water are considered by ACP (see also Figure 2.2, Part I):

Option 1: Water is directly recycled from tailbay to forebay without making use of storage ponds. A pumping station beside the tailbay returns water continuously to the forebay.

Option 2: The lower lock spills into a lower storage pond. The pumping station returns water continuously from the lower pond to the forebay.

Option 3: The lower lock spills into the lower storage pond and the upper lock draws water from an upper storage pond. The pumping station returns water continously from lower pond to upper pond.



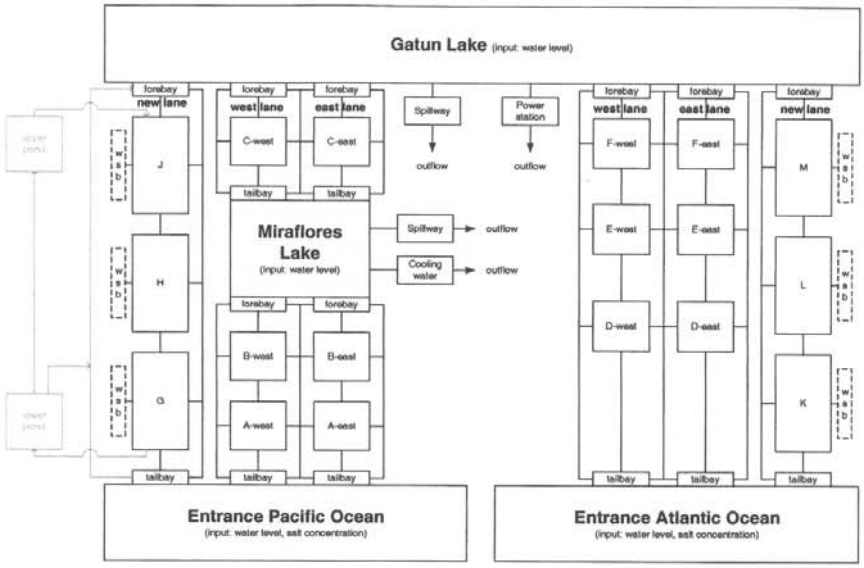
Recycling option 3: pond to pond recycling (source: Consorcio Post-Panamax)

The effects of water recycling on the salt concentration levels of Gatun Lake and Miraflores Lake is studied for three-lift Post-Panamax Locks (all three options), two-lift Post-Panamax Locks (option 3) and single-lift Post-Panamax locks (option 3). Water recycling at the Pacific side of the canal is only considered for dry periods when the fresh water supply stops and the water level of Gatun Lake drops below the minimum required level for navigation. Different scenarios for the control of the water level of Gatun Lake are studied. Main elements in these scenarios are: the possible use of water saving basins connected to the Post-Panamax Locks and a reduction of the quantities of water that are spilled at Gatun Dam and / or used for hydropower generation.

2.2 Simulation model for salt water intrusion

The salt-intrusion process through the locks on the Panama Canal is simulated with a numerical model. This model was set up for the existing situation (see Report A, issued June 2003) and has been extended and adapted to the situation with a new shipping lane and Post-Panamax Locks. Three configurations of Post-Panamax Locks have been modelled: three-lift, two-lift and single-lift lock systems. These lock systems are provided with water saving basins (wsb's) which can either be put in operation or switched off (see Reports B, C and D, issued September 2003). The model predicts the salt water load on Gatun Lake and Miraflores Lake caused by lock operations, taking into account water level fluctuations of the lakes, water releases at Gatun Dam and Miraflores Dam, and tidal variations and salt concentration variations in the seaside tailbays.

In the framework of the present study the simulation model has been extended with a water recycling system at the Pacific side of the canal. The above mentioned recycling options 1, 2 and 3 have been modelled for the 3-lift lock configuration of Post-Panamax Locks (see red lines in scheme below). Option 3 has been modelled for the 2-lift and 1-lift lock configurations. When water recycling options are active in the simulation model, recycling actions are executed each time that a ship passes the Post-Panamax Locks at the Pacific side of the canal. The quantity of water that is recycled is equal to the quantity of water that would be spilled into the tailbay when no recycling system was active. When the locks are provided with water saving basins a smaller quantity of water is recycled. Also the water quantity that is lost as a result of a turn around operation is recycled at the moment that the turn around operation is executed. In this way the total quantity of recycled water balances with the total loss of water caused by lock operations, similar as in the pre-design of the recycling system made by Consorcio Post-Panamax (CPP).



Three water recycling options for 3-lift lock configuration in simulation model

Ship movements are defined in the simulation model between Pacific Ocean or Atlantic Ocean and Gatun Lake, and reverse. These ship movements are simulated as a series of subsequent actions; water recycling forms the last action. Three basic steps can be distinguished in the lockage process:

- Step I: the water levels of two adjacent basins are equalized; water is transferred from higher basin to lower basin and if relevant water saving basins (wsb's) of the higher basin (lock chamber) are filled and wsb's of the lower basin (lock chamber) emptied.
- Step II: lock gates are opened and the ship moves from one basin to the adjacent one; a net water quantity equal to the ship's volume is displaced in the reverse direction and density flows develop.
- Step III: water that is lost by the operation of the locks at the Pacific side of the canal is recycled.

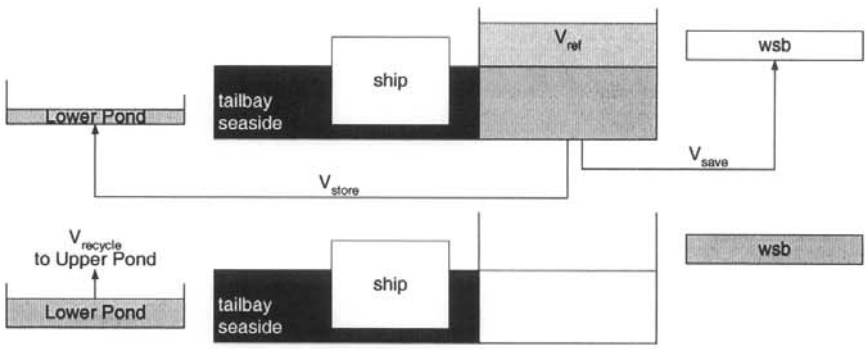
The first two steps repeat each time that a ship moves from one basin to another, the last step is executed when the full uplockage or downlockage operation at the Pacific side of the canal has been concluded (or after a turn around operation has been executed).
A set of mass conservation equations is used to describe and quantify both the water and salt transfer between the two adjacent basins and, if relevant, between these basins (lock chambers) and corresponding wsb's. Salt exchange coefficients e_x are applied in the salt balance equations in combination with a reference volume V_{ref}. In step I the reference volume V_{ref} equals the quantity of water that is transferred from higher basin to lower basin to equalize the water levels of the two basins. In the case of wsb's a part V_{save} of volume V_{ref} is supplied to or withdrawn from the wsb's of the respective lock chambers. In step II the reference volume V_{ref} equals the quantity of water in the higher basin. The ship's submerged volume S plays a role in it. In step III the quantity $V_{recycle}$ represents the quantity of water

that is recycled from tailbay to forebay (direct recycling, option 1), from lower storage pond to forebay (option 2) or from lower storage pond to upper storage pond (option 3). The products $e_x.V_{ref}.c$ (c = salt concentration), $e_x.V_{save}.c$, $e_x.S.c$, and $e_x.V_{recycle}.c$ all represent a certain quantity of salt in the salt balance.

Water balance and salt balance equations are extensively treated in previous reports (see Report A for the existing situation, and Reports B, C and D for the future situation with Post-Panamax Locks).

As an example we give here the equations which describe the salt balance in step I of the uplockage process in the case that water saving basins and water storage ponds (option 3) are applied. Equations are shown both for lower lock and upper lock. Also the salt-balance equations of step III, in the case that water is recycled from lower storage pond to upper storage pond, are given. Equations which are used in step II are not effected by the recycling of water; they are treated in Reports A, B, C and D.

Step I, tailbay → lower lock, water recycling option 3



Salt balance equations:

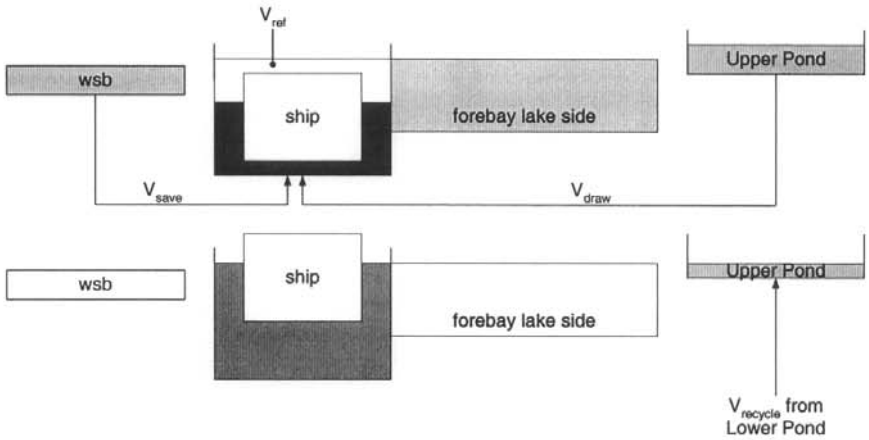
$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_{wsbfill} \cdot V_{save} \cdot c_{high1}) - (e_{LPfill} \cdot V_{store} \cdot c_{high1}) - (e_x \cdot (V_{ref} - V_{save} - V_{store}) \cdot c_{high1})}{V_{high2}}$$

$$c_{wsbhigh2} = \frac{(V_{wsbhigh1} \cdot c_{wsbhigh1}) + (e_{wsbfill} \cdot V_{save} \cdot c_{high1})}{V_{wsbhigh2}}$$

$$c_{LP2} = \frac{(V_{LP1} \cdot c_{LP1}) + (e_{LPfill} \cdot V_{store} \cdot c_{high1})}{V_{LP2}}$$

Note: subscript *high* refers to the higher basin of two adjacent basins, subscrift *low* to the lower basin, subscript *wsbhigh* refers to the wsb 's of the higher basin, subscript *wsblow* to the wsb's of the lower basin, subscript *LP* refers to the lower storage pond of the recycling system, subscript *UP* to the upper storage pond, subscript *1* refers to the beginning of the step, subscript *2* to the end of the step.

Step I, upper lock → forebay, water recycling option 3



Salt balance equations:

$$c_{low2} = \frac{(V_{low1} \cdot c_{low1}) + (e_{wsbempty} \cdot V_{save} \cdot c_{wsblow1}) + (e_{UPempty} \cdot V_{draw} \cdot c_{UP1}) + (e_x \cdot (V_{ref} - V_{save} - V_{draw}) \cdot c_{high1}}{V_{low2}}$$

$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_x \cdot (V_{ref} - V_{save} - V_{draw}) \cdot c_{high1}) + ((V_{ref} - V_{save} - V_{draw}) \cdot c_{lake1})}{V_{high2}} = c_{forebay2}$$

$$c_{wsblow2} = \frac{(V_{wsblow1} \cdot c_{wsblow1}) - (e_{wsbempty} \cdot V_{save} \cdot c_{wsblow1})}{V_{wsblow2}}$$

$$c_{lake2} = c_{lake1} - \frac{(V_{ref} - V_{save} - V_{draw})}{V_{lake}} \cdot c_{lake1}$$

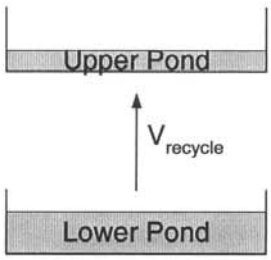
$$c_{UP2} = \frac{(V_{UP1} \cdot c_{UP1}) - (e_{UPempty} \cdot V_{draw} \cdot c_{UP1})}{V_{UP2}}$$

Similar equations are valid for step I of the downlockage process.

The exchange coefficients used in step I are always positive or nil, meaning that transfer of water through the water filling and emptying system from one basin to another does not allow for a salt transfer in the opposite direction. The exchange coefficients e_x , $e_{wsbfill}$ and e_{LPfill} can be greater than 1; this indicates that the water portion that is transferred from one basin to another has a higher salt concentration than the water in the basin where it is withdrawn from. For example, water that is withdrawn from the higher lock chamber and spilled into the wsb and lower lock chamber has, generally, a higher salt concentration than the

initial water in the higher lock chamber (volume averaged). This, since the water is drawn from the water body near the floor with a higher than average salt concentration. The exchange coefficients e_x , $e_{wsbfill}$ and e_{LPfill} are selected on the basis of measurements in situ, on results of Delft3D computations and on considerations regarding upper and lower limit values (see Reports A, B, C, D, E-partI for further explanations). The exchange coefficients $e_{wsbempty}$ and $e_{UPempty}$ are always set to 1 in the present study. We assume that the water in the wsb's and upper pond is fully mixed up during filling; the water that is subsequently withdrawn has thus an equal salt concentration as the water in the wsb's and upper pond prior to the withdrawal.

Step III, lower storage pond → upper storage pond, water recycling option 3



Salt balance equations:

$$c_{LP2} = \frac{(V_{LP1} \cdot c_{LP1}) - (e_{LP\text{-}UP} \cdot V_{recycle} \cdot c_{LP1})}{V_{LP2}}$$

$$c_{UP2} = \frac{(V_{UP1} \cdot c_{UP1}) + (e_{LP\text{-}UP} \cdot V_{recycle} \cdot c_{LP1})}{V_{UP2}}$$

For the upward transfer of water from lower storage pond to upper storage pond we select a value 1 for the exchange coefficient $e_{LP\text{-}UP}$. This choice supposes that the water in the lower storage pond is fully mixed up during filling and has thus an uniform density and salt concentration.

Step III is executed at the end of uplockage and downlockage operations and after a turn around. The latter is only required after a change from northbound ships to southbound ships, since this operation causes a water loss to the tailbay.

2.3 Exchange of salt water between forebay and lake

Since the simulation model uses water volumes and volume-averaged salt concentrations of the various basins as base quantities, special attention is needed for the exchange of salt water between lock chambers and lakes. In the real situation salt water enters a lake when the lock gates are open and a ship enters or leaves the lock chamber. This salt water generally intrudes in the form of a salt tongue, that propagates over the bottom. The

propagation velocity is dependent on the actual density difference; the propagation velocity in forebays and tailbays of the locks in Miraflores Lake may be up to 0.3 m/s, in forebays of the locks in Gatun Lake up to 0.1 - 0.2 m/s. After some time most salt water has intruded the lake. Generally, however, some salt water will still be in the neighbourhood of the locks when a next ship approaches. When as a part of the lockage operation the water level of the lock chamber is equalized with the water level of the forebay some salt water may therefore be flushed back. Also when the lock gates are opened and the ship moves from lock chamber to the lake or reverse, some effect may occur in exchange flows and density flows when salt water is present near the locks. For these reasons it is required that the simulation model has provisions to keep the intruded salt water temporarily near the locks. These provisions are realised by designing separate forebays and tailbays between lock chambers and lakes. The exchange of salt water is initially between the lock chambers and the forebays or tailbays; subsequently the salt water is exchanged with the lake. A lineair function of time is applied in the simulation model for the exchange of salt water. After a period of 0.5 hour (Miraflores Lake) or 1 hour (Gatun Lake) the salt water is fully exchanged and the concentration of the forebay or tailbay has become equal to the salt concentration of the lake. The exchange of salt water with the lake is executed at the moment that the next ship approaches the forebay or tailbay from the lake side or, in the case that the next ship is in the lock chamber, prior to water withdrawal from the forebay or water spillage to the tailbay.

The salt balance equations for the exchange of salt water between forebay and lake read:

$$c_{forebay2} = c_{forebay1} - e_x \cdot (c_{forebay1} - c_{lake1})$$

$$c_{lake2} = c_{lake1} + e_x \cdot (c_{forebay1} - c_{lake1}) \cdot \frac{V_{forebay}}{V_{lake}}$$

Similar equations are applied between tailbay and lake (Pedro Miguel Locks).
A linear function of time is applied in the exchange coefficient to model the time dependent exchange of salt water:

$$e_x = \frac{\Delta t}{T} \cdot e_{xfull}$$

with:

e_x = exchange coefficient used in simulation (-)
e_{xfull} = 1 (full salt exchange)
Δt = time difference (s) between two subsequent ship passages or between a ship passage and a turn around
T = exchange time (s)

If $\Delta t/T > 1$ then $\Delta t = T$, and $e_x = e_{xfull} = 1$.
A period T = 3600 s is selected for the forebays in Gatun Lake and T = 1800 s for forebays and tailbays in Miraflores Lake. If $\Delta t/T < 1$ a part of the salt water is still in the forebay at the moment that the next ship arrives, and contributes to the salt balance equations.

When a water recycling system has been installed, the water lost by operation of the Post-Panamax Locks at the Pacific side of the canal is either directly pumped back from tailbay to forebay, pumped back from lower pond to forebay or pumped back from lower pond to upper pond. In particular when water is pumped into the forebay, the salt concentration near the locks will rise. For the determination of salt exchange coefficients related to operations between forebay and upper lock (water levelling, exit or entering of a ship) it is important to know in which way the salt concentration of the forebay is effected by recycling of water. In other words when salt water is directly or indirectly (through lower pond operation) pumped into the forebay, we have to know which portion remains near the locks and contributes to the salt water exchange between forebay and upper lock (a part of the salt water may flow back into the upper lock during levelling up or during a ship movement).

Delft3D computations have been made to assess the effect of recycling on salt concentration levels in the forebay. From these computations it appeared that on the average a higher salt concentration is present in the forebay. In Swinlocks simulations the effect of recycling can be obtained when the exchange coefficient e_{xfull} in:

$$e_x = \frac{\Delta t}{T} \cdot e_{xfull}$$

is set to about 0.9. This choice implies that the water of the forebay has always a somewhat higher salt concentration in Swinlocks simulations than the water of the lake, as is required. The salt transfer from forebay to Gatun Lake is a little delayed, compared to the normally applied value $e_{xfull} = 1.0$ in simulations, but the final salt concentration of the lake is not effected (apart from the fact that some more salt water is sluiced back through lock operations).

2.4 Water control scenarios Gatun Lake

Since the Post-Panamax Locks on the new shipping lane cause extra water losses, the water balance of Gatun Lake will be changed, meaning that an additional water quantity has to be supplied to Gatun Lake from new water sources and / or a lesser water quantity released at Gatun Dam to maintain the water level of Gatun Lake. As an alternative the water that is lossed by lock operations in the new lane at the Pacific side of the canal may be recycled; this option is only considered for dry periods when there is a shortage of fresh water. Water saving basins at the Post-Panamax Locks help to reduce the loss of water.

Different scenarios for the control of the water level of Gatun Lake are considered by ACP. An overview of scenarios is presented in the table below.
In the *baseline scenario* (scenario 1) all water losses from Gatun Lake caused by operation of the new Post-Panamax Locks (the new locks are provided with wsb's), are compensated by a supply of fresh water from new water sources. Scenario 2 is like scenario 1, but in scenario 2 the Post-Panamax Locks have no wsb's.
In scenario 3 (locks with wsb's) and scenario 4 (locks without wsb's) the extra water losses caused by operation of the new locks are partly or fully compensated by a lesser water release at Gatun Dam; the remaining portion, if any, is supplied to Gatun Lake from new water sources.

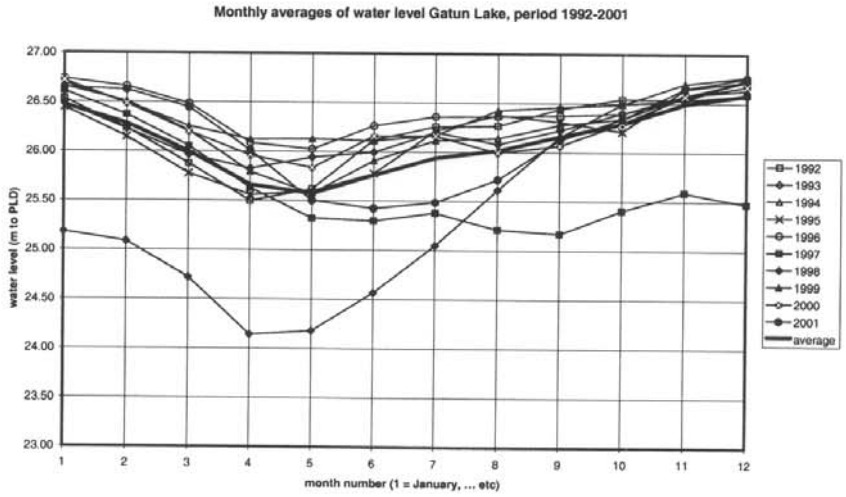
In scenarios 5, 7 and 9 (locks with wsb's) and 6, 8 and 10 (locks without wsb's) the extra water losses caused by the new locks are compensated by a lesser water release at Gatun Dam; if insufficient, in dry periods, the water lost by operation of the new locks at the Pacific side of the canal is recycled; in the case that this is still insufficient the remaining portion is supplied to Gatun Lake from new water sources.

Scenarios 5 through 10 are applied in the present study. Scenarios 7 through 10 with recycling from a lower pond to the forebay in Gatun Lake or with direct recycling from the tailbay to the forebay, are only applied in combination with the 3-lift lock configuration of Post-Panamax Locks. A scenario with 1-lift locks without wsb's is not studied since ACP has disregarded this option.

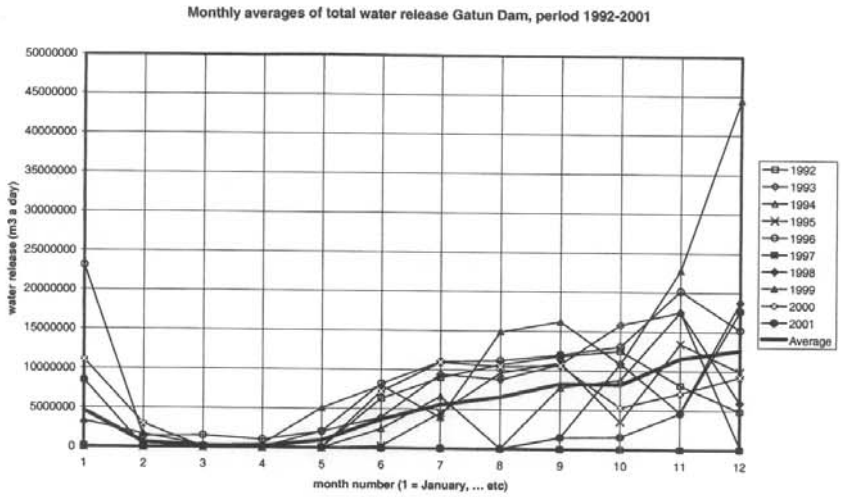
Scenario	*Description*	*3-lift locks*	*2-lift locks*	*1-lift locks*
1 baseline scenario	wsb's *no* reduction of water releases at Gatun Dam extra fresh water supply to Gatun Lake	*B1*	*C1*	*D1*
2	*no* wsb's *no* reduction of water releases at Gatun Dam extra fresh water supply to Gatun Lake	*B2*	*C2*	*D2*
3	wsb's water releases at Gatun Dam are *reduced* if needed, extra fresh water supply to Gatun Lake	*B3*	*C3*	*D3*
4	*no* wsb's water releases at Gatun Dam are *reduced* if needed, extra fresh water supply to Gatun Lake	*B4*	*C4*	*D4*
5	wsb's water releases at Gatun Dam are *reduced* if needed, recycling of water; lower pond > upper pond if needed, extra fresh water supply to Gatun Lake	**B5**	**C5**	**D5**
6	*no* wsb's water releases at Gatun Dam are *reduced* if needed, recycling of water; lower pond > upper pond if needed, extra fresh water supply to Gatun Lake	**B6**	**C6**	
7	wsb's water releases at Gatun Dam are *reduced* if needed, recycling of water; lower pond > Gatun Lake if needed, extra fresh water supply to Gatun Lake	**B7**		
8	*no* wsb's water releases at Gatun Dam are *reduced* if needed, recycling of water; lower pond > Gatun Lake if needed, extra fresh water supply to Gatun Lake	**B8**		
9	wsb's water releases at Gatun Dam are *reduced* if needed, recycling of water; tailbay > Gatun Lake if needed, extra fresh water supply to Gatun Lake	**B9**		
10	*no* wsb's water releases at Gatun Dam are *reduced* if needed, recycling of water; tailbay > Gatun Lake if needed, extra fresh water supply to Gatun Lake	**B10**		

The effects of water recycling on the salt concentration levels of Gatun Lake and Miraflores Lake have been studied for ship traffic intensities of 1, 5, 10 and 15 Post-Panamax ship transfers a day in the new shipping lane. The present traffic intensities in the existing two shipping lanes (36 ship transfers a day for both lanes) were maintained in the salt intrusion simulations. A traffic intensity of 15 Post-Panamax ship transfers a day is expected for year 50 after opening of the new lane. The mutual comparison of results for different scenarios is done for year 50.

The quantities of water lost by lock operations, spilled at Gatun Dam, supplied from fresh water sources, and recycled at the Pacific side of the canal are depending on the number of ship transits in the new shipping lane, but also on the seasonal variations in rainfall, which are reflected in the water levels of the lakes and the water release quantities.
In this study we have initially worked with averaged monthly averages of the water levels and the water release quantities (they have been averaged over a period of 10 years; the data of the period 1992-2001 was used, see figures below). The extremes in this period (the dry El Nino year 1997 and the very wet year 1999) were thus filtered off, which is required when long term predictions of the salt concentration are made. To get insight into the effects of the extremes in the hydraulic conditions, we have re-run simulations on the basis of the actual seasonal variations in the period 1992-2001 (monthly averages).
Next figures present the monthly averages of the water level of Gatun Lake and the water releases at Gatun Dam in the period 1992-2001, and the average values of the monthly averages. These average values have initially been used in the salt-water intrusion simulations.
Similar data of the seasonal variations of the water level of Miraflores Lake has been used in the simulations.

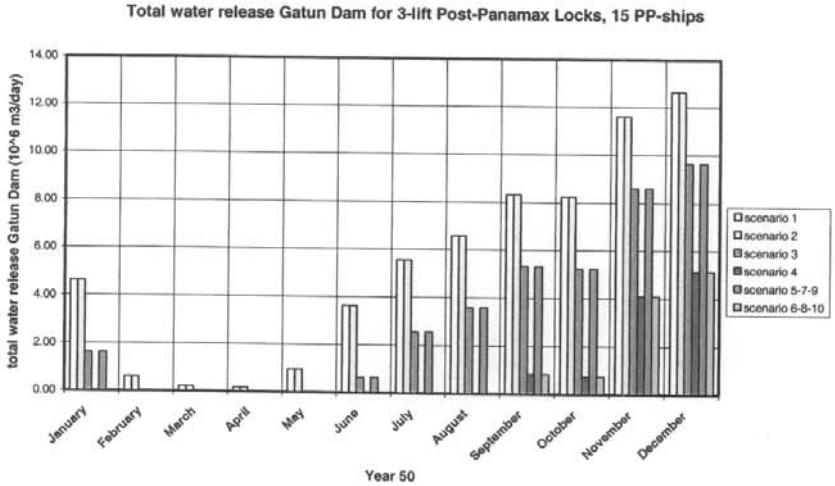


Monthly averages of water level Gatun Lake, period 1992-2001

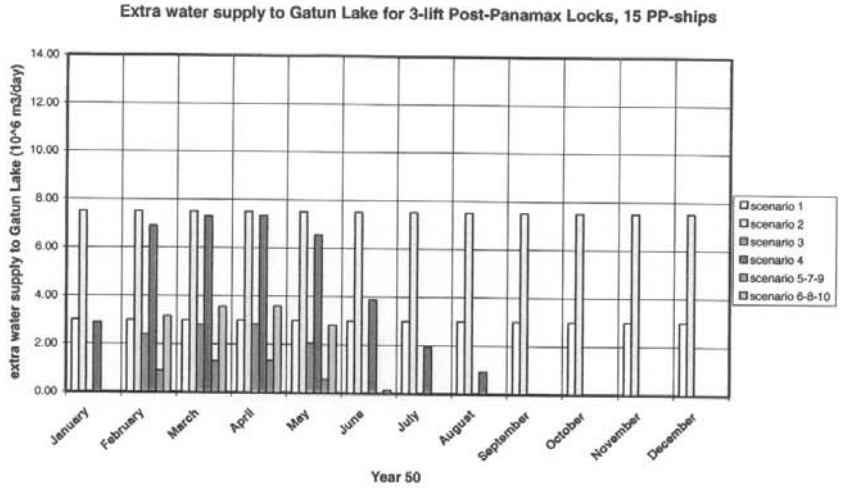


Monthly averages of water releases at Gatun Dam, period 1992-2001

As an example we present in the next charts the extra quantities of water that are supplied from fresh water sources to Gatun Lake and released at Gatun Dam, in the case of 3-lift Post-Panamax Locks and a ship traffic intensity of 15 Post-Panamax ships a day (year 50), for scenarios 1 – 10, initial simulations. The water release values of scenario 1 correspond to the average values of the monthly averages.

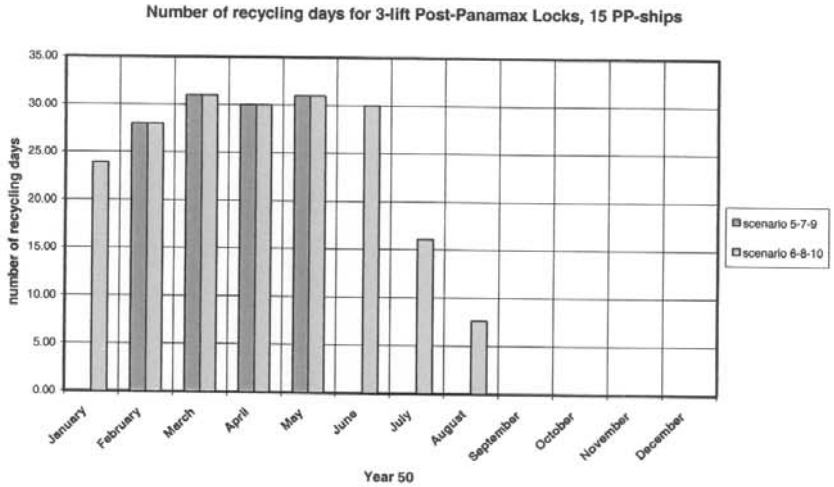


Water releases at Gatun Dam in initial simulations, 3-lift locks, 15 PP-ships/day



Extra water supplies to Gatun Lake in initial simulations, 3-lift locks, 15 PP-ships/day

From the above figure it appears that extra fresh water supplies are still required when water is recycled at the Pacific side of the canal (scenarios 5 – 10).
The number of recycling days in scenarios 5 – 10 is shown in next figure for the 3-lift locks, in the case of a ship-traffic intensity of 15 Post-Panamax ships a day.

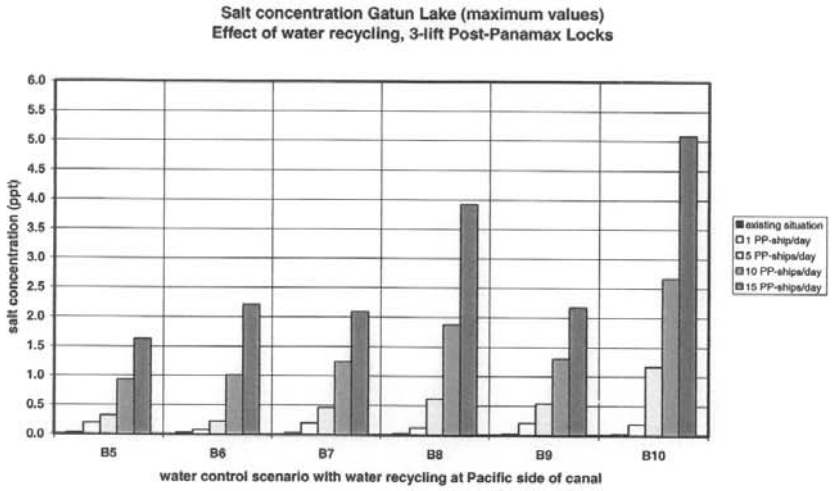


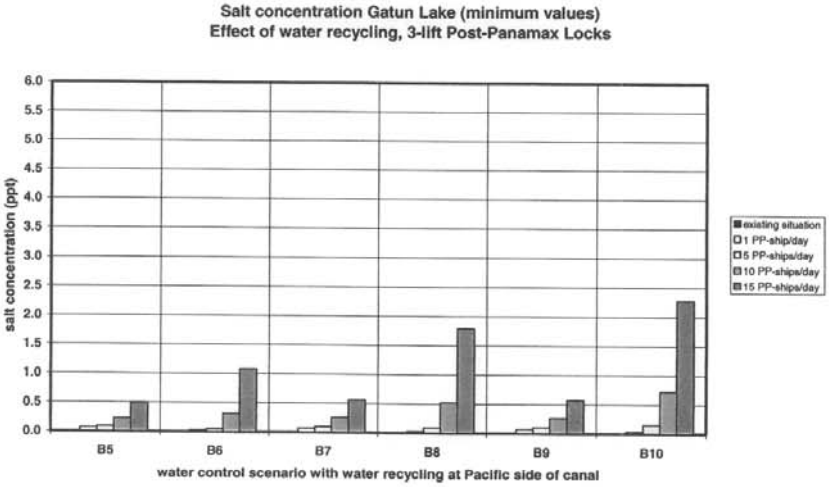
Number of recycling days in initial simulations, 3-lift locks, 15 PP-ships/day

2.5 Effect of water recycling on salt concentration levels

2.5.1 3-lift locks

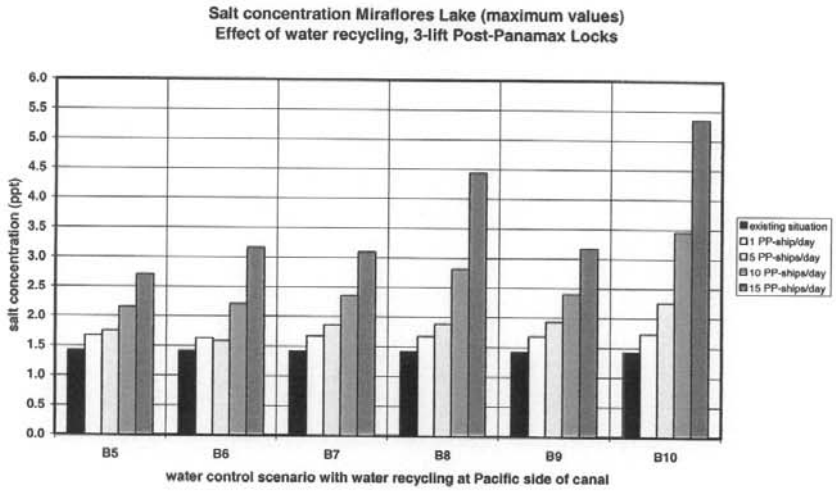
The effect of water recycling is analyzed for ship traffic intensities of 1, 5, 10 and 15 Post-Panamax ships a day in addition to the 'normal' 36 ship transfers in the existing two shipping lanes. The salt concentration levels of Gatun Lake and Miraflores Lake appear to be very sensitive to the number of Post-Panamax ship transfers a day and the water control scenario practised for Gatun Lake.

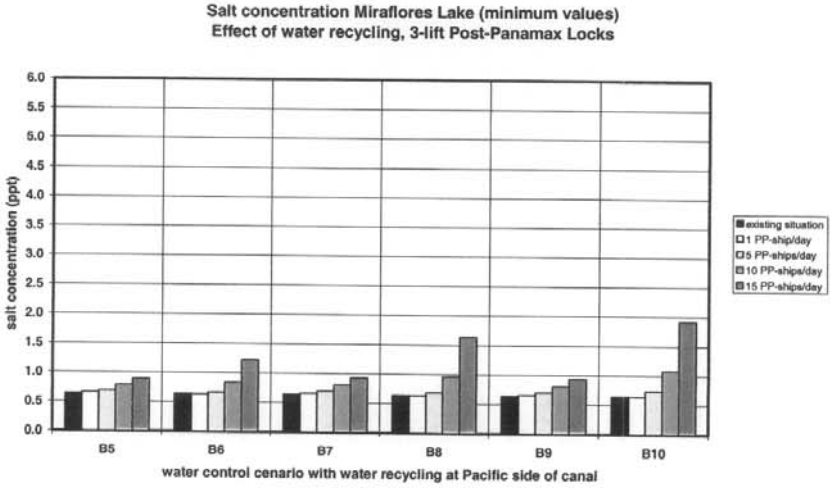




Maximum and minimum salt concentration Gatun Lake, initial simulations, 3-lift locks

The above charts show the maximum and minimum values of the volume-averaged salt concentration of Gatun Lake as a function of number of ships and water control scenario (3-lift locks). From these figures it appears that the salt concentration of Gatun Lake rises considerably for all ship traffic intensities and scenarios, compared to the present situation. As may be expected, direct water recycling from tailbay to forebay (scenarios B9 and B10) is the most unfavourable recycling option, recycling of water from lower storage pond to upper storage pond (scenarios B5 and B6) is the least unfavourable option. In general, the use of water saving basins is favourable when water is recycled (scenarios B5, B7 and B9), since the quantity of salt water that is recycled and intrudes the lakes is smaller. When water recycling is not practised water saving basins cause a stronger salt water intrusion, because a lesser quantity of fresh water is involved in the lockage process.

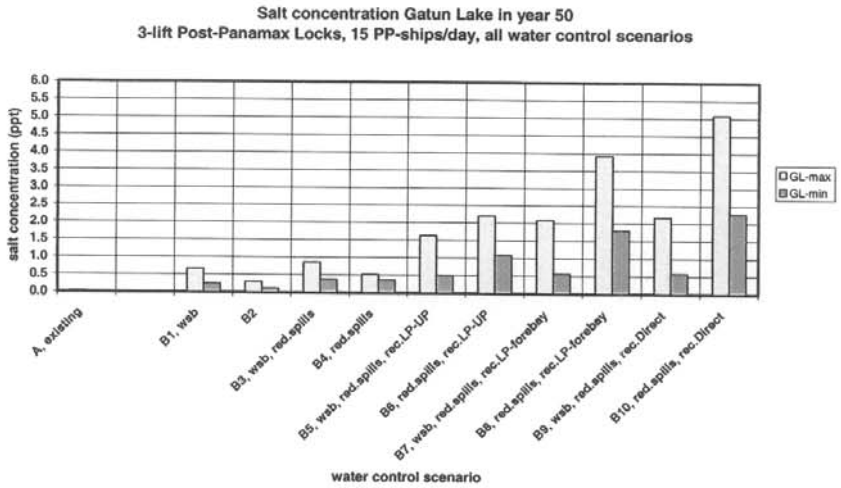




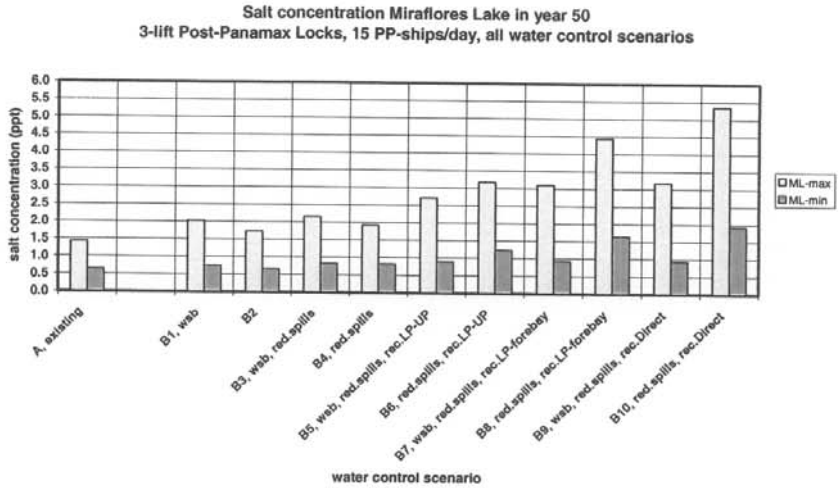
Maximum and minimum salt concentration Miraflores Lake, initial simulations, 3-lift locks

The salt concentration of Miraflores Lake rises also for all ship traffic intensities and all scenarios, as appears from the above figures. Since Miraflores Lake is by-passed by the new shipping lane the effect of the new shipping lane and recycling is an indirect effect, and is therefore less markedly.

The results of the present and former simulations (all scenarios B1 – B10, see table on page 2-9) are collected in the figures below. Volume-averaged salt concentrations of Gatun Lake and Miraflores Lake are shown for a ship-traffic intensity of 15 Post-Panamax ships a day, which corresponds to the traffic level of year 50 after opening of the new shipping lane. From the view point of salt water intrusion prevention, the figures clearly demonstrates that scenarios with water recycling in dry periods of the year (B5 – B10) are a bad alternative for scenarios (B1 – B4), where fresh water is supplied from new water sources to compensate for the water losses of the Post-Panamax Locks. In all water recycling scenarios the volume-averaged salt concentration of Gatun Lake rises in year 50 above the fresh-water limit. (Note: A value of 200 mg/l chloridity is used in the Netherlands as a fresh-water limit value; this corresponds to about 400 mg/l or 0.4 ppt salinity. In the USA a value of 250 mg/l cloridity (about 0.5 ppt salinity) is used as an upper limit for drinking water (Environmental Protection Agency standard)).

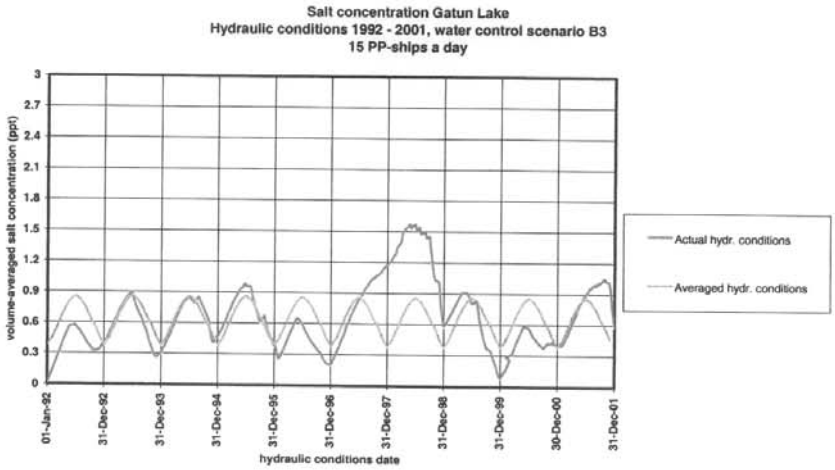


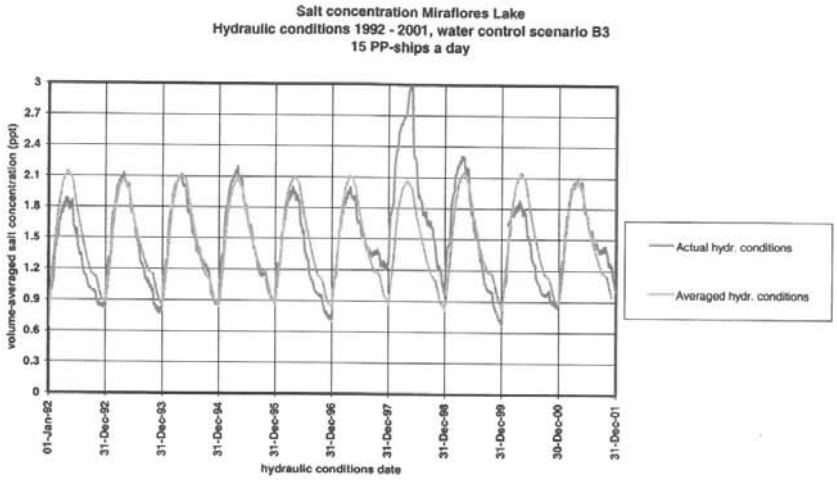
Salt concentration Gatun Lake, 3-lift locks, 15 ships a day, all scenarios



Salt concentration Miraflores Lake, 3-lift locks, 15 ships a day, all scenarios

The above figures are valid for averaged seasonal variations. Some simulations for the 3-lift locks have been repeated with the actual water levels of Gatun Lake and Miraflores Lake and the actual water releases at Gatun Dam as input. The actual data of the period 1992-2001 (monthly averages, see charts on pages 2-10 and 2-11) have been used. This period includes the dry El Nino year 1977 and the very wet year 1999. Results of the simulations for a ship traffic intensity of 15 Post-Panamax ships a day (year 50) are shown in next charts for a period of 10 years, with actual and averaged hydraulic conditions as in the period 1992-2001. The results are valid for scenario B3, no water recycling, see table on page 2-9.

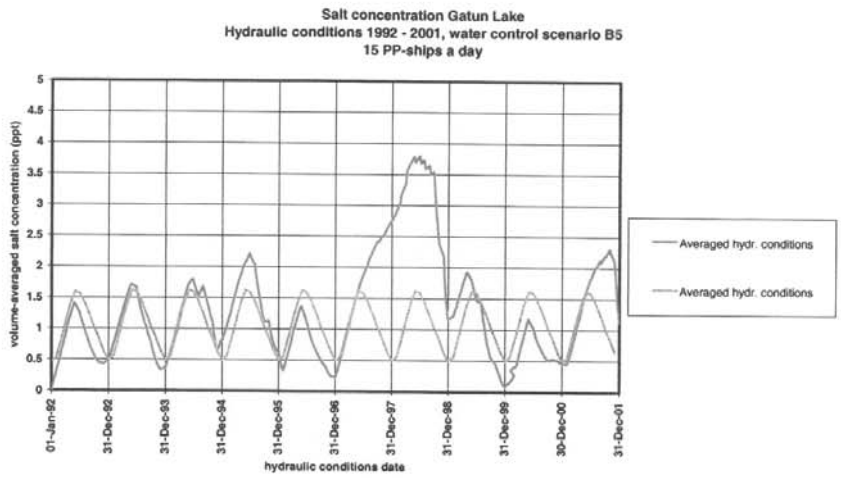


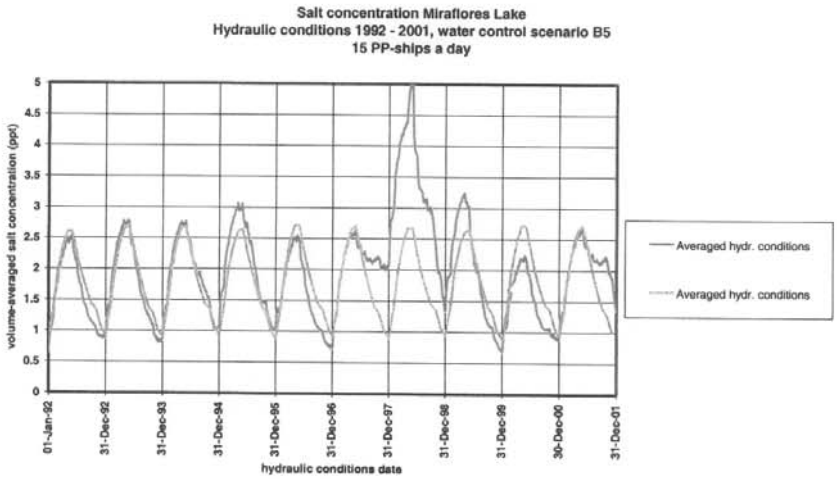


Salt concentration Gatun Lake and Miraflores Lake, 3-lift locks, 15 ships a day, scenario B3 (no recycling), actual and averaged hydraulic conditions

The effects of the dry El Nino year 1997 and the extreme low water level of the lakes in the first half of 1998 are clearly visible in the results. The salt concentration of Gatun Lake strongly increases in this period. The salt concentration of Miraflores Lake is indirectly effected (the new shipping lane bypasses the lake), and increases as well. The next, wet year 1999 causes a strong reduction of the salt concentration in Gatun Lake; the salt concentration of Miraflores Lake follows. As can be seen (compare blue line with grey line) the salt concentration of Gatun Lake is about twice as high in 1998 when actual hydraulic conditions are taken into account, and in the next wet year 1999 the salt concentration drops much farther than with average hydraulic conditions. The latter is caused by the heavy rainfall and spillage of large amounts of water at Gatun Dam in the second half of the wet year 1999.

Similar results are obtained in scenarios B5 (recycling from lower pond to upper pond) and B9 (direct recycling from tailbay to forebay). As is shown in next figures for scenario B5 the effects of actual hydraulic conditions instead of averaged hydraulic conditions, i.e. stronger seasonal variations of the salt concentration of the lakes, are somewhat intensified when water recycling is practised.





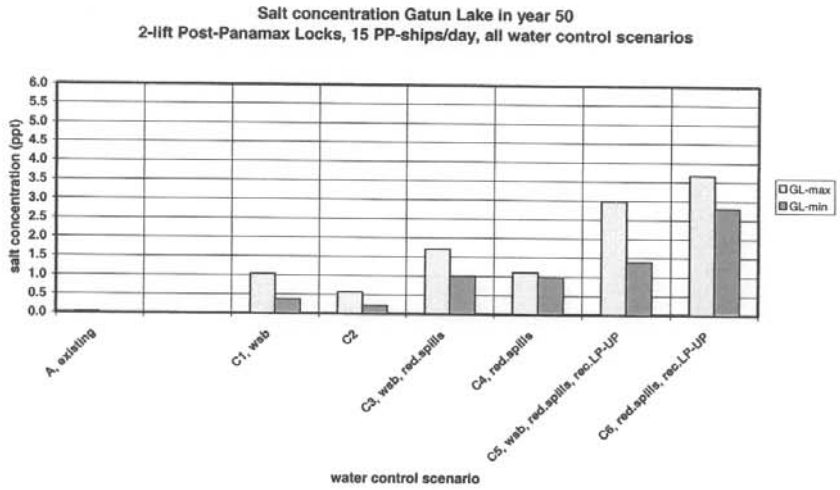
Salt concentration Gatun Lake and Miraflores Lake, 3-lift locks, 15 ships a day, scenario B5 (recycling from lower pond to upper pond), actual and averaged hydraulic conditions

2.5.2 2-lift locks and 1-lift locks

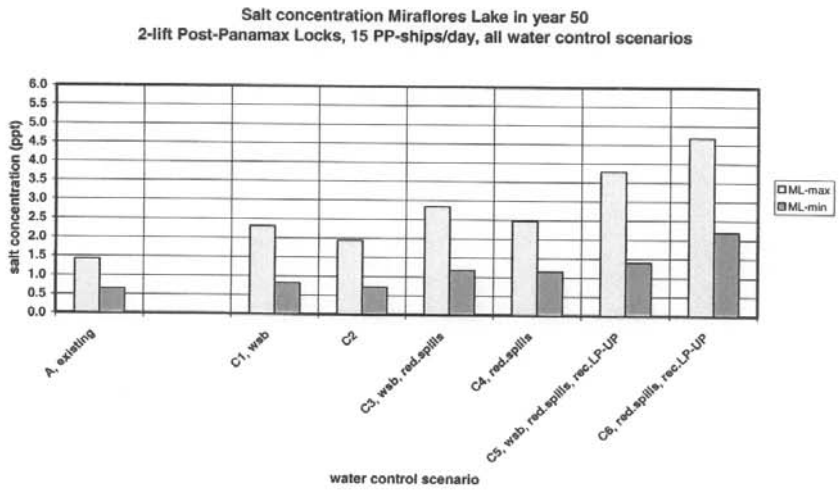
A limited number of salt intrusion simulations have been executed for 2-lift locks and 1-lift locks applying recycling option 3 (recycling from lower storage pond to upper storage pond), see table on page 2-9. These simulations have been run with averaged hydraulic conditions of the period 1992-2001, so that the extremes in seasonal variations were filtered off. In next charts the results of these simulations (volume-averaged salt concentration of Gatun Lake and Miraflores Lake) are compared with the results of previous simulations

without recycling. The comparison is done for year 50, with a ship traffic intensity of 15 Post-Panamax ships a day in the new shipping lane.

Results for 2-lift locks:

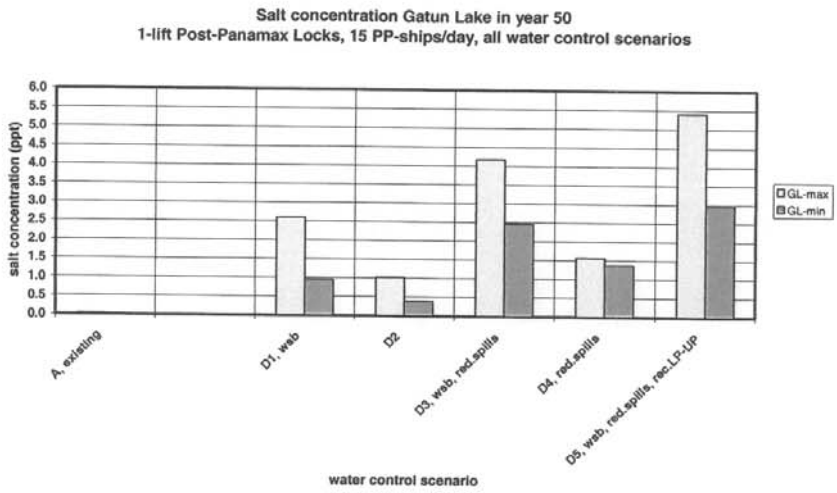


Salt concentration Gatun Lake, 2-lift locks, 15 ships a day, all scenarios

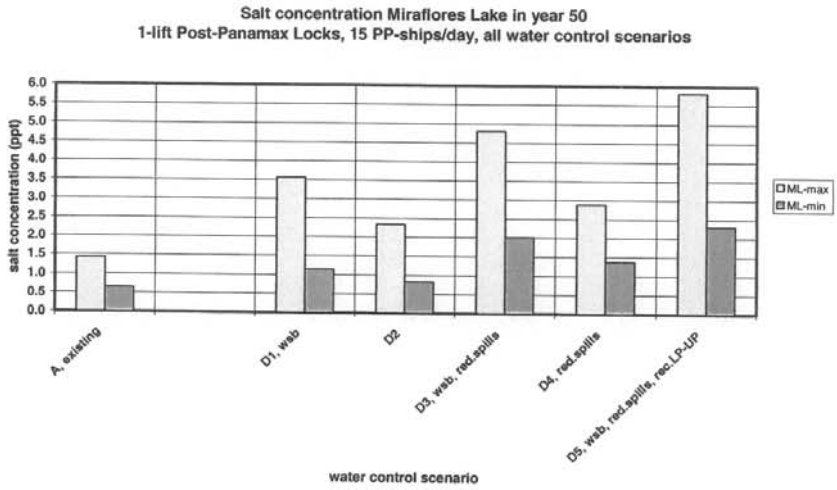


Salt concentration Miraflores Lake, 2-lift locks, 15 ships a day, all scenarios

Results for 1-lift locks:



Salt concentration Gatun Lake, 1-lift locks, 15 ships a day, all scenarios



Salt concentration Miraflores Lake, 1-lift locks, 15 ships a day, all scenarios

2.6 Conclusions water recycling

A study has been conducted into the effects of water recycling at the Pacific side of the canal on salt concentration levels of Gatun Lake and Miraflores Lake. Water recycling is considered by ACP as an alternative for the supply of water from new water sources. When, in dry periods, the fresh water supply stops and the water level of Gatun Lake drops below the minimum required level for navigation, water recycling may partly compensate the water losses caused by lock operations.
The salt water intrusion was analysed for a ship traffic intensity of 1, 5, 10 and 15 Post-Panamax ships a day. The latter ship-traffic intensity is expected for year 50 after opening of the third lane. The number of ship transits in west - and east shipping lane was maintained at the present 18 ships a day in each lane. Different scenarios for the control of the water level of Gatun Lake were applied, including different options for water recycling. These options were: (1) direct recycling from tailbay to forebay, (2) recycling from lower storage pond to forebay, (3) recycling from lower storage pond to upper storage pond. The effects of water recycling were studied for three-lift Post-Panamax Locks (all three options), two-lift Post-Panamax Locks (option 3) and single-lift Post-Panamax locks (option 3). The salt intrusion simulation model Swinlocks has been extended with these recycling options. Main elements in the water control scenarios of Gatun Lake are: the use of water saving basins for the Post-Panamax Locks and a reduction of the quantities of water that are spilled at Gatun Dam and / or used for hydropower generation.

The general conclusions that emerge from the salt water intrusion simulations are:

- Water recycling at the Pacific side of the canal causes a strong increase of the salt concentration levels of Gatun Lake and Miraflores Lake. As may be expected, direct water recycling from tailbay to forebay is the most unfavourable recycling option. Recycling from lower pond to upper pond is the least unfavourable option; in that case the salt concentration level of Gatun Lake may be twice as high as in scenarios where fresh water is supplied from new sources instead of water recycled, provided that wsb's are applied. The use of wsb's is favourable when water recycling is practised, since in that case a lesser quantity of salt water needs to be recycled.
- From the view point of salt water intrusion prevention scenarios which make use of water recycling are a bad alternative. This holds for all lock configurations and all ship traffic intensities.
- Despite water recycling at the Pacific side of the canal still additional fresh water from new water sources is required in dry periods.

Attention has also been paid to the effects of the extremes in seasonal hydraulic variations such as dry El Nino years or very wet years. In dry years the water level of Gatun Lake drops to a minimum, water releases at Gatun Dam are stopped, and - as a future option - recycling of water is started. Heavy rainfall in wet years is the reason that much fresh water is supplied to Gatun Lake and to limit the rise of the water level a large amount of water is spilled at Gatun Dam.
The hydraulic conditions of the period 1992 – 2001, including the dry year 1997 and the wet year 1999, have been modelled in the salt water intrusion simulation model Swinlocks. Simulations have been executed for 3-lift Post-Panamax Locks (with water saving basins) for different water control scenarios of Gatun Lake and different ship traffic intensities in the new shipping lane.

The extremes in the hydraulic conditions clearly showed up in the results of the salt water intrusion simulations. A dry year caused a sharp increase of the volume-averaged salt concentration of Gatun Lake, while the spillage of huge amounts of water in a wet year caused a strong drop of the salt concentration. Miraflores Lake is not directly effected by navigation in the new shipping lane (the new shipping lane bypasses the lake), but the extremes in the seasonal hydraulic variations showed up as well in the volume-averaged salt concentration of Miraflores Lake.
When instead of averaged seasonal variations real variations are appplied as input in the simulation model the maximum salt concentration of Gatun Lake and Miraflores Lake may be a factor up to about 2 higher in dry years, but may at the same time be much smaller in wet years (hydraulic conditions as in the period 1992 – 2001 form the basis for this comparison). This holds for all simulated ship traffic intensities. It appeared also that the effect of the extremes in hydraulic conditions was intensified when water was recycled.

For the prediction of future salt concentration levels of the lakes, which is aimed to be used in a mutual comparison of different lock configurations or an analysis of mitigation measures, the best approach is still to start from averaged seasonal hydraulic variations. For final design purposes also the effects of the extremes in hydraulic conditions should be taken into account.

3 Salt water intrusion mitigation measures

A study has been conducted into the possibilities to reduce the salt water intrusion through the locks of the Panama Canal. Alternative mitigation systems have been identified, reviewed and described, and the effectivity and fit for use at the Panama Canal have been assessed.

3.1 Process of salt water intrusion

In view of an evaluation of the effectiveness of salt water intrusion mitigation measures insight is required into the most critical moments during uplockage and downlockage operations. Next phases are identified which are most important:

- The phase in which the ship sails from the lower lock chamber to the tailbay is a critical phase of the downlockage process: the return flow brings a lot of salt water from the tailbay into the lock chamber, while also a strong density current develops which propagates at relatively high speed into the lock chamber (caused by the great density difference $\Delta\rho$ between tailbay and lock chamber).
- The phase at uplockage, when a ship sails from the tailbay to the lower lock chamber, is also a critical phase, in particular when the gates of the lock are opened long before the ship enters. Density flows cause an almost full exchange of water in that case.
- Both during downlockage and uplockage the filling jets cause a considerable mixing of the water in the receiving lock chambers, resulting in a more or less uniform salt concentration after completion of the water levelling process. This is clearly unfavourable, in particular at downlockage, since this mixing is the cause that more salt water migrates to higher locks and forebay.
- Generally spoken, downlockage of ships is most critical in view of salt water intrusion. More salt water is transferred in upstream direction when a ship sails down than when a ship sails up. This has two major reasons: (i) in the semi-convoy mode of operation the empty lower lock chamber (downlockage) contains more salt water before the water is levelled up than at uplockage when a ship is in the lower lock chamber, and (ii) when after levelling up the next ship enters the lock chamber (downlockage) more salt water is transferred in upstream direction because of the water displacement of the ship. Measures to limit or mitigate the intrusion of salt water should therefore preferably optimal be designed for downlockage operations.

3.2 Mitigation measures

3.2.1 Overview of measures

The methods aimed to reduce the salt water intrusion can be subdivided in three groups, each group directed on measures or actions in a specific phase of the lockage process. The next measures are distinguished:

A Reduce the quantity of salt water that intrudes a lock chamber and subsequently intrudes the canal:
   1. Operational measures
   2. Delay and reduce the exchange of salt water and fresh water between tailbay and lock chamber or lock chamber and forebay by means of pneumatic barriers (or air bubble screens)
   3. Limit the exchange of salt water and fresh water between lock chamber and forebay by means of special provisions, like an adjustable sill on the floor

B Remove the salt water that has passed the locks:
   1. Flush the area near the locks using the lock filling system or special sluices to discharge the water
   2. Drain the salt tongue through a slit in the floor at the upstream side of the lock gates immediately after the tongue exits the lock chamber and enters the canal
   3. Catch the salt water in a pit at the upstream side of the locks and flush the pit

C Prevent the upward migration of salt water from the lower lock chamber:
   1. Make use of the density difference between salt and fresh water and the step in the floor to prevent the migration of salt water from the lower lock chamber to higher levels
   2. Remove the salt water from the lower lock chamber

Special lock systems such as mechanical lifts are not discussed since they have not been developed so far for large seagoing vessels and are also not considered by ACP as a viable alternative for the conventional locks.

3.2.2 Feasibility and effectivity of measures

A Reduce the quantity of salt water that intrudes a lock chamber and subsequently intrudes the canal:

A1 Operational measures

Operational measures that are feasible and may lead to a meaningful reduction of the salt water intrusion are (i) optimize the lockage process (minimize the number of lockages) and (ii) reduce the total opening time of the lock gates, especially the tailbay gates, to a period of about 15 minutes. Both measures reduce the salt water intrusion caused by density differences. A minimization of the number of lockages is already practised by ACP for the existing locks, insofar as safety regulations enable this, and this measure should also be put in practice when the Post-Panamax Locks have been realised. The dimensions of Post-Panamax vessels and Panamax Plus vessels are however such that they can hardly be combined with the current Panamax ships in one lock chamber; the effect of this measure will therefore be limited.

A2 Delay and reduce the exchange of salt water and fresh water by means of pneumatic barriers

Pneumatic barriers in tailbay and forebay may reduce the total salt water intrusion of Post-Panamax Locks to maximum 30% (expected upper limit). The ship-bound salt water intrusion is not prevented. The required air discharge is about 250 m^3/s (at atmospheric pressure) for a barrier in the tailbay; a second barrier in the forebay may require a twice as little air discharge; this second barrier has a lesser effect. Since pneumatic barriers have not yet been applied in water with a depth of 20 m or more, a further study into the efficiency is

advisable. The pneumatic barrier has the advantage that it neither causes an additional fresh water loss, nor a delay for shipping, but small yachts can not safely pass the pneumatic barriers.

A3 Limit the exchange of salt water and fresh water between lock chamber and forebay by means of an adjsutable sill

An adjustable sill at the entrance to the forebay may reduce the salt water intrusion of Post-Panamax Locks to a maximum of 5%. The ship-bound salt water intrusion is not prevented. When the adjustable sill malfunctions there is a risk of a collision of a passing ship. The adjustable sill must therefore be designed in such a way that damage of the ship is prevented. The sill has the advantage that no extra fresh water is lost. Shipping is not delayed.

B Remove the salt water that has passed the locks:

B1 Flush the area near the locks

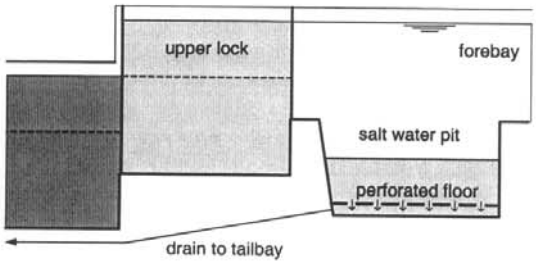
The direct flushing method may be feasible for Gaillard Cut, not for the area near Gatun Locks. An effective flushing requires the availability of a large quantity of fresh water throughout the year, which is however questionable at the Panama Canal. The efficiency of the flushing method is expected to be relatively small, as far as the full Gatun Lake is considered. Flushing may help to keep the salinity of the water in the area near the drinking water intake in Gaillard Cut below the fresh-water limit value, but a better approach would than be to withdraw the drinking water directly from Madden Lake. To prevent hindrance for shipping, flushing may require a separate flushing channel that bypasses the locks. In general, flushing will not cause a delay for shipping, provided that hindrance in forebay and tailbay is prevented and flushing periods are selected well. An intermittent mode of flushing at high discharge is more effective than a continous flushing with little discharge.

B2 Drain the salt tongue through a slit in the floor

A system that returns the salt water through a slit in the floor at the upstream side of the locks may be effective in reducing the salt water intrusion (expected upper limit 30% - 60%), but the total water loss (fresh water and salt water) may at the same time be considerable. The total water loss from the lake is of the same order of magnitude as the normal loss of a 3-lift Post-Pamamax Lock (without water saving basins). The process of salt water drainage is difficult to control, also because of the differences between uplockage and downlockage, which makes that fresh water inevitably escapes with the salt water through the drain. When the drain water is directly returned into the tailbay ships may experience some hindrance and as a result shipping may be delayed.

B3 Catch the salt water in a pit at the upstream side of the locks and flush the pit

When a salt water pit is constructed at the upstream side of the locks the greater part of the salt water that intrudes the forebay can be caught and subsequently be discharged at low speed into the tailbay (expected upper limit of salt water intrusion reduction 60% - 90%). The pit should be sufficient deep to minimize mixing of salt water and fresh water when ships sail over, and have sufficient volume. The loss of fresh water through the drain can be reduced when a perforated floor is applied in the pit (vertical withdrawal of salt water similar as in the existing locks). In that case the total loss of water (salt water and fresh water) will be much smaller than with a slit in in the floor. The risk of hindrance for shipping caused by the discharge of water into the tailbay is also smaller; a delay for shipping is therefore not likely.

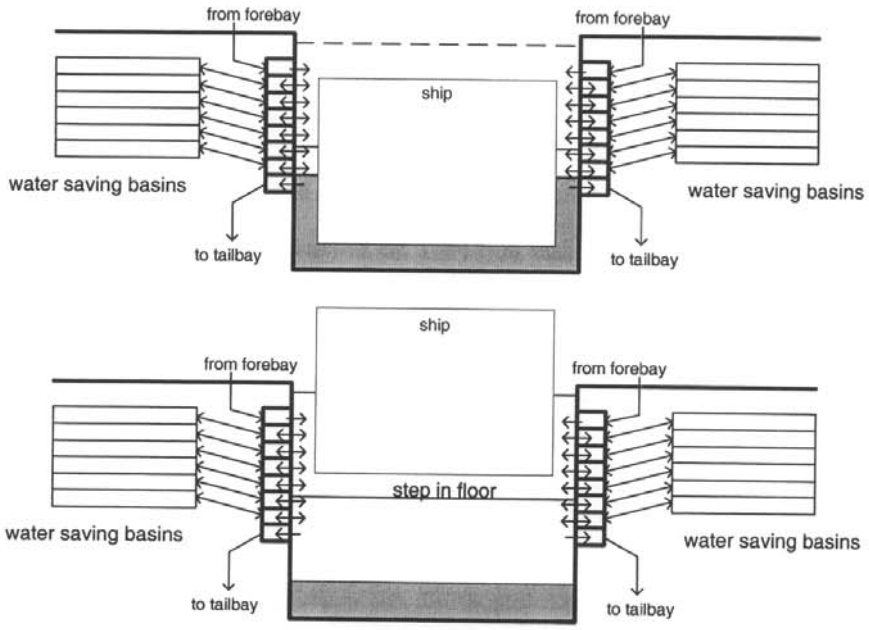


Withdrawal of salt water from salt water pit with perforated floor

C Prevent the upward migration of salt water from the lower lock chamber:

C1 Make use of the density difference between salt and fresh water and the step in the floor to prevent the migration of salt water from the lower lock chamber to higher levels

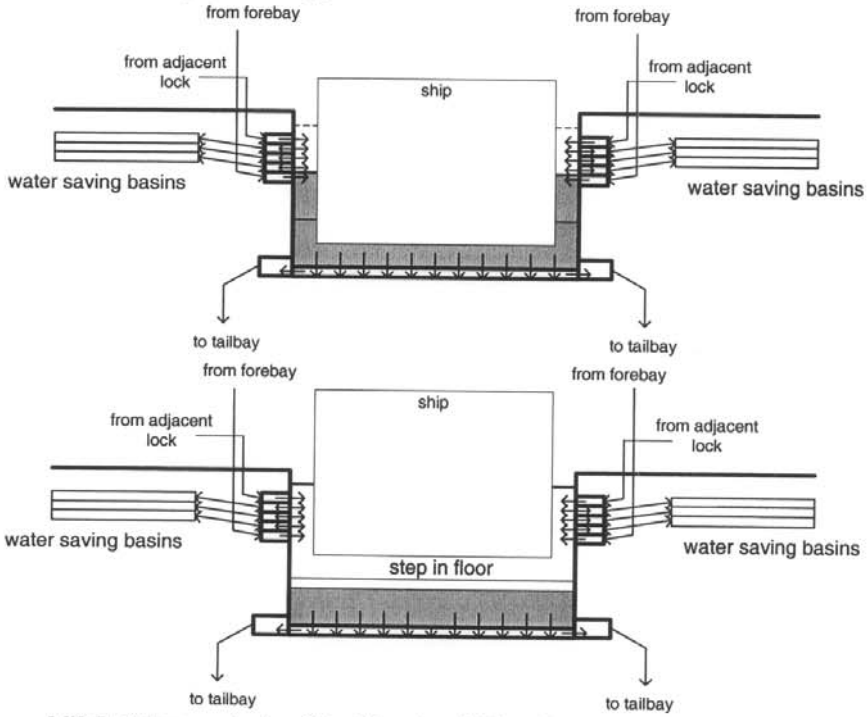
A considerable reduction of the salt water intrusion can be obtained with a system that is designed to keep the salt water in the lower lock chamber during lock operations (expected upper limit of salt water intrusion reduction 90%). The upward step in the floor at the upstream side of the lower lock chamber forms a crucial element of this system. In view of the required step height the system is best suited for a 1-lift lock configuration (with water saving basins; 1-lift locks without wsb's are not considered). Another crucial element of the system is the wall filling / emptying system with openings in both lock walls above the salt water layer in the lock chamber. By means of a careful filling and emptying, mixing of salt water and fresh water can for the greater part be prevented. In the case of a 1-lift lock configuration the salt water remains below the level of the step in the floor, which prevents an escape of salt water to the forebay, provided that the ship moves slowly without using too much it's engine. The system does not cause an additional water loss. Since lock filling and - emptying as well as ship manoeuvring have to be done very carefully, a delay of shipping is unevitable. However, the required total lockage time of the 1-lift locks may be smaller than with a normal 3-lift lock configuration or even a normal 2-lift lock configuration. In view of the large tidal range it may be necessary to install vertical lifting gates in the lower fill openings in the walls of the locks at the Pacific side. A thorough study into all relevant aspects of this system is required when applied to the Post-Panamax Locks.



1-lift Post-Panamax Locks with wsb's and wall filling / emptying system; ship in lock chamber; uplockage; situation before and after filling

C2 Partly remove the salt water from the lower lock chamber

Salt water intrusion can effectively be reduced with a system that is designed to exchange the salt water in the lock chamber with fresh water from the forebay (expected upper limit of salt water intrusion reduction 90%). The system is only necessary in the lower lock chamber and is suited for 3-lift and 2-lift lock configurations. The fresh water is supplied through openings in the lock walls (the lowest openings are located near the initial salt water surface), while the salt water is simultaneously discharged to the tailbay through openings in the floor. This is a delicate process since the supplied fresh water and the withdrawn salt water have to balance, while the supplied fresh water may not mix with the salt water. If carefully executed, mixing of salt water and fresh water can for the greater part be prevented. The exchange of salt water is stopped when the salt water – fresh water interface is ample below the level of the step in the floor at the entrance to the next lock. The step in the floor prevents an escape of salt water to higher locks and forebay in the phase that lock gates are open, provided that ships move slowly and don't use too much the engine. The system causes an additional water loss. This water loss can be prevented when water storage basins are applied, but the application of these basins reduces the effectiveness of the system, since accumulation of salt water in the storage basins will occur. In addition, pumps are required in the case of water storage basins. Lock filling and - emptying as well as ship manoeuvring have to be done very carefully, which are the reason that a delay of shipping is inevitable. The system is rather complex and requires a careful operation, in particular at the Pacific side, where a large tidal fluctuation occurs. A thorough study into all relevant aspects of the system is required when applied to the Post-Panamax Locks.



3-lift Post-Panamax Locks with wsb's and wall filling / floor emptying system; ship in lock chamber; uplockage; situation before and after filling

3.3 Conclusions mitigation measures and recommendations

3.3.1 Conclusions

In the previous sections we have discussed several measures to mitigate the salt water intrusion. Most of these measures or systems have been applied in existing shipping locks and / or tested in laboratory conditions. Generally spoken, the mitigation of salt water intrusion is a delicate matter. The results of measures are strongly dependent on a careful operation of the locks, the prevailing hydraulic conditions, shipping intensities etc.
The hydraulic conditions at the Panama Canal are favourable in the sense that the canal water level is always much higher than the sea water level, contrary to for example locks in low-situated delta areas, where the sea level can be higher and lower than the canal water level. A complicating factor for salt water intrusion mitigation measures is, however, the large tidal amplitude at the Pacific side of the canal.

In any case existing mitigation systems, which have proven to be effective, can not simply be applied to the Post-Panamax Locks. Each measure requires a thorough study on the effectiveness under the conditions that exist at the Panama Canal. This study can partly be done by numerical simulations, but most measures need a simulation and verification in physical scale models. Special attention is required for the problem of marine growth and siltation, if relevant in the Panama Canal area, since they may endanger the proper functioning of some of the mitigation measures.

In view of a well-balanced selection of mitigation measures it is necessary that the maximum allowed salt water load through the locks is known for Gatun Lake. This salt water load should be assessed on the basis of maximum salt concentration levels at sensitive locations of Gatun Lake. The maximum salt concentration levels of Gatun Lake should therefore first be defined. The relationship between the salt water load through the locks and the salt concentration levels at specific locations may be established using a 3-dimensional numerical flow model of the lake. This relationship is required as a function of ship traffic intensity and seasonal hydraulic variations, for different configurations of Post-Panamax Locks. The Post-Panamax lock configuration is of importance since the quantity of water that is lost through lockage operations, is related to the lock design.

Apart from the analysis of the maximum allowed salt water load, a first selection can already be made of feasible, effective mitigation measures. These measures should be developed to an initial, global design level and the effectiveness further studied.

Promising, highly effective mitigation measures are:

- *Measure C1* (keep the salt water in the lock chamber); this measure is suited to 1-lift locks, does not cause an extra loss of water from the lake, but has the disadvantage that the operation of the locks is rather complex; the measure causes also a longer lock operating time, but compared to the total lock operating time of a 3-lift lock this may be acceptable
- *Measure C2* (partly remove the salt water from the lower lock chamber); this measure is suited to 3-lift locks and 2-lift locks; it causes a considerable extra loss of fresh water

(unless separate water storage basins are applied, which however reduce the effectiveness); the lock operation is even more complex than with measure C1 and requires a longer operating time, which is the reason that ship handling is delayed.

- *Measure B3* (catch the intruded salt water in a deep pit and flush); this measure is suited to all lock configurations, but causes a considerable extra loss of water (the loss of water is smaller when a perforated floor is constructed in the pit, which limits the escape of fresh water)

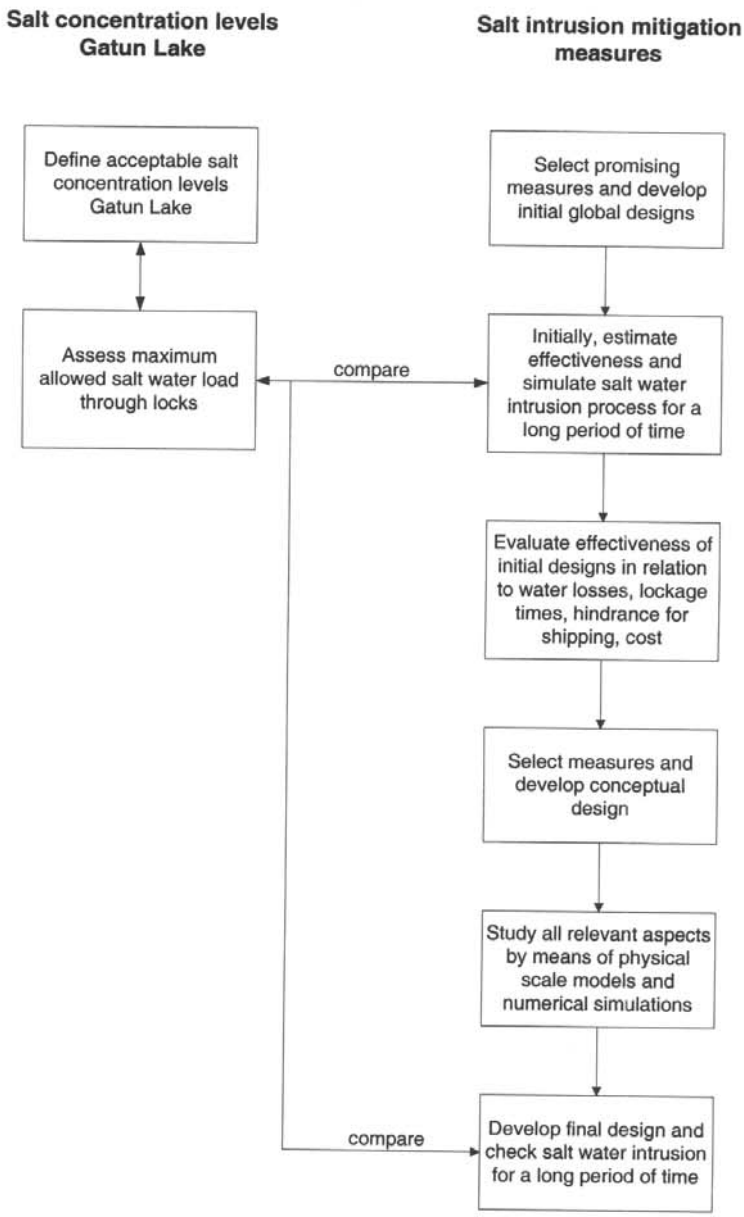
Pneumatic barriers (air bubble screens) are less effective but may be used together with other measures to improve the effectiveness.

3.3.2 Recommendations

To solve the problem of a too high salt water intrusion into Gatun Lake we recommend the following:

1. Define the acceptable salt concentration levels at specific locations of Gatun Lake
2. Assess the maximum allowed salt water load on Gatun Lake through the existing and Post-Panamax Locks. The relationship between the salt water load through the locks and the salt concentration levels at specific locations of Gatun Lake may be established using a 3-dimensional numerical flow model of the lake. This relationship is required as a function of ship traffic intensity and seasonal hydraulic variations, for different configurations of Post-Panamax Locks
3. Select promising and feasible measures to reduce the intrusion of salt water and develop these measures to an initial, global design level, appropriate for specific Post-Panamax lock configurations
4. Estimate the effectiveness of these measures for the conditions that are present in the Panama Canal
5. Make simulations for a longer period of time of the reduced salt water intrusion process, to assess the effectiveness of selected measures under seasonal hydraulic variations, for different ship traffic intensities and for specific Post-Panamax lock configurations, and compare with the allowed salt water load; to that purpose the simulation model Swinlocks may be used
6. Evaluate the effectiveness of selected measures in relation to the water loss from the lake, lockage times, hindrance for shipping, and cost, for different configurations of Post-Panamax Locks
7. Decide on salt mitigation measures and select Post-Panamax lock configuration; develop an apropriate measure or group of measures to a conceptual design level
8. Thoroughly study all aspects of the conceptual design that may effect the effectiveness, under relevant operational conditions, by means of numerical computations and physical scale model studies
9. Develop to a final design together with the selected configuration of Post-Panamax Locks
10. Check the salt water intrusion of the final design for a longer period of time as a function of ship traffic intensity and seasonal hydraulic variations.

The above activities are reflected in the next schedule:


Salt concentration levels Gatun Lake
Salt intrusion mitigation measures
Define acceptable salt concentration levels Gatun Lake
Select promising measures and develop initial global designs
Assess maximum allowed salt water load through locks
compare
Initially, estimate effectiveness and simulate salt water intrusion process for a long period of time
Evaluate effectiveness of initial designs in relation to water losses, lockage times, hindrance for shipping, cost
Select measures and develop conceptual design
Study all relevant aspects by means of physical scale models and numerical simulations
compare
Develop final design and check salt water intrusion for a long period of time