Prepared for:

Autoridad del Canal de Panamá

Salt Water Intrusion Analysis
Panama Canal Locks

Future situation: Post-Panamax Locks

Report F
Study, modeling and analysis of salt water intrusion mitigation systems for revised 3-lift lock configurations

April 2005

Q3696

WL | delft hydraulics

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Study, modeling and analysis of salt water intrusion mitigation systems for revised 3-lift lock configurations

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CLIENT:	Autoridad del Canal de Panamá (ACP)
TITLE:	Salt water intrusion analysis Panama Canal Locks. Future situation: Post-Panamax Locks. Report F. Study, modeling and analysis of salt water intrusion mitigation systems for revised 3-lift lock configurations

ABSTRACT:

On June 30, 2004, the Autoridad del Canal de Panamá (ACP) awarded WL | Delft Hydraulics the contract for study, numerical modeling and analysis of salt water intrusion mitigation systems, which are aimed to reduce the salt water intrusion into Gatun Lake and Gailliard Cut through the future Post-Panamax Locks. The study has been undertaken for a 3-lift lock system.

Different salt-water intrusion mitigation systems have been analysed. In support to the analysis the experience with systems used in the Netherlands has been collected and made available by the The Ministry of Transport and Public Works of the Netherlands. Four systems were selected for a further modeling using the salt water intrusion simulation model SWINLOCKS. The effects of the selected mitigation systems in terms of salt water load and fresh water use have been presented in this Report F for various water control scenarios and ship traffic intensities.

Though with the help of the SWINLOCKS model a comparison of lock designs on the subject of salt water intrusion and water losses can be made, and a selection of the most suited lock design and most promising mitigation system is possible, there is still a need for further studies on the salt water intrusion in the final design stage of the selected Post-Panamax Locks. These studies should focus on the process of salt water intrusion through the locks and on the functioning of the proposed mitigation system, but also other (related) aspects need a further study. A brief description of studies has been presented in the present Report F.

REFERENCES: Contract No SAA-135358, dated 30 June 2004

VER	ORIGINATOR	DATE	REMARKS	REVIEW	APPROVED BY
01	T.H.G. Jongeling	Jan.2005		R.J. de Jong	
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Summary of Report F

1 Introduction

The Autoridad del Canal de Panamá (ACP) has awarded WL | Delft Hydraulics the contract for study, numerical modeling and analysis of salt water intrusion mitigation systems, which are aimed to reduce the salt water intrusion into Gatun Lake and Gaillard Cut through the future Post-Panamax Locks (contract No SAA-135358, dated 30 June 2004). The results of earlier studies conducted by WL | Delft Hydraulics (contract SAA-74337 and contract SAA-110830) form a starting point for the present study, but the present study concentrates on a *revised* design of a *three-lift lock system*. The selected dimensions of the proposed Post-Panamax locks are: nominal length 457.32 m (1500 ft), width 54.86 m (180 ft), and depth 16.76 m (55 ft). These dimensions are significantly larger than the dimensions of the existing Panamax-size locks, which measure 33.5 m wide by 305 m long by 13 m deep. The nominal dimensions of a Post-Panamax vessel have been selected by ACP as: length 385.7 m (1265 ft) beam 45.72 m (150 ft), and draft 15.24 m (50 ft, in tropical fresh water).
To the purpose of the numerical simulation of salt water intrusion the existing model SWINLOCKS has been extended. This simulation model was earlier developed by WL | Delft Hydraulics under ACP-contracts SAA-74337 and SAA-110830.

The objectives of the present services include:

- analysis of alternative mitigation systems; this analysis is supported by case studies of salt water intrusion mitigation systems used in the Netherlands (contribution by Ministry of Public Works)
- modeling of selected mitigation systems in the existing model SWINLOCKS
- modeling of Post-Panamax lock system in the existing model SWINLOCKS with revised lock chamber dimensions (3-lift locks with 2 wsb's per lift and 3-lift locks with 3 wsb's per lift)
- simulation and analysis of the salt water intrusion for selected mitigation systems for two configurations of proposed Post-Panamax locks (three-lift locks with 2 wsb's each lift, three-lift locks with 3 wsb's each lift) and for selected hydraulic conditions, ship-traffic intensities and water control scenarios; mutual comparison of systems and concluding analysis
- explanation how results of simulations can be used in further water quality and salt dispersion studies.

2 Alternative mitigation systems

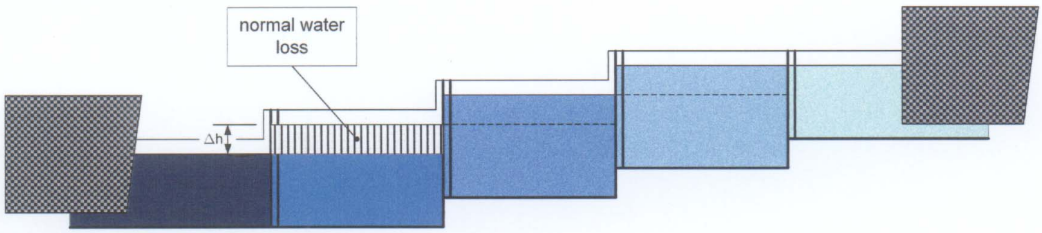
In the previous Report E (WL | Delft Hydraulics, April 2004) we have discussed several measures to mitigate the salt water intrusion. Most of these measures or systems have been applied in existing shipping locks and / or tested in laboratory conditions. In practice it appears that the mitigation of salt water intrusion is a delicate matter. The effects 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 favorable 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.
Existing mitigation systems, which have proven to be effective, can not simply be applied to the Post-Panamax Locks. They have been designed for single lift locks with water-level differences between salt water tailbay and fresh water forebay up to about 4 m, which is considerably smaller than the total lift of about 26 m at the Panama Canal. Consequently, flow velocities in these lock chambers are generally also smaller than in the Panama Canal Locks. Higher flow velocities cause a stronger turbulence and generally also a stronger mixing of salt and fresh water, which is unfavourable in view of a mitigation of salt water intrusion.

In the inception phase we have presented different mitigation systems, which are suited for application at the Post-Panamax Locks. In consultation with ACP six of these mitigation systems have been selected for a further evaluation. Later, the option of desalination of the intruded salt water has been added. The experience with mitigation systems of existing locks in the Netherlands was used in the evaluation. The evaluation has been concluded with a mutual comparison of the mitigation systems; next items formed a part of the evaluation:

1. Expected effectiveness
2. Corresponding total water loss per lockage
3. Delay for shipping
4. Hindrance for shipping
5. Complexity of the system and ease of operation
6. Construction cost

The water loss of locks and mitigation systems is generally expressed in this study in terms of the 'normal' water loss. The 'normal' water loss is defined as the product of Δh, see next figure, and the area of the lock chamber (including two gate recesses). The quantity Δh is 1/3 of the water level difference between Gatun Lake and the oceans, the latter being 25.7 m on average.



The evaluation of mitigation systems revealed the following (see also next table):

- System 1, *stepwise flushing of all lock chambers (dummy lockage)*, is the cheapest system (no extra cost), has a good effectiveness that corresponds to a moderate extra water loss. A delay for shipping is expected in the case of a relay mode of operation.
- System 2, *flushing of middle lock and upper lock*, has a higher effectiveness at a similar water loss. A delay for shipping is expected in the case of a relay mode of operation.

Attention is required for the closure of valves in culverts with flowing water. Some extra construction costs have to be made.

- System 4, *enhanced flushing of upper and lower lock chamber*, is the most effective system, but the extra water loss is highest. A delay for shipping is expected in the case of a relay mode of operation. In view of the negative head across gates, rolling gates are required that close off at two sides. Attention is also required for the closure of valves in culverts with flowing water. Extra construction costs are to be made.
- System 6, *exchange of salt water with fresh water in lower lock chamber*, is a very complex system that has carefully to be operated (delay for shipping is unavoidable). The effectiveness is high but this is achieved at the cost of a relatively high extra water loss. This water loss can be prevented when water storage basins are applied, though this will reduce the effectiveness to some extent. Transverse forces may occur on the ship in the lower lock chamber. It is the most expensive system.
- System 9, *catch salt water in a deep pit and drain the salt water away to the tailbay*, has a high effectiveness at a moderate extra water loss. The drainage of salt water does not cause delays for shipping nor hindrance. Since the salt water in the pit is not immediately at rest after inflow, a salt concentration monitoring system may be needed to optimize the drainage programme. A regular monitoring may also be required in view of siltation of the pit. The construction of the deep pit with drainage system is expensive.
- System 10, *pneumatic barrier*, has a low effectiveness, but causes no extra water losses. It can only successfully be applied when the lock gates to tailbay and forebay are shortly opened. The system is cheap, but the cost of operation (power for operation of air compressors) may be high.
- The option of *desalination of intruded salt water* has a high effectiveness at a relatively small extra water loss. The construction cost and the cost of operation are extremely high, when compared to the other systems.

Aspect	*System 1*	*System 2*	*System 4*	*System 6*	*System 9*	*System 10*	*Desali-nation*
upper limit of effectiveness (% reduction of salt load)	72	86	94	85	85	20	90
corresponding total water loss, wsb's not in operation (as % of normal water loss)	150	150	200	180	162	100	120
delay for shipping	yes, in case of relay mode	yes, in case of relay mode	yes, in case of relay mode	yes	no	no	no
hindrance for shipping	little	little	little	possibly transverse forces on ship	no	little for small yachts	no
complexity of system / ease of operation / points of attention	simple	not complex; closure of valves in flowing water	not complex; neg. head of gates; closure of valves	complex system; careful operation	not complex; possibly siltation of pit	simple	not complex
cost amplifier	1.00	1.05	1.10	1.48	1.40	1.02 cost of operation!	> 10 ?? also high energy cost!

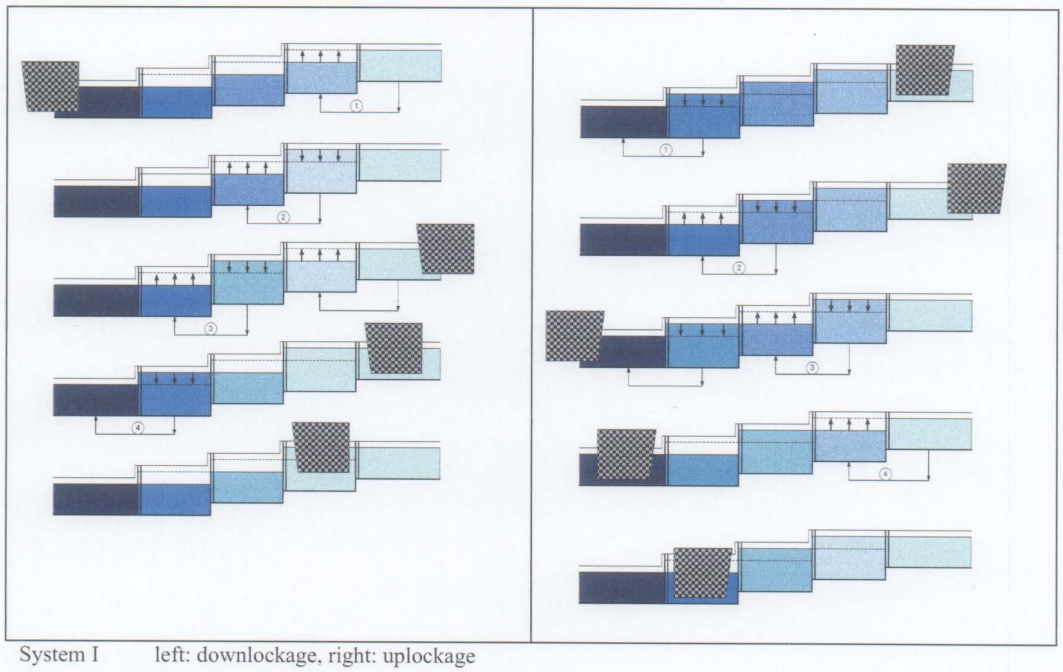
Note: mitigation system is operated after each downlockage of a ship

The delay for shipping caused by operation of a mitigation system is in particular of importance, since delays may effect the capacity of the new shipping lane. Post-Panamax ships are most probably not allowed to pass the canal at night, which means that the daylight window has to be used to handle the ships. The capacity of the new lane is thus constraint by the length of the daylight window, but is also depending on lock operation times and on the way that ships are guided. In the so-called 'relay mode' of operation locomotives guide the ship halfway and return to their original position. The ship is taken over by other locomotives, which guide the ship further through the locks. This 'relay mode' has been developed for the existing locks with a 'locomotive on single track system', and has the advantage that a second ship can already been handled before the first ship has left the last chamber of the 3-lift lock system. A similar time-saving effect can be obtained in the new locks when tugboats assist the Post-Panamax vessels all the way through the locks.

When the operation of a mitigation system requires some extra time between two subsequent lockages, the capacity of the locks is effected, in particular when a 'relay mode' of operation (or similar) is applied. The maximum number of Post-Panamax ships that can be handled per day may then be reduced.

After a careful consideration at the meeting with ACP of 12 October 2004, next four mitigation systems have been selected for a further analysis using the simulation model SWINLOCKS:

Mitigation system I:
stepwise flushing of all lock chambers ('dummy' lockage)

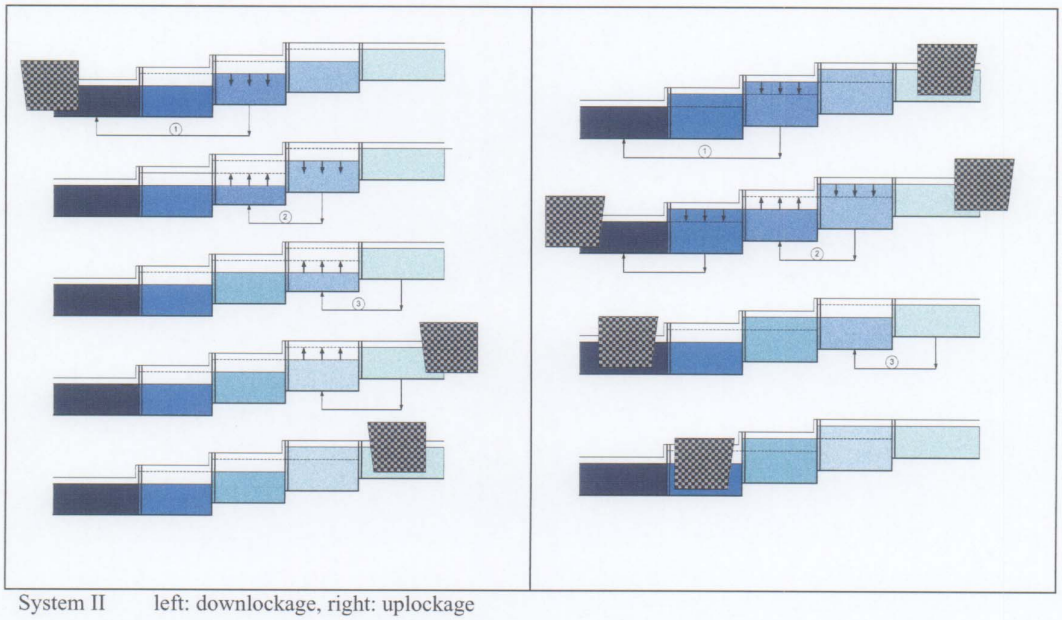


System I left: downlockage, right: uplockage

features:

- no special provisions required; standard operation between two lockages

Mitigation system II:
flushing of middle and upper lock chamber

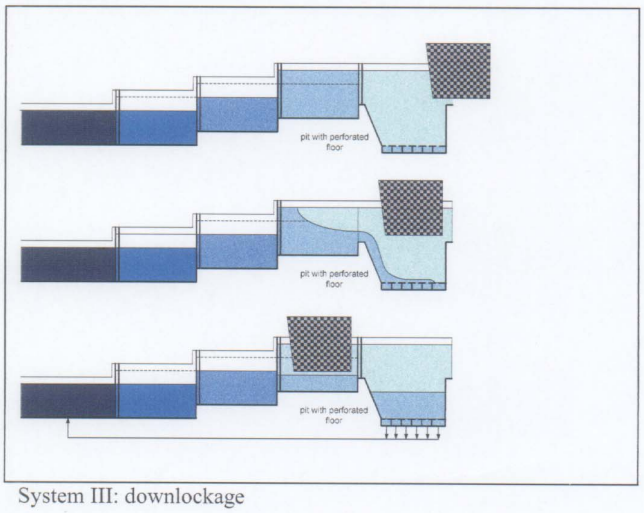


System II left: downlockage, right: uplockage

features:

- separate culverts required between middle lock and tailbay with control valves
- at uplockage: valves in culverts have to be closed when the water of the middle lock is at the pre-defined low level, meaning that the valves are closed when conduits are running at full capacity

Mitigation system III:
flushing of salt water from pit with perforated floor

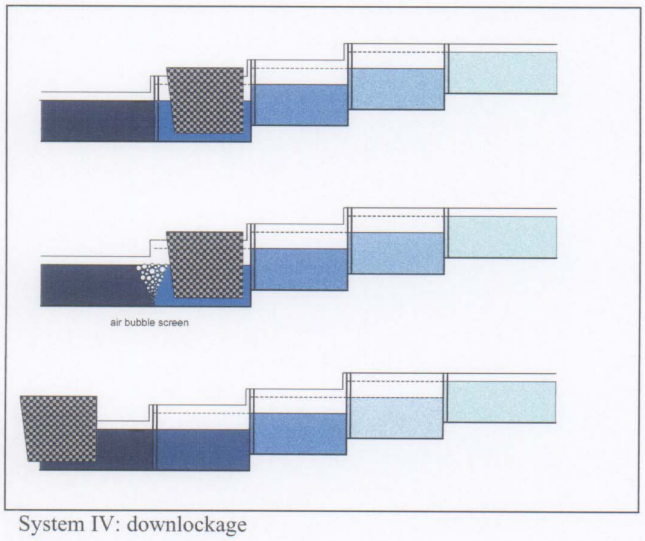


System III: downlockage

features:

- salt collecting pit at upstream side of upper lock required with perforated floor and drainage system; separate culverts and control valves required to tailbay

Mitigation system IV:
pneumatic barrier at the entrance to lower and upper lock chamber



System IV: downlockage

features:

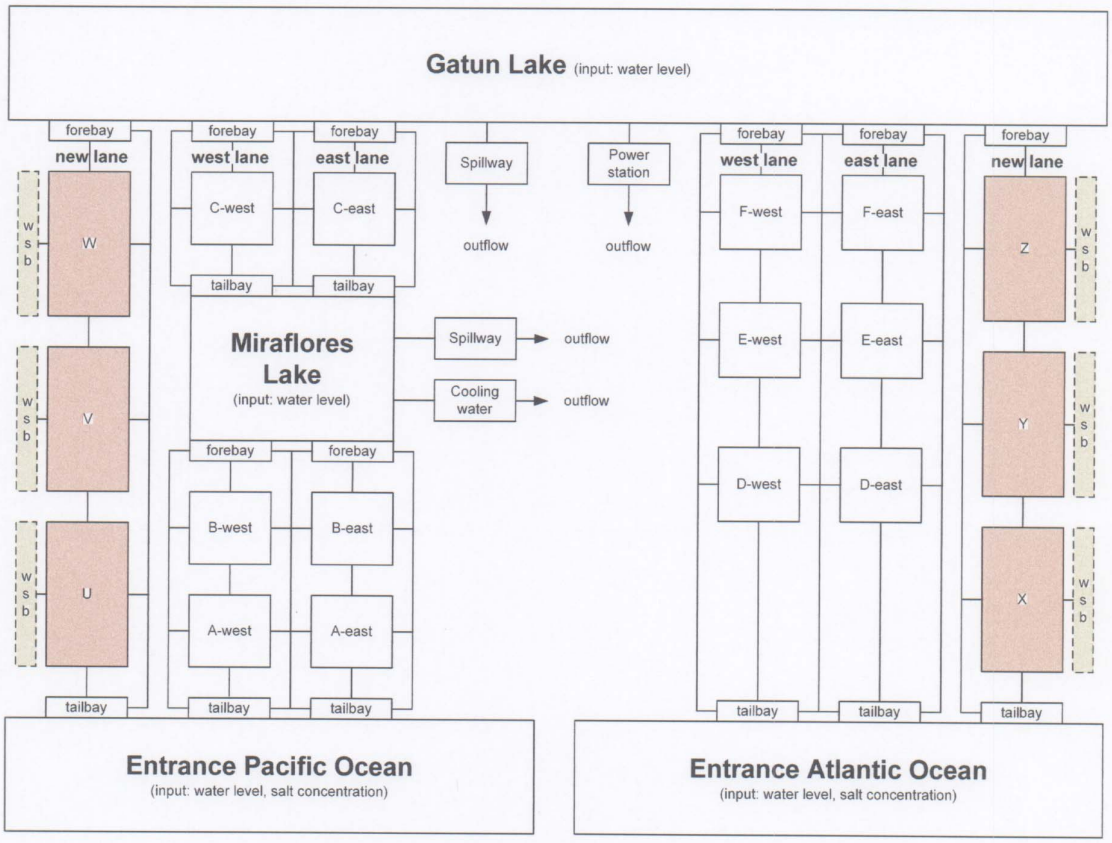
- air bubble screen at entrance to lower lock and, alternatively, upper lock chamber required (air compressors needed)
- the ship-bound exchange of water is not prevented with the pneumatic barriers

Mitigation systems I and II have in common that they cause a delay for shipping when a relay-mode or similar time-saving mode of operation is applied in ship locking. Systems III and IV do not cause a delay. Mitigation systems I – IV have been modeled in the salt water intrusion simulation model SWINLOCKS.

3 Extension of SWINLOCKS

The numerical salt water intrusion simulation model SWINLOCKS (developed by WL | Delft Hydraulics under ACP-contracts No SAA-74337 and No SAA-110830) has been used to study the effectiveness of the four selected mitigation systems. For a full description of the existing model reference is made to our earlier reports (Reports A – D, see Section 1.3).

In short, the simulation model consists of a number of separate basins, which represent the various lock chambers, forebays and tailbays, and lakes of the Panama Canal system, each basin having a certain water level, water volume and salt concentration, and being mutually connected (see next scheme, valid for the future situation with three-lift Post-Panamax Locks). When a ship sails from ocean to ocean it passes the various basins, causing a net transport of water from lakes to oceans and a migration of salt water from basin to basin.



Water from Gatun Lake and Miraflores Lake goes stepwise down during uplockage and downlockage of ships, mixing up with the water in the lower locks during filling. When water saving basins are in use, water from the lock chamber is temporarily stored during leveling down (together with a part of the salt water in the lock chamber) and returned into the lock chamber during leveling up. When lock gates are open and a ship moves in or out, the ship's volume is exchanged and density flows occur between basins with different densities. The simulation model SWINLOCKS computes the transport of water and the migration of salt between the various basins in a schematized way, using the water volume

and the volume-averaged salt concentration of the basins as base variables. In a water balance and salt balance analysis changes are evaluated after each step of an uplockage or downlockage process.

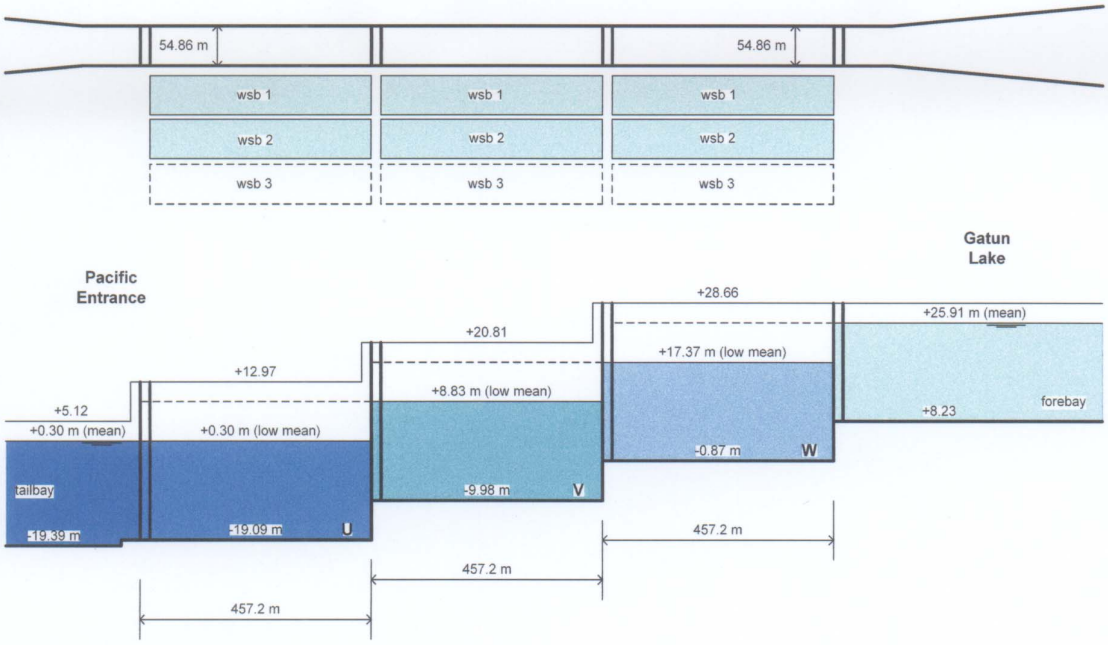
For the *salt balance* of the lakes we start from the following:
Salt water intrudes into the lakes through the existing and future locks. All other water sources (Alhajuela Lake - Chagres River, creeks and rivers, precipitation, ground water) supply fresh water to the lakes. The outflow of saline water occurs through the spillways of Gatun Lake (spillage of surplus water, water for power generation) and Miraflores Lake (spillage of surplus water, cooling water). The outflow of saline water through other offtakes (drinking water, industrial water, ground water flow, evaporation) is nil or can be neglected in the analysis. That is also the reason why these offtakes are not separately modeled in SWINLOCKS: the effect of inflow and outflow of *fresh* water on the water volume of the lakes is included in the water levels of the lakes, which are prescribed as a function of time. The effect of a change of the water volume of the lakes on the salt concentration is accounted for in the salt balance analysis.

ACP has reconsidered the nominal dimensions of Post-Panamax vessels (a smaller beam of 45.72 m (150 ft) instead of the former 54.86 m (180 ft) has been selected), and in coherence with it also the dimensions of the locks, which have been reduced. It was therefore required to extend the simulation model with a revised 3-lift lock system with lock chamber dimensions, which are smaller than the sizes of the lock chambers used in previous simulations. Two options for water saving basins have been modeled:

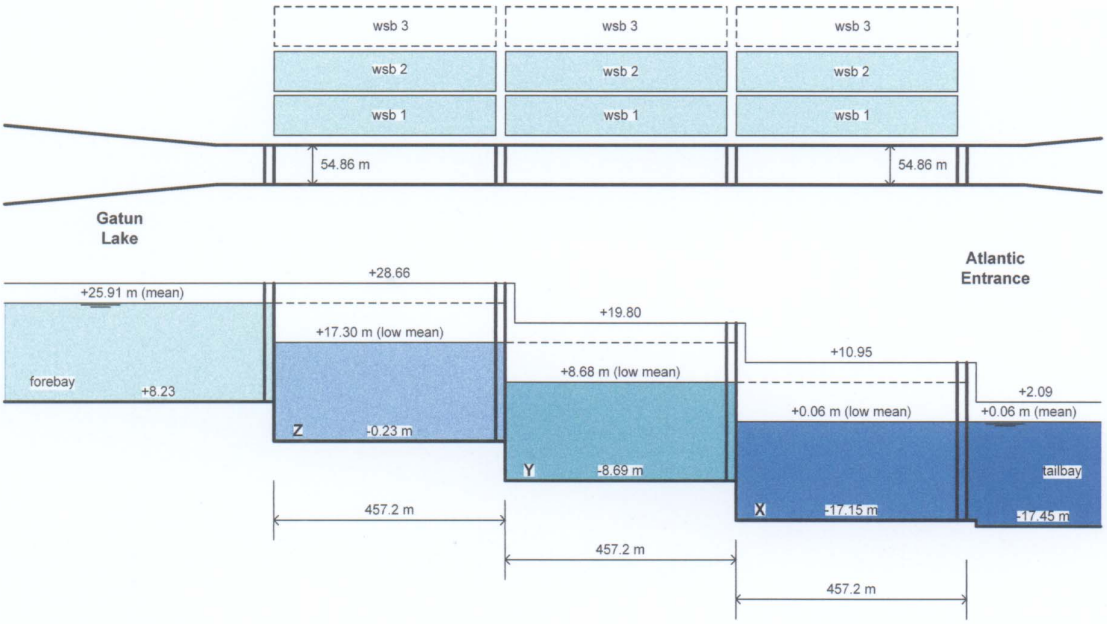
- **Configuration E**: revised 3-lift locks with 2 wsb's per lift (wsb's can be switched off); nominal length 457.2 m, width 54.86 m, depth over sill 16.76 m (1500 ft x 180 ft x 55 ft), keel clearance 1.52 m (5.0 ft)
- **Configuration F**: revised 3-lift locks with 3 wsb's per lift (wsb's can be switched off); nominal length 457.2 m, width 54.86 m, depth over sill 16.76 m (1500 ft x 180 ft x 55 ft), keel clearance 1.52 m (5.0 ft).

A keel clearance of 1.52 m (5 ft) is selected by ACP for the present study as a preferred value, but it may appear from other studies that a keel clearance of 1.52 m is not safe enough for shipping. In that case a keel clearance of 3.05 m (10 ft) may be selected, giving a depth over the sill of 18.3 m (60 ft).

Next figures present a schematic picture of the revised 3-lift Post-Panamax Locks at the Pacific side and the Atlantic side of the canal respectively.



SWINLOCKS: revised 3-lift Post-Panamax Locks at Pacific side



SWINLOCKS: revised 3-lift Post-Panamax Locks at Atlantic side

The sill levels of the lock chambers and forebays have been derived by ACP taking into account a minimum operating water level of PLD +25.0 m (+82.0 ft) in Gatun Lake, a ship draft of 15.24 m (50 ft), and a keel clearance of 1.52 m (5.0 ft). The nominal dimensions of a Post-Panamax vessel were selected by ACP as: beam 45.73 m (150 ft), draft 15.24 m (50 ft, in tropical fresh water) and length 385.7 m (1265 ft).

Similar as in the earlier CPP design a multiport filling and emptying system is assumed for the revised 3-lift locks, with openings in both lock chamber walls just above the bottom along the full lock chamber length. The bottom of the lock chambers is flat without sills.

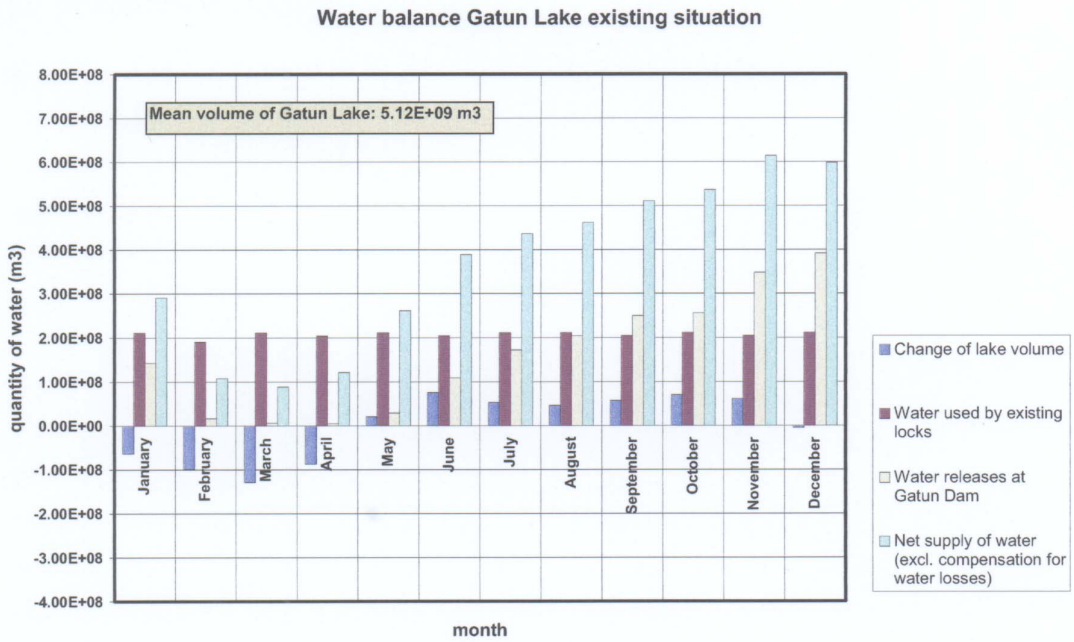
Mitigation systems I – IV have been modeled in SWINLOCKS.
Mitigation system I (stepwise flushing of all lock chambers) is in operation after uplockage or downlockage of a ship, but not necessarily after each ship lockage. The mitigation action is executed in SWINLOCKS through a separate mitigation scenario, which describes the subsequent steps of water transfer from forebay to tailbay. Water saving basins are not active during execution of this scenario. The quantity of water that is used to flush the lock chambers in the mitigation action can be varied; the maximum quantity is equal to the 'normal' water loss. A lesser quantity can be selected using a reduction factor λ ($\lambda = 1$ means no reduction) in the water balance formulas; different values of λ can be selected for uplockage and downlockage. Salt exchange coefficients are used in the salt balance formulas that describe the transfer of salt.
Mitigation system II (flushing of middle lock and upper lock) has been modeled in a similar way as mitigation system I.
Mitigation system III (flushing of salt water from a pit with perforated floor) has been modeled as a last action within a normal uplockage or downlockage scenario of a ship. The quantity of water that is used in the flushing operation may be varied, using a reduction factor λ, similar as for mitigation system I, in the water balance formulas.
Mitigation system IV (air bubble screen at the entrance to the lower lock and, alternatively, also at the entrance to the upper lock) has been modeled within a normal uplockage or downlockage scenario of a ship. The effect of the pneumatic barrier is realised by a multiplication of the exchange coefficient e_x, used in the salt balance of the move ship step, with a reduction factor ξ; different values of ξ can be selected for uplockage and downlockage, and for the barrier at the lower lock and the upper lock. The pneumatic barrier can be put out of action by selecting $\xi = 1$.

The salt exchange coefficients used in the mitigation systems I and II are based on, but not fully equal, to the exchange coefficients which are used in the normal water leveling steps of lock chambers. The salt exchange coefficients of mitigation system III have been derived on the basis of density-flow simulations with our numerical program Delft3D. In the present study we start from the assumption that all the salt water in the salt pit is drained away when we select $\lambda = 1.25$ at downlockage (corresponding to an estimated water loss of the order of magnitude of 100% - 150 % of the 'normal' water loss) and $\lambda = 0.5$ at uplockage (corresponding to an estimated water loss of the order of magnitude of 25% - 75 % of the 'normal' loss). When in simulations a lesser value for λ is applied a proportionally lesser quantity of salt water is drained away. The portion remaining in the salt pit is finally lost to Gatun Lake. The salt exchange coefficient used in the salt balance quantifies the escape of salt water to the lake and is thus depending on the reduction factor λ.
The values of the reduction factor ξ in the salt balance formulas of mitigation system IV are selected on the basis of experimental data.
For all four mitigation systems it applies that the choice of coefficients has to be founded by a further experimental study in the final design stage of the Post-Panamax Locks.

4 Water control Gatun Lake

For the present study ACP has selected a minimum operating level of Gatun Lake of PLD +25.0 m (PLD + 82.0 ft) and a maximum operating level of PLD +27.13 m (PLD + 89.0 ft). This is a somewhat broader operational range than the range of present representative water levels, based on 10-year averages, which varies between a minimum of PLD +25.57 m (+83.89 ft) and a maximum of PLD + 26.58 m (+87.22 ft); a broader water level range is favorable since this enables a better utilization of the storage capacity of the lake.
The water level of Miraflores Lake will be maintained at the present water level of about PLD +16.6 m (PLD +54.4 ft).

The present water balance of Gatun Lake is shown in next figure. Starting from the 10-year averaged water level variation of the lake the change of water volume throughout the year has been computed (mean water volume of lake: 5.12 km^3).



The water quantity that at present is used by the existing locks (36 ship transfers per day) and the quantity of water that is released at Gatun Dam are separately shown in the above figure. Both quantities sum up to 4.42 x 10^9 m^3 for one year, which is equal to 86% of the mean lake volume. It means that Gatun Lake is almost fully refreshed each year.
The quantity of water that balances with these losses corresponds to the net supply of water to the lake (= the natural inflow of water from the catchment area minus evaporation and seepage losses and minus the quantity of water that is withdrawn for water consumption etc.).

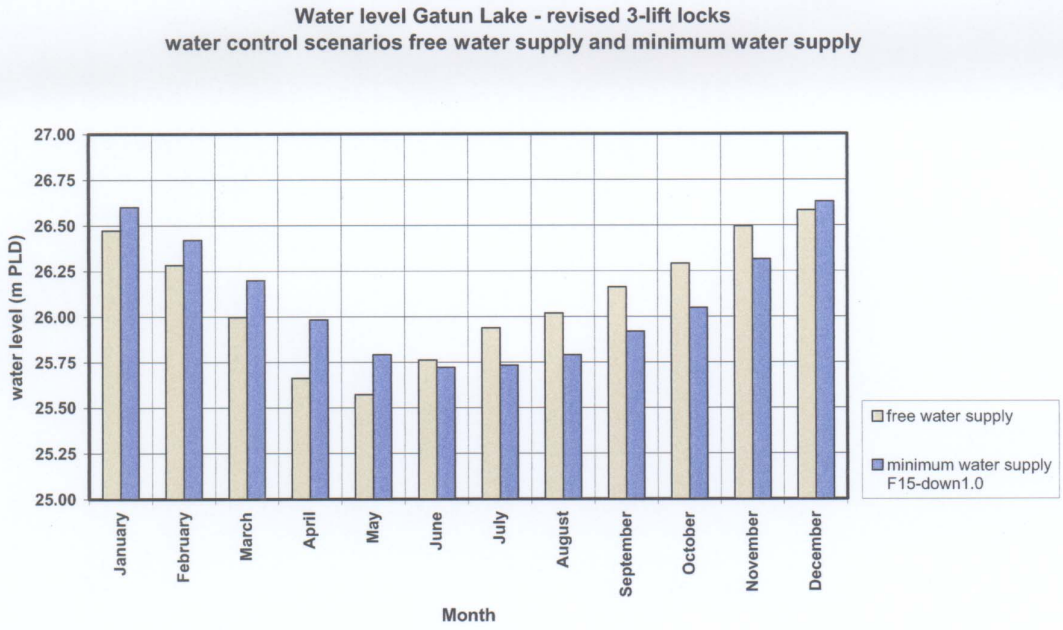
After construction of the Post-Panamax Locks more water will be lost from Gatun Lake. The losses will grow as the ship traffic on the Panama Canal intensifies and the number of lockage operations increases. The losses can partly be compensated by a lesser release of water at Gatun Dam. When this is not sufficient extra water has to be supplied from new

water resources. In the case that the Post-Panamax Locks are provided with water saving basins, a lesser quantity of water is lost from Gatun Lake. But at the same time, the operation of salt water intrusion mitigation systems causes, generally, an extra loss of water.

Various water control scenarios have been applied for Gatun Lake in previous and present SWINLOCKS simulations. The two main water control scenarios in the present simulations are:

- Free extra water supply to Gatun Lake
  In this water control scenario the present, 10-year averaged water level variation is maintained and the extra water losses caused by operation of the new locks and mitigation systems are instantaneously (partly or fully) compensated by a lesser release of water at Gatun Dam (the 10-year averaged water release data is applied); when this is not sufficient extra water is supplied to Gatun Lake from new water resources (free extra water supply when needed; starting point is that sufficient extra fresh water is available throughout the year). The water level varies between PLD +25.57 m (+83.89 ft) and PLD + 26.58 m (+87.22 ft), is independent of the water losses of Post-Panamax Locks and mitigation systems and remains far from the adopted limits PLD +25.0 m (+82.0 ft) and PLD + 27.13 m (+89.0 ft)).
- Minimum extra water supply to Gatun Lake
  In this scenario the concept of a proportional reduction of the water releases at Gatun Dam is applied. The water releases are reduced to compensate for the extra water losses caused by the operation of the new locks and mitigation systems, and are scheduled in such a way throughout the year (compared to the present, 10-year averaged water releases at Gatun Dam), that the supply of extra fresh water from new water resources is minimized. The extra supply of fresh water is scheduled in proportion to the *present* water releases throughout the year, meaning that most extra water is supplied in the wet season. This is favorable since, generally, more water is available in the wet season. The water level of Gatun Lake varies about an average value of PLD +26.1 m (+85.6 ft, similar as at present) and is controled between a minimum of PLD +25.0 m (PLD + 82.0 ft) and a maximum of PLD +27.13 m (PLD + 89.0 ft) throughout the year. The water level is dependent of the water losses of Post-Panamax Locks and mitigation systems.

The difference between the two water control scenarios for the water level of Gatun Lake is shown in next figure, that presents the water level that is used in the simulations with 'free water supply' and – as an example – simulation F15-down1.0 with 'minimum water supply' (revised 3-lift locks, 3 wsb's/lift, mitigation system I applied at downlockage, $\lambda = 1.0$).



ACP plans also to control the water releases of Gatun Lake in such a way that the supply of extra water, needed for the operation of the Post-Panamax locks and mitigation systems, is minimum. For that reason the latter water control scenario was the preferred scenario in the programme of SWINLOCKS simulations.

The concept - as applied in the simulations - of a proportional reduction of the water releases at Gatun Dam throughout the year and a proportional extra water supply if needed, resulting in a minimum extra water supply to Gatun Lake, can not be applied in the real situation since the actual rainfall and rainfall distribution over a year is not known in advance. Yet, the extra water supply can be minimized when water is only released when the water level threatens to exceed the upper limit level of Gatun Lake. When the spill capacity of Gatun Dam is sufficient to instantaneously discharge floods caused by intensive showers in the water shed area, the water level at which the release of water shall start, can be chosen close to the upper limit level of the lake.

A programme of simulations has been set up, that enabled the study of the mitigation systems for next conditions:

- revised 3-lift locks without wsb's, 2 wsb's per lift and 3 wsb's per lift
- 15, 10 and 5 Post-Panamax vessels per day, in addition to the present ship traffic intensity of 36 ship transfers per day in existing locks
- solely operation of mitigation system I, II, III or IV
- operation of mitigation systems at uplockage and downlockage versus operation of mitigation system at downlockage only
- intensive use of mitigation system I (at each downlockage operation) versus a less intensive use of mitigation system I (resulting in a smaller effectiveness but a lesser water loss)

- keel clearance of ship 3.05 m (10 ft) instead of 1.52 m (5 ft); this required a 1.52 m (5 ft) lower lock chamber floor elevation in simulations
- a combination of mitigation system I (stepwise flushing of all three lock chambers) and mitigation system IV (pneumatic barrier)
- real hydraulic conditions as occurred in the period 1992 - 2001

Simulations with real hydraulic conditions as occurred in the period 1992 – 2001, are useful to check the influence of real water level variations of the lakes in comparison to 10-year averaged water level variations and related water releases. However, it should be noted that the water balance of Gatun Lake in these simulations was different compared to the water balance in the 1992 – 2001 period, since extra water losses occurred, which were caused by the operation of the new locks and mitigation systems.

After having studied the results of some initial simulations, ACP had a preference for mitigation system I, possibly to apply in combination with mitigation system IV (advantages of system I: relatively high effectiveness, no additional investments needed for the Post-Panamax locks, system can be used as needed with varying intensity). For that reason, more attention was paid in the programme of simulations to mitigation system I than to the other mitigation systems.

5 Results of simulations and conclusions

In this section we first summarize general conclusions for all four selected and studied mitigation systems I – IV.

Then we compare into more detail the results of simulations for revised 3-lift locks without wsb's, with 2 wsb's/lift and with 3 wsb's/lift, for 15 Post-Panamax vessels per day. The preferred mitigation system I (stepwise flushing of locks, 'dummy lockage') is applied at downlockage operations, but we analyse also the salt water intrusion when no mitigation system is active. In addition, we compare the effects of the two main water control scenarios for Gatun Lake: minimum extra water supply and free extra water supply.

Finally, we analyse other aspects: ship traffic intensity, combined use of mitigation systems I and IV, effect of real hydraulic conditions, and effect of greater keel clearance. The analysis is focused on the volume-averaged salt concentration of the lakes and on water releases / extra water supplies of Gatun Lake.

Mitigation systems I - IV:

- In the present study four different salt-intrusion mitigation systems have been selected for modeling in SWINLOCKS and analysis of the effectiveness. The salt water intrusion and the effect of mitigation systems I – IV thereupon has been simulated for revised 3-lift locks without wsb's, with 2 wsb's/lift and with 3 wsb's/lift.
- Without mitigation system the *revised* 3-lift Post-Panamax locks with smaller dimensions than the original 3-lift locks (earlier CPP design) cause a lesser salt water load. The reduction of the volume-averaged salt concentration of Gatun Lake is 20% -

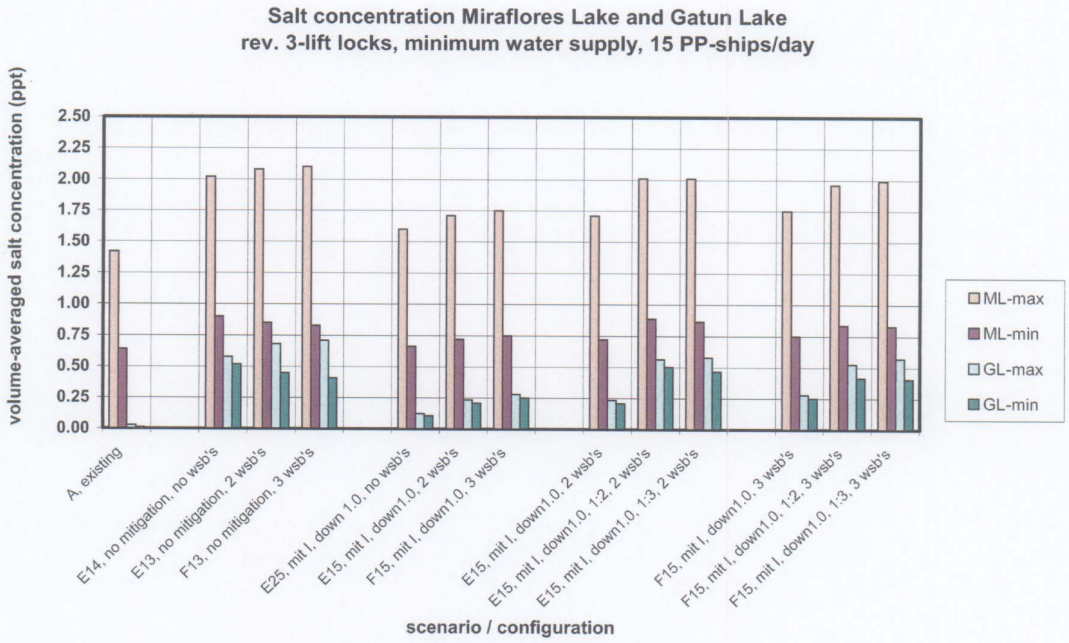
25% (valid for 15 Post-Panamax vessels/day). The net yearly supply of water to Gatun Lake (= extra water supply – water release) is also considerably smaller.

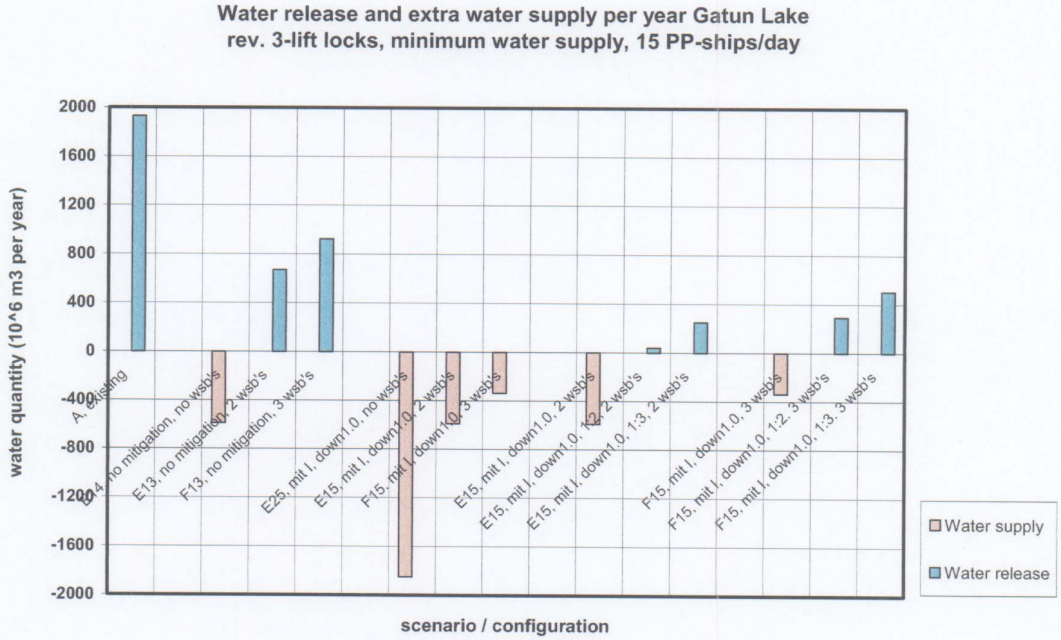
- All four studied mitigation systems reduce the salt load on Gatun Lake, and to a lesser extent on Miraflores Lake (through Pedro Miguel locks). The effect of the mitigation systems is somewhat better when mitigation systems are combined with the revised 3-lift locks with 2 wsb's per lift (configuration E) than combined with the revised 3-lift locks with 3 wsb's per lift (configuration F). This is caused by a better 'flushing' of the lock chambers in the case of 2 wsb's per lift (causing a greater lockage loss, systems I and II), but also the greater extra fresh water supply to Gatun Lake or the lesser water release at Gatun Dam plays a role in the salt balance of the lake.
- From the viewpoint of salt water intrusion mitigation, mitigation system II (flushing of middle and upper lock chamber) is the best option, immediately followed by mitigation system I (stepwise flushing of all three lock chambers). Mitigation system III (salt pit at upstream side of upper lock) has a somewhat smaller effect than earlier expected, but the effectiveness can be improved when the salt pit is made deeper than a depth of 17.0 m as was adopted for the present simulations. Mitigation system IV (pneumatic barrier at the entrance to both the lower lock chamber and the upper lock chamber) has a relatively small effect, but has the advantage of a zero water loss.
- When the mitigation systems are applied both at downlockage and at uplockage of ships the effect of the mitigation systems is somewhat better than when operation of the mitigation systems is limited to downlockage of ships only. However, this is at the cost of a twice as high water loss.

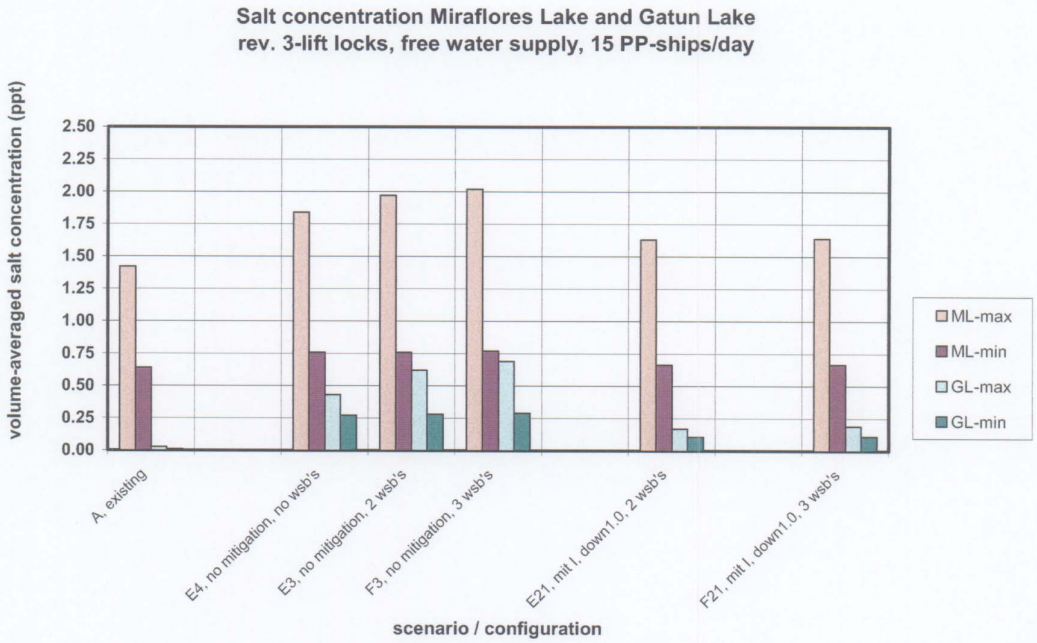
The above conclusions apply to mitigation systems which are operated at a maximum effectiveness, which means that a maximum quantity of water is used in the operation of the mitigation system; consequently the water loss caused by operation of the mitigation systems is relatively high (apart from mitigation system IV, pneumatic barrier, that is operated without a loss of water). Mitigation systems I, II and III can also be operated using a smaller quantity of water, but this reduces the effectiveness. This mode of operation is not studied.

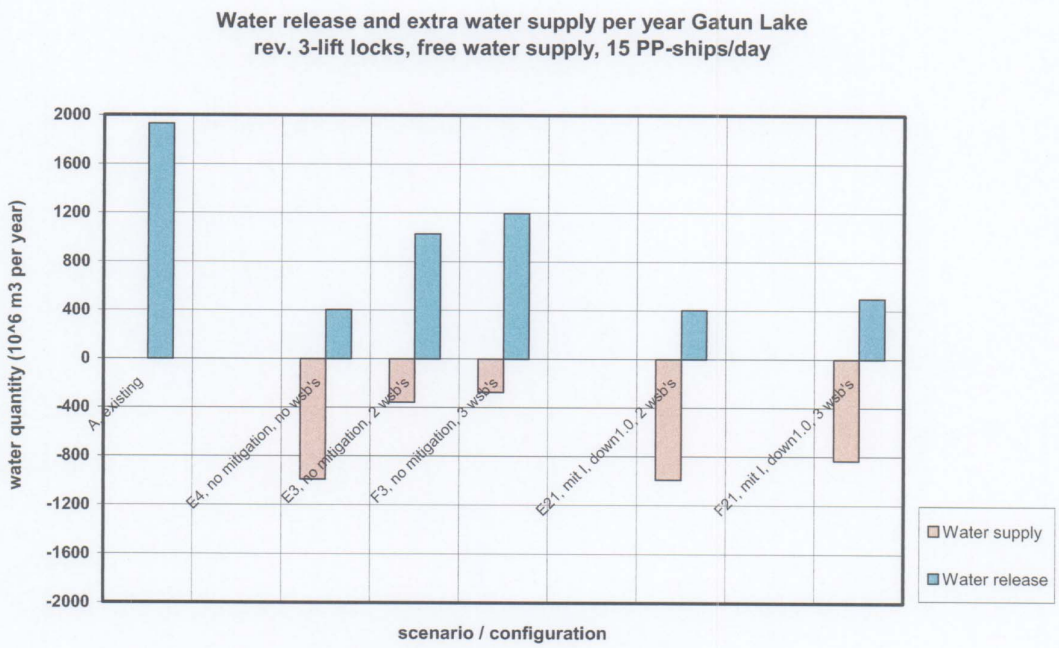
Mitigation system I:

Most salt water intrusion simulations have been executed for mitigation system I. Mitigation system I does not require extra investments for the revised 3-lift locks. The system can be deployed when needed and has a high effectiveness when operated after downlockage of each ship. For that reason it is the preferred system of ACP, possibly in combination with mitigation system IV. Results of simulations for a ship traffic intensity of 15 Post-Panamax vessels per day are presented in next figures (configuration E: 2 wsb's per lift, configuration F: 3 wsb's per lift); a distinction is made between the water control scenarios 'minimum water supply' and 'free water supply'. Mitigation system I is only operated after downlockage of ships; a maximum quantity of water is applied ('down1.0', λ = 1.0). The indication 1:2 or 1:3 means that the mitigation action is executed after each 2nd or 3rd ship.


Salt concentration Miraflores Lake and Gatun Lake
rev. 3-lift locks, minimum water supply, 15 PP-ships/day
volume-averaged salt concentration (ppt)
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
A, existing
E14, no mitigation, no wsb's
E13, no mitigation, 2 wsb's
F13, no mitigation, 3 wsb's
E25, mit I, down 1.0, no wsb's
E15, mit I, down1.0, 2 wsb's
F15, mit I, down1.0, 3 wsb's
E15, mit I, down1.0, 2 wsb's
E15, mit I, down1.0, 1:2, 2 wsb's
E15, mit I, down1.0, 1:3, 2 wsb's
F15, mit I, down1.0, 3 wsb's
F15, mit I, down1.0, 1:2, 3 wsb's
F15, mit I, down1.0, 1:3, 3 wsb's
scenario / configuration
ML-max
ML-min
GL-max
GL-min


Water release and extra water supply per year Gatun Lake
rev. 3-lift locks, minimum water supply, 15 PP-ships/day
water quantity (10^6 m3 per year)
2000
1600
1200
800
400
0
-400
-800
-1200
-1600
-2000
A, existing
E14, no mitigation, no wsb's
E13, no mitigation, 2 wsb's
F13, no mitigation, 3 wsb's
E25, mit I, down1.0, no wsb's
E15, mit I, down1.0, 2 wsb's
F15, mit I, down1.0, 3 wsb's
E15, mit I, down1.0, 2 wsb's
E15, mit I, down1.0, 1:2, 2 wsb's
E15, mit I, down1.0, 1:3, 2 wsb's
F15, mit I, down1.0, 3 wsb's
F15, mit I, down1.0, 1:2, 3 wsb's
F15, mit I, down1.0, 1:3, 3 wsb's
scenario / configuration
Water supply
Water release


Salt concentration Miraflores Lake and Gatun Lake
rev. 3-lift locks, free water supply, 15 PP-ships/day
volume-averaged salt concentration (ppt)
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
A, existing
E4, no mitigation, no wsb's
E3, no mitigation, 2 wsb's
F3, no mitigation, 3 wsb's
E21, mit I, down1.0, 2 wsb's
F21, mit I, down1.0, 3 wsb's
scenario / configuration
ML-max
ML-min
GL-max
GL-min


Water release and extra water supply per year Gatun Lake
rev. 3-lift locks, free water supply, 15 PP-ships/day
water quantity (10^6 m3 per year)
2000
1600
1200
800
400
0
-400
-800
-1200
-1600
-2000
A, existing
E4, no mitigation, no wsb's
E3, no mitigation, 2 wsb's
F3, no mitigation, 3 wsb's
E21, mit I, down1.0, 2 wsb's
F21, mit I, down1.0, 3 wsb's
scenario / configuration
Water supply
Water release

From these results for a ship traffic intensity of 15 PP-ships/day we conclude:

- When no mitigation system is applied and revised 3-lift locks are not provided with water saving basins, an extra supply of water from new water resources to Gatun Lake is necessary. With 2 wsb's/lift or 3 wsb's/lift, no mitigation, there is a net surplus of water throughout the year, so that water is available for hydropower generation, but there is also a lesser 'flushing' of lock chambers, causing a greater salt water intrusion and higher salt concentration levels of the lakes.
- The water control scenario 'free water supply' requires always a supply of extra water, also when wsb's are in operation, but in the wet season water is released. In the water control scenario 'minimum water supply' the available water is better utilized, which leads to a minimum supply of extra water to Gatun Lake (but the sum of water release and extra water supply per year is the same in both scenarios).
- The lockage loss is reduced with 50% and 60% respectively when 2 wsb's/lift or 3 wsb's/lift are applied (no mitigation system active). The lesser the lockage loss, the lesser the supply of extra water to Gatun Lake and / or the greater the release of water at Gatun Dam, and the stronger the salt concentration variation of Gatun Lake throughout the year, see next table. The supply of extra water has thus a damping effect on the salt concentration variation throughout the year. (Note: the relative lockage loss for each ship transfer is 100%, when the Post-Panamax Locks have no wsb's.)

Simulation	*extra water supply*	*no of wsb's per lift*	*relative lockage loss of PP-locks*	*Gatun Lake salt concentration (ppt, volume-averaged)*		
				range	*variation*	*mean*
E14	minimum	0	100%	0.52 – 0.58	0.06	0.55
E13	minimum	2	50%	0.45 – 0.68	0.23	0.56
F13	minimum	3	40%	0.41 – 0.71	0.30	0.56
E4	free	0	100%	0.27 – 0.43	0.16	0.35
E3	free	2	50%	0.28 – 0.62	0.34	0.45
F3	free	3	40%	0.29 – 0.69	0.40	0.49

- The mean volume-averaged salt concentration of Gatun Lake (mean of maximum and minimum in a year) is not reverse proportional to the Post-Panamax lockage losses (and thus the number of wsb's), see above table, since also the extra water supplies, the water releases at Gatun Dam and the shipping in the existing locks play a role in the water balance and salt balance of Gatun Lake.
- The water control scenario 'minimum water supply' is the better option from the view point of conservation of water, but is less favourable in view of salt concentration levels, which are higher, while also less water is available for hydropower generation. Compare results of E14-E13-F13 with E4-E3-F3 in above table.
- The water control scenario 'minimum water supply' causes a lesser variation of the salt concentration of Gatun Lake than the scenario 'free water supply', mainly because minimum salt concentration values, which occur at the end of the wet season, remain high. Compare results of E14-E13-F13 with E4-E3-F3 in above table.
- When mitigation system I is applied at downlockage (Post-Panamax Locks) the salt water load on Gatun Lake and thus the volume-averaged salt concentration is considerably reduced, see next table. The reduction of the mean salt concentration is between 50% and 80%, dependent on the number of wsb's and the water control scenario applied. It is however, remarkable that the effect of mitigation system I strongly reduces,

when the mitigation system is only used after each second (1:2) or third (1:3) ship downlockage (studied for water control scenario 'minimum water supply', but this effect will most probably also occur at water control scenario 'free water supply'). The reduction of the effectiveness when the system is only applied each 2nd or 3rd downlockage operation, is most probably caused by the fact that higher salt concentrations can build up in the upper lock chamber in the semi-convoy mode of operation. But also the different water balance of Gatun Lake when the mitigation system is less intensive used (less water supply, greater water release at Gatun Dam, different distribution of water over Gatun Dam and Gatun locks) plays a role.

Simulation	*extra water supply*	*no of wsb's per lift*	*Gatun Lake mean vol-aver. salt conc. (ppt) no mitigation*	*Gatun Lake: reduction of mean salt concentration mit. I compared to no mitigation (%)*		
				mit I, down1.0, 1:1	*mit I, down1.0, 1:2*	*mit I, down1.0, 1:3*
E14 – E25	minimum	0	0.55	79%	-	-
E13 – E15	minimum	2	0.56	61%	6%	7%
F13 – F15	minimum	3	0.56	53%	16%	13%
E4	free	0	0.35	-	-	-
E3 – E21	free	2	0.45	69%	-	-
F3 – F21	free	3	0.49	69%	-	-

Next table shows the corresponding relative water loss per ship transfer caused by operation of the Post-Panamax locks and mitigation system I.

Simulation	*extra water supply*	*no of wsb's per lift*	*relative lockage loss of PP-locks each ship transfer no mitigation*	*relative lockage loss of PP-locks and mitigation system I, for each ship transfer*		
				mit I, down1.0, 1:1	*mit I, down1.0, 1:2*	*mit I, down1.0, 1:3*
E14 – E25	minimum	0	100%	150%	-	-
E13 – E15	minimum	2	50%	100%	125%	67%
F13 – F15	minimum	3	40%	90%	65%	57%
E4	free	0	100%	-	-	-
E3 – E21	free	2	50%	100%	-	-
F3 – F21	free	3	40%	90%	-	-

- Generally, the indirect effect of the Post-Panamax locks, which by-pass Miraflores Lake, on the salt concentration of Miraflores Lake is relatively small. Extra salt water intrudes through Pedro Miguel Locks; the salt load varies with the salt concentration of Gatun Lake and varies thus with the configuration of Post-Panamax Locks, application of a mitigation system, and the water control scenario of Gatun Lake.

We now discuss other aspects:

Effect of Post-Panamax ship traffic intensity:

- As may be expected the salt water intrusion increases with the ship traffic intensity. Detailed results of simulations are presented in Section 7.1.2. In next table the volume-averaged mean salt concentration of Gatun Lake is shown for 15, 10 and 5 PP-ships/day (mean of maximum and minimum in a year). No mitigation, mitigation system I and

combination of mitigation systems I and IV are compared. As is shown, the relationship between volume-averaged salt concentration and the number of ship transfers is non linear, since also the water releases / water supplies play a role, as well as the shipping in the existing lanes.

Simulation	*extra water supply*	*no of wsb's per lift*	*mitigation system*	*Gatun Lake: mean salt concentration at various PP-traffic intensities*		
				15 PP/day	*10 PP/day*	*5 PP/day*
E14	minimum	0	no mit.	0.55	0.22	0.04
E13	minimum	2	no mit.	0.57	0.22	0.08
F13	minimum	3	no mit.	0.56	0.25	0.10
E25	minimum	0	mit I, down1.0	0.11	0.09	0.03
E15	minimum	2	mit I, down1.0	0.22	0.11	0.04
F15	minimum	3	mit I, down1.0	0.27	0.11	0.04
E19	minimum	2	mit I, down1.0 + mitIV, d0.2	0.19	0.10	0.04
F19	minimum	3	mit I, down1.0 + mitIV, d0.2	0.23	0.10	0.04
E4	free	0	no mit.	0.35	0.13	0.03
E3	free	2	no mit.	0.45	0.20	0.08
F3	free	3	no mit.	0.49	0.24	0.11
E21	free	2	mit I, down1.0	0.14	0.07	0.03
F21	free	3	mit I, down1.0	0.15	0.07	0.03

Next table shows the corresponding extra water supply and water release per year:

Simulation	*extra water supply*	*no of wsb's per lift*	*mitigation system*	*Gatun Lake: extra water supply / water release in 10^6 m^3 per year, various PP-traffic intensities*					
				15 PP/day		*10 PP/day*		*5 PP/day*	
				supply	*release*	*supply*	*release*	*supply*	*release*
E14	minimum	0	no mit.	-589	0	0	250	0	1090
E13	minimum	2	no mit.	0	670	0	1090	0	1510
F13	minimum	3	no mit.	0	922	0	1258	0	1593
E25	minimum	0	mit I, down1.0	-1848	0	-589	0	0	670
E15	minimum	2	mit I, down1.0	-589	0	0	250	0	1090
F15	minimum	3	mit I, down1.0	-337	0	0	418	0	1174
E19	minimum	2	mit I, down1.0 + mitIV, d0.2	-589	0	0	250	0	1090
F19	minimum	3	mit I, down1.0 + mitIV, d0.2	-337	0	0	418	0	1174
E4	free	0	no mit.	-992	402	-524	774	-219	1309
E3	free	2	no mit.	-357	1027	-219	1309	-81	1590
F3	free	3	no mit.	-274	1196	-164	1421	-54	1647
E21	free	2	mit I, down1.0	-992	402	-524	774	-219	1309
F21	free	3	mit I, down1.0	-835	498	-455	873	-191	1365

- Initially, up to a ship traffic intensity of about 5 PP-ships/day, the effect of operation of the Post-Panamax Locks on the volume-averaged salt concentration of Gatun Lake is

still relatively small; in this initial period there is time to monitor the salt water intrusion and to decide on an appropriate use of the mitigation system.

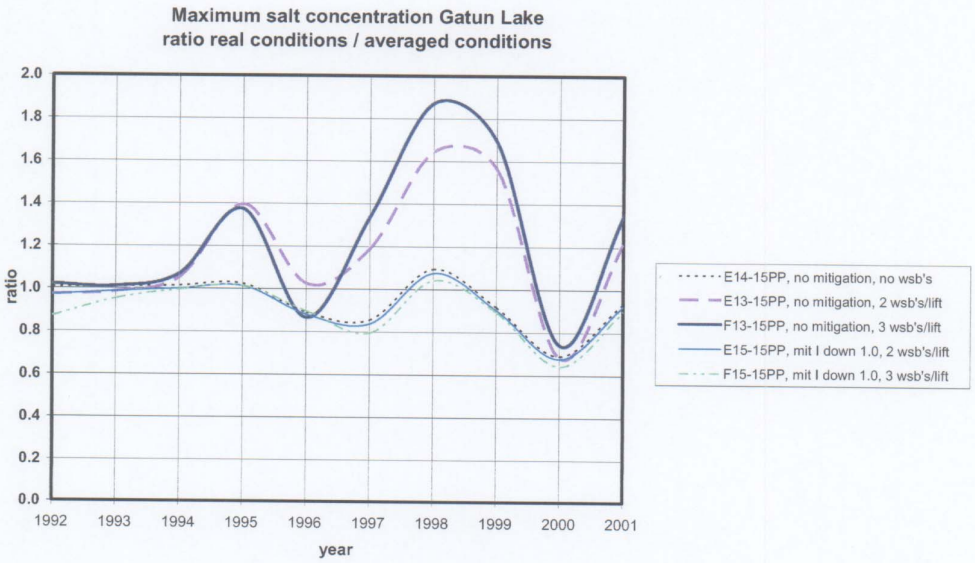
- In the initial period there is no need to supply extra water to Gatun Lake, provided that water control scenario 'minimum water supply' is applied.

Combined use of mitigation systems I and IV:

- Combined use of mitigation systems I and IV may reduce the volume-averaged salt concentration of Gatun Lake with about 15% compared to solely use of mitigation system I. It should be noted however, that no experimental data is available for pneumatic barriers which are installed in water with such a great depth as at the Panama Canal. The functioning of pneumatic barriers in deep water needs to be checked.
- When the salt concentration of Gatun Lake is considered, revised 3-lift-locks with 2 wsb's/lift and mitigation system I (operated at downlockage) are more or less equivalent to revised 3-lift locks with 3 wsbs/lift and the combination of mitigation systems I and IV (operated at downlockage), see results in red in above tables. Some water can thus be saved by applying 3 wsb's instead of 2 wsb's/lift, while the resulting extra salt water intrusion is combated by a pneumatic barrier that is installed at the entrance to upper lock chamber and lower lock chamber.

Effect of real hydraulic conditions

- When the real hydraulic conditions of the period 1992-2001 are taken as starting point for simulations instead of averaged conditions, the variation of the volume-averaged salt concentration of Gatun Lake is stronger. This is shown in next figure, where the ratio of the *maximum* volume-averaged salt concentration at real conditions and the *maximum* volume-averaged salt concentration at averaged conditions has been plotted for a few cases. From this figure it appears: the more extra fresh water is supplied to Gatun Lake (E14, E15, F15) the lesser the ratio varies about 1. Clearly, the supply of extra water has a damping effect on the salt concentration variation. This effect is studied for water control scenario 'minimum water supply'. A similar effect may be expected for water control scenario 'free water supply'.



- The simulations in which real hydraulic conditions of the period 1992 – 2001 have been taken as starting point indicate that the variation from year to year of the salt concentration of Gatun Lake may be twice as high as computed for averaged hydraulic conditions.

Effect of greater keel clearance:
The effect of a 1.52 m (5 ft) greater water depth in the lock chambers of the revised 3-lift locks on the salt water intrusion is relatively small (a 1.52 m lower floor level in view of a ship keel clearance of 3.05 m (10 ft) instead of 1.52 m (5 ft)). The greater depth has no effect on lockage losses, losses caused by mitigation systems, extra water supplies to Gatun Lake and water releases at Gatun Dam. When 3.05 m (10 ft) keel clearance is required for safe shipping, the results of the salt intrusion simulations presented in this report for a keel clearance of 1.52 m (5 ft) in the lock chambers of the revised 3-lift locks, can approximately be applied.

6 Main conclusions and recommendations

When sufficient water from new water resources can be made available, the best option from the view point of salt water intrusion mitigation is to build Post-Panamax shipping locks without water saving basins. Stepwise flushing of all lock chambers (mitigation system I) should at least be done after each downlockage operation. Extra water should be supplied to Gatun Lake to immediately compensate the losses caused by operation of the new locks and the mitigation system (free water supply). In that case the intrusion of salt water is most effective combated and the present quantities of water remain available for hydropower generation at Gatun Dam.

However, it is questionable whether an abundant quantity of extra water can be made available or is acceptable. It is therefore that ACP wishes to minimize the water losses caused by operation of Post-Panamax locks and mitigation systems, but it is clear that with a growing Post-Panamax ship traffic intensity the need of supplying extra water to Gatun Lake increases. ACP plans to control the water releases at Gatun Dam in such a way that the supply of extra water throughout the year is minimum. This will generally lead to a higher salt concentration level of Gatun Lake than with a free supply of extra water.

Water control scenarios that are focused on a minimum supply of extra water to Gatun Lake ask for an active and careful planning of the water releases at Gatun Dam. This may put stronger demands on the operation of power station and spillways of Gatun Dam. Moreover, since a considerably smaller quantity of water is available at Gatun Dam for the generation of electrical power, a search for additional sources of energy may be necessary.
The concept of a minimum extra water supply to Gatun Lake requires that water at Gatun Dam is only released when the water level threatens to exceed the upper limit level of Gatun Lake. When the spill capacity of Gatun Dam is sufficient to instantaneously discharge the water caused by intensive showers in the water shed area, the water level at which the release of water shall start, can be chosen close to the upper limit level of the lake.

A minimum loss of water is obtained when the Post-Panamax locks are provided with water saving basins and the lock chambers are optimally used (e.g. lockage of two ships at a time, when possible). Mitigation systems cause a considerable additional loss of water. Since the intrusion of salt water at uplockage of ships is much smaller than at downlockage, the mitigation systems should preferably only be operated at downlockage. This reduces the water losses of the mitigation system with a factor 2.

From the viewpoint of water conservation the option of 3 wsb's per lift is better than the option of 2 wsb's/lift, but the extra saving of water in the case of 3 wsb's/lift has to be considered in relation to the total loss of water caused by operation of locks *and* mitigation systems, and in relation to the somewhat higher salt water load. The higher salt water load in the case of 3 wsb's/lift can be combated with a pneumatic barrier (mitigation system IV) at the entrance to lower lock chamber and upper lock chamber.

We advise to choose the option of 3 wsb's/lift in combination with mitigation system I (stepwise flushing of all lock chambers) and to make provisions in the design of the locks, that enable an easy construction of additional pneumatic barriers (mitigation system IV) after the locks have been realised, if needed. It should be noted however, that pneumatic barriers are most effective when the open time of the gates at the entrance to the lock chambers is minimized. This implies that the gates are only shortly opened to pass a ship, but as a result water level differences across the gates will occur, which are caused by the tide variation (in particular at the Pacific side). These water level differences can be prevented, if needed, when the valves of the culvert system between the tailbay and the lower lock chamber are kept open (this causes also an additional salt water intrusion, but it is a better option than leaving the gates open). In conclusion, the present operation of the existing locks, that permits an early opening of the gates, can not be maintained, when pneumatic barriers are applied.

It is advised to operate mitigation system I after each downlockage operation, since the simulations indicate that the effectiveness strongly reduces when the mitigation system is only used each second or third downlockage. As a consequence, when the relay-mode of operation or a similar time saving mode is applied in ship locking, a part of the saved time is needed for mitigation operations between two subsequent lockages. The capacity of the new lane will thus be effected. It is therefore advised to study the most efficient way of handling the ships in the locks and operating mitigation system I.
When delays are not acceptable, mitigation system III (salt collecting pit) is the best alternative.

Initially, when the Post-Panamax shipping intensity is still low, there is time to evaluate the salt water intrusion in the real situation and to decide on the most optimal use of mitigation system I, possibly in combination with mitigation system IV. To that purpose an efficient salt water intrusion monitoring system should be installed at both sides of the canal.

It is advised to check the proper functioning of pneumatic barriers (mitigation system IV) prior to the decision of installation, since data on application in deep water, like the Panama Canal, do not exist..

7 Further studies

The simulation model SWINLOCKS has been set up for the purpose of predicting the salt water load on Gatun Lake and Miraflores Lake after the new, third shipping lane of the Panama Canal has been realized and new, bigger Post-Panamax Locks have been constructed and have come into operation. The simulation model offers the possibility to compare the salt intrusion effects of various designs of Post-Panamax Locks, with or without water saving basins, with or without salt intrusion mitigation systems, for various water control scenarios of Gatun Lake, and for different Post-Panamax ship traffic intensities, and to compare the possible future situation with the existing situation. It is thus a tool for decision makers to get insight in the possible environmental effects of the future Post-Panamax Locks, both in terms of salt water intrusion and additional fresh water needs.

Since the simulation model SWINLOCKS is not able to compute the time-dependent dispersion of salt water in the lakes, the computed volume-averaged salt concentrations do not provide a picture of salt water concentrations in the lakes. It is however most likely that strong variation of the salt concentration will occur in Gatun Lake and Gaillard Cut. The intruded salt water propagates along the bed of the shipping channels and follows the deeper parts of the lake (for example the gully of the old Chagres River). It may than concentrate in the deeper area near the outlets in Gatun Dam or remain in the deepened part of the shipping channel in Gaillard Cut. Full 3-dimensional density flow computations may give insight in the salt dispersion processes of the lake.

The computations with the 3d flow model should be done for a sufficient long period of time, taking into account the seasonal variations of precipitation, lake water levels, water supplies and water releases, time dependent salt water loads through the shipping locks and the developments in ship traffic intensities. The effects of sailing ships (effects caused by screw race and return currents, in particular relevant in Gaillard Cut) and wind should be taking into account. It is doubtful however, whether these very complicated computations are fully feasible; in any case it requires huge modeling and computational efforts.
Therefore, more schematized 2d flow computations (depth averaged) should be done to study the overall flow patterns in Gatun Lake and Gaillard Cut without the effects of density differences, followed by schematized 3d flow computations for relevant parts of the lakes, for example Gaillard Cut or the northern area of Gatun Lake, which include the local density flows. This computational approach is more attractive and also more within reach of the present possibilities.
The schematized computations will give insight in the highly important local salt water flows, including the flows towards and near the outlets of Gatun Dam, and may also give a reliable indication of the salinity levels in the neighbourhood of for example the drinking water inlet in Gailllard Cut near Paraiso. The 3d flow computations can be done using the salt water loads computed with the salt water intrusion simulation model SWINLOCKS, as input. The 2d and 3d flow computations require the modeling of the bathymetry of Gatun Lake and Gaillard Cut in the areas of interest. Boundaries of the modeled areas and the boundary conditions have carefully to be selected.

ACP is advised to investigate the possibilities of 2d and (local) 3d flow computations for the selected configuration of Post-Panamax Locks, including a salt intrusion mitigation system. These computations will provide a better insight into the salt dispersion processes. As a

result, the value of salt exchange coefficients used in SWINLOCKS simulations, in particular the coefficients used in water releases at Gatun Dam, can better be assessed. When it appears that the presently applied coefficients are not optimally suited to predict the salt water load and the release of salt water, it is advised to repeat some selected SWINLOCKS simulations with adapted coefficients.

Though with the help of the SWINLOCKS simulations a comparison of lock designs on the subject of salt water intrusion and water losses can be made, and a selection of the most suited lock design is possible, there is still a need for further studies on the salt water intrusion in the final design stage of the selected Post-Panamax Locks. These studies will focus on the process of salt water intrusion through the locks and on the functioning of the proposed mitigation systems, but also other (related) aspects need a further study. All aspects should be studied in their mutual connection.

Important study subjects are:

- The filling and emptying system of the locks (operation of the culverts, operation of the water saving basins, flow capacity of the system, filling and emptying times, control of the fill and emptying process in view of a well distributed inflow and outflow of water, inertia effects in culverts possibly causing an overshoot in the lock chamber, siltation in culverts, air entrainment in culverts, possible cavitation phenomena, dynamic forces on valves).
- (Density) flow phenomena in the lock chambers during levelling up or down, mixing processes, internal wave phenomena, translatory wave phenomena.
- (Dynamic) forces on lock gates and on the ship due to flows, waves and density differences, hawser forces of the ship.
- (Density) flow phenomena and wave phenomena in the lock chambers, forebays and tailbays when lock gates are opened, effects of moving ships.
- Functioning of selected mitigation systems.
- Manoeuvring of approaching ships.

The studies on the salt water intrusion should in particular be focused on density flow phenomena and mixing processes in the lock chambers, forebays and tailbays of the final design of the locks, including water saving basins and mitigation systems. Mitigation systems I and II require a check of the phenomena which occur at a stepwise transfer of water from lock chamber to lock chamber without opening the gates of the locks; mitigation system III (salt pit) requires a check of the inflow process of salt water and the subsequent discharge of water from the salt pit; the functioning of mitigation system IV (pneumatic barrier) has to be checked for deep water as at the Panama Canal. For all four mitigation systems it applies that the choice of coefficients used in SWINLOCKS simulations has to be founded by a further experimental study in the final design stage of the Post-Panamax Locks.

Scale modeling is advised in combination with numerical modeling. The tests in scale models are needed to study the physical processes and to sustain the detailing of the design, while mathematical models can be used to study overall processes and long term water quality effects. The scale models should preferably comprise a tailbay – lock configuration, a lock – lock configuration and a lock – forebay configuration, including the related water saving basins and mitigation system elements.

Strongly related to the operation of Post-Panamax Locks and the combat of salt water intrusion into Gatun Lake is the availability of extra fresh water from new water resources. It is advised to thoroughly study the future water control of Gatun Lake, taking into account the natural variations of the precipitation in the watershed area, the growing need of water for operation of the existing and Post-Panamax locks, including mitigation systems, the growing need of fresh water for households and industry, the need of water for electrical power generation, and considering also the demands made by a preservation of a sound aquatic environment. This requires an integrated water basin management approach.

When a minimum supply of extra fresh water is opted for, the water of Gatun Lake has to be maintained in the wet season at an as high as possible level. In such a water control method water is only released from the lake when the water level threatens to exceed the upper limit level. When the spill capacity of Gatun Dam is sufficient to instantaneously discharge floods caused by intensive showers in the water shed area, the water level at which the release of water shall start, can be chosen close to the upper limit level of the lake. This has to be studied more in detail, also in relation to the use of water for electrical power generation at Gatun Dam, and in relation to possible additional fresh water reservoirs in the future.

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

Report F
Study, modeling and analysis of salt water intrusion mitigation systems for revised 3-lift lock configurations

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1 Introduction

The Autoridad del Canal de Panamá (ACP) has awarded WL | Delft Hydraulics the contract for study, numerical modeling and analysis of salt water intrusion mitigation systems, which are aimed to reduce the salt water intrusion into Gatun Lake and Gaillard Cut through the future Post-Panamax Locks (contract No SAA-135358, dated 30 June 2004). The results of earlier studies conducted by WL | Delft Hydraulics (contract SAA-74337 and contract SAA-110830) form a starting point for the present study.

ACP has initiated the conceptual development of new shipping locks that will service Post-Panamax vessels. The selected dimensions of the proposed Post-Panamax locks are: nominal length 457.32 m (1500 ft), width 54.88 m (180 ft), and depth 16.77 m (55 ft). These dimensions are significantly larger than the dimensions of the existing Panamax-size locks, which measure 33.5 m wide by 305 m long by 13 m deep. Several lock configurations ranging from a single-lift system to a three-lift system, with or without water saving basins, have been studied. The present study concentrates on a *three-lift lock system*.

The new Post-Panamax Locks may, to some degree, increase the salt water intrusion into Gatun Lake. Earlier studies executed by WL | Delft Hydraulics have shown that both the number of lifts of the new locks and the application of water saving basins effect the quantity of salt sea water that is transmitted through the locks to Gatun Lake. The new locks require also a greater quantity of fresh water for canal operation.

The issue of salt water intrusion into Gatun Lake caused by the operation of existing and proposed Post-Panamax Locks is a very important environmental concern and plays a serious role in the evaluation of proposed Post-Panamax Locks. The evaluation requires a comprehensive understanding of the process of salt water intrusion through the locks in relation to the operation of the locks, the use of water saving basins (wsb's) and the available options to control the water level in Gatun Lake and Miraflores Lake (by means of water supply from fresh water resources and release of water through outlets).

1.1 Objectives of the study

The control of the salt water intrusion through the new Post-Panamax Locks is a delicate matter. The intrusion of salt water can (partly) be prevented by application of salt-water intrusion mitigation systems, which should be maximum effective at a minimum of fresh water loss or at a minimum of energy consumption. They must at the same time have no significant impact on lock operation and shipping. The study of these mitigation systems, the numerical modeling of selected systems, the simulation of the salt water intrusion with mitigation systems in operation, and the analysis of the effects of the selected systems are the subjects of the present contract. To the purpose of the numerical simulation of salt water intrusion the existing model SWINLOCKS will be extended. This simulation model was earlier developed by WL | Delft Hydraulics under ACP-contracts SAA-74337 and SAA-110830.

The results of the present study on mitigation measures may serve as input for a further water quality modeling of Gatun Lake (this is beyond the scope of the present contract).

The objectives of the present services include:

- analysis of alternative mitigation systems; this analysis is supported by case studies of salt water intrusion mitigation systems used in the Netherlands (contribution by Ministry of Public Works)
- modeling of selected mitigation systems in the existing model SWINLOCKS
- modeling of Post-Panamax lock system in the existing model SWINLOCKS with revised lock chamber dimensions (3-lift locks with 2 wsb's per lift and 3-lift locks with 3 wsb's per lift)
- simulation and analysis of the salt water intrusion for selected mitigation systems for two configurations of proposed Post-Panamax locks (three-lift locks with 2 wsb's each lift, three-lift locks with 3 wsb's each lift) and for selected hydraulic conditions, ship-traffic intensities and water control scenarios; mutual comparison of systems and concluding analysis
- explanation how results of simulations can be used in further water quality and salt dispersion studies.

1.2 Phasing of the study / structure of the report

The study has two main components: (i) study and evaluation of mitigation systems, which have been agreed in the inception phase, and (ii) after selection of suited mitigation systems: modeling of selected mitigation systems, numerical simulation and analysis of results.
Feasible alternative mitigation systems, which have been put forward in the inception phase, are discussed in Chapter 2. Six of them have been chosen at the kick-off meeting of 12 July 2004 and have been studied more into detail; some attention has also been paid to the option of desalination of the intruded salt water. The results of this study are presented in Chapter 3.
At the meeting with ACP on 12 October 2004 four of the studied mitigation systems have been selected for a further numerical modeling, simulation and analysis. The required adaptation and extension of the simulation model SWINLOCKS is discussed in Chapter 4. Adaptation was necessary in view of the revised 3-lift lock configuration with new sizes and either two water saving basins or three water saving basins per lift. The model has also been extended with the selected four mitigation systems.
The hydraulic boundary conditions for the salt water intrusion simulations and water control scenarios for Gatun Lake are discussed in Chapter 5. The results of initial simulations are presented in Chapter 6, the results of further simulations are presented in Chapter 7. Results are analysed, the effects of different mitigation systems mutually compared, and conclusions drawn on effectiveness and applicability for the Post-Panamax Locks of the Panama Canal. Finally, in Chapter 8, we explain how the results of simulations can be used in further salt dispersion studies for Gatun Lake, and we present an overview of (physical scale model) studies, which are advised for the final design stage; these studies focus on the process of salt water intrusion through the revised 3-lift locks and the effect of mitigation systems thereof.

The study on mitigation systems has been executed in the period July – December 2004.

1.3 Previous Reports

The present study is the continuation of earlier studies commissioned by ACP to WL | Delft Hydraulics. These studies, all on the subject of salt water intrusion through the Panama Canal Locks, are described in the next reports:

Report A
Existing situation: Field data collection, development and validation of simulation model, analysis of salt water intrusion (ACP contract SAA-74337; Q3039, June 2003)

Reports B, C and D (combined in one binder)
Future situation: Post-Panamax Locks. Report B: single-lift locks, Report C: three-lift locks, Report D: two-lift locks (ACP contract SAA-74337; Q3039, September 2003)

Report E
Future situation: Post Panamax Locks. Part I: Effect of water recycling at Pacific side of canal, Part II: Alternative methods to mitigate salt water intrusion (ACP contract SAA-110830; Q3476, April 2004)

2 Alternative mitigation systems

Different mitigation systems, which are appropriate for application at the Post-Panamax Locks, are presented in this chapter. Six of them have been chosen by ACP at the kick-off meeting of 12 July 2004 for a further evaluation.
At first we summarize the conclusions regarding the process of salt water intrusion through the locks of the Panama Canal and the recommendations concerning mitigation measures as presented in the previous Report E. Then we discuss mitigation systems which may be suited for application at the Post-Panamax Locks and we explain which systems have been selected for a further evaluation.

2.1 Salt water intrusion process in existing locks

WL | Delft Hydraulics has undertaken salt concentration measurements in the existing locks, the forebays and tailbays of the locks, Gatun Lake, Gaillard Cut and Miraflores Lake, both in the period December 2001 (end of wet season) and the period April 2002 (end of dry season). These in-situ measurements gave a good picture of the hydraulic processes which govern the intrusion of salt water during uplockage and downlockage of ships. In short these processes are: density flows which develop between adjacent basins with different density (and thus different salinity / temperature) when gates are opened, return currents caused by the moving ship, propeller action of the ship, and specific hydraulic phenomena which occur during filling and emptying of the lock chambers by means of a bottom filling / emptying system.

General conclusions based on our salinity measurements and visual observations are:

- The lock filling system with openings in the bottom causes a mixing up of the water in the lock chamber, resulting in a more or less uniform salt concentration after the lock has leveled up. As an example next figures show salt concentration profiles at one location in a lower lock chamber (without ship) before and after leveling up.

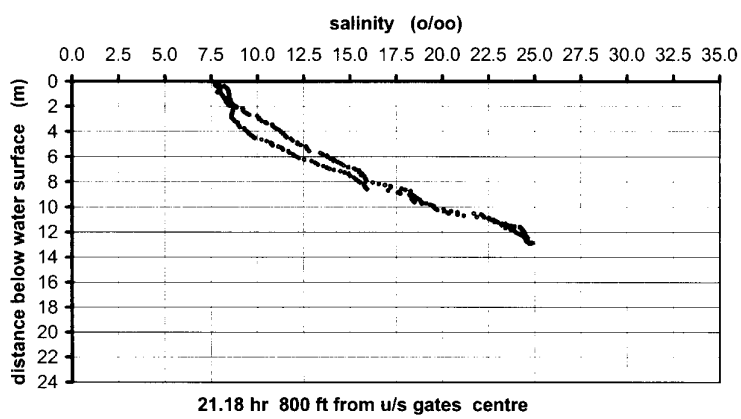


Figure 2.1 Downlockage: salt concentration lower lock chamber after exit of ship, before filling

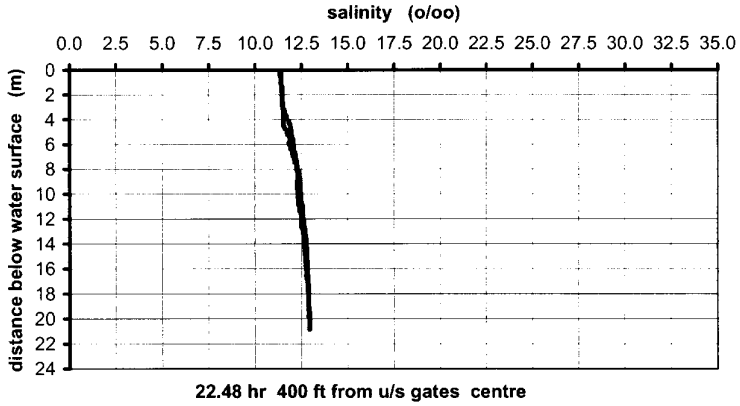


Figure 2.2 Downlockage: salt concentration lower lock chamber after exit of ship, after filling

- Density flows and the movement of the ship cause an exchange of salt and fresh water between basins after the gates have been opened; internal density waves and a more or less layered water system remain in the lock chamber after the gates have been closed. Next picture shows the variation of the salt concentration at one location in a lower lock chamber as a function of time, after exit of the ship and before leveling up. From this figure it appears that internal density waves occur, which travel in longitudinal direction of the lock and are reflected at upstream and downstream boundaries.

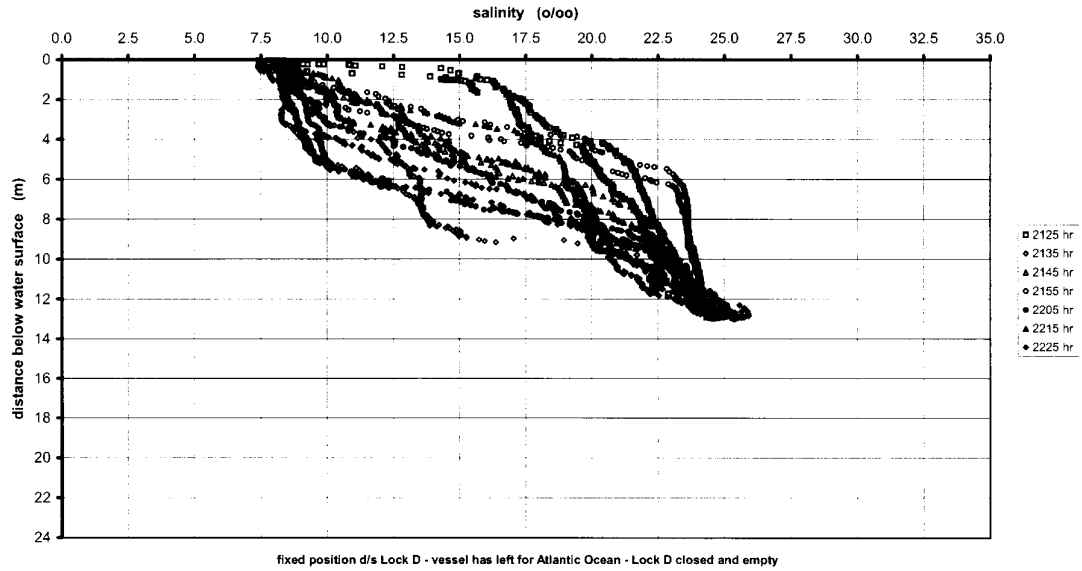


Figure 2.3 Downlockage: salt concentration lower lock chamber after exit of ship as a function of time

- The propeller of the ship causes a local mixing in the area near the stern.
- Emptying of the lock chamber through the openings in the bottom does not strongly affect the vertical salinity gradient in the remaining upper portion of the water (no

important mixing during leveling down); the water is mainly drawn from the region with more saline water near to the bottom.

- Important transverse density phenomena do not occur in the lock chambers.
- Average salinity levels decrease in each higher lock chamber; the upward step in the bottom at the entrance to a higher lock acts as a barrier for salt water intrusion, but during downlockage the return current sustains the inflow of saltier water over the upward step into the higher lock.
- A more or less cyclic pattern of salt water intrusion occurs, which is caused by alternate periods of uplockage and downlockage of ships.

In general, more salt is transported in upstream direction during downlockage than during uplockage. Also the semi-convoy mode of operation, practised at the Panama Canal, is of importance: from salt water intrusion simulations with the SWINLOCKS model it appears that the salt concentration of the upper lock rises to a maximum at the end of a period with downlocking ships, due to salt accumulation effects, while at the end of a period with uplocking ships a minimum salt concentration value is found.

The dimensions of the ships are also of importance. Bigger ships cause a stronger return current and a greater water exchange and are thus unfavourable in the case of downlockage. Smaller ships cause a lesser return flow (favourable), but this lesser flow is simultaneously reason that the development of density flows is less hampered (unfavourable). In addition, smaller ships come in groups, and require more time for operation. As a consequence, gates may be open during a longer period of time, causing a greater exchange of salt water, in particular when no step is present in the bottom (this holds for locks which connect to the tailbays).

Measurements have shown that the temperature of the water in the Pacific Entrance is lower in the dry season than in the wet season and the salinity is higher. As a consequence, more salt water intrudes in the dry season than in the wet season at the Pacific side. Contrary, the temperature and salinity of the water in the Atlantic Entrance hardly change during a year. The salt water intrusion at the Atlantic side, therefore, does not show a similar strong variation as at the Pacific side.
Due to a lower water level of Gatun Lake in the dry season a lesser quantity of fresh water is used in lock operations, which has an adverse effect on salt water intrusion both at the Atlantic and the Pacific side.

When salty water has intruded the forebays it propagates as a relatively thin layer along the bottom (density flow) and follows a path in the deeper shipping channel towards deeper areas of the lakes. Diffusion occurs under the influence of fresh water currents, but flow velocities must be relatively high to break up the salt water layer. Since this is generally not the case the salt water tongue can move in the opposite direction as the prevailing fresh water currents; Gaillard Cut is an example of a location where such opposed flows may occur. Also due to sailing ships and wind action diffusion occurs, but this is most probably of lesser importance for the salt dispersion process in the lakes. Sailing ships may cause disturbances of the salt water tongue.

At present the salinity level of Gatun Lake is very low. The intrusion of salt water through Gatun Locks is limited, thanks to the 3-lift lock systems. At the Pacific side Miraflores Lake forms a buffer, which damps the intrusion of salt water through Pedro Miguel Locks. Apart

from that, in an average year the inflow of fresh rain water into Gatun Lake is so high, that in addition to the water that is lost at the locks and the water that is used for the generation of hydropower, a lot of water has to be spilled at Gatun Dam. The total outflow (locks, power station, and spillway) amounts to about 85% of the volume of the lake, which means that quite a lot of the intruded and diffused salt water is flushed out.
The salinity level of the small Miraflores Lake is much higher at present than the salinity level of Gatun Lake, and is above the fresh-water limit of about 450 mg/litre (0.45 ppt) dissolved salt.
With the present operation of the locks, the present ship traffic intensity and the present water level control measures the salinity levels in the lakes can be regarded as stable (but they vary as a function of wet and dry season). In the dry season the salinity levels increase; in the wet season the abundant quantity of fresh rain water is the reason that a part of the salt in the lakes can be washed away through the spillways.

2.2 Salt water intrusion process in future Post-Panamax Locks

The above sketched general picture of the salt water intrusion process is as well valid for the future Post-Panamax Locks, but there are also some differences.
The preliminary designs of the future Post-Panamax Locks have either a bottom filling system or a wall filling system with openings immediately above the bottom. The latter system causes an almost similar mixing effect as a bottom filling system; both variants are comparable with the bottom filling system of the existing locks.

Preliminary designs have been made for one-lift, two-lift and three-lift lock configurations. From Delft3D simulations it appears that the bottom - or wall filling system of 1-lift and two-lift locks causes a strong mixing up of the water in the receiving lock chamber, similar as occurs with the bottom filling system of a 3-lift lock system.

The future locks may be provided with water saving basins; their effect is limited to the phase, when water levels of neighbouring locks are equalized. The water saving basins are connected to the bottom / wall filling system and are always operated in the same sequence. The initial water level difference between a water saving basin and the lock chamber is only a fraction of the total water level difference between adjacent lock chambers; the flow velocity of the filling jets will thus be smaller when water saving basins are applied. Despite of the lower flow velocities the filling jets still cause a full mixing of the water in the receiving lock chamber, as is demonstrated by Delft3D computations. 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. The effect of water saving basins is thus a greater inflow of salt water into Gatun Lake.

One difference to be mentioned is also that the future third shipping lane bypasses Miraflores Lake. At present, Miraflores Lake acts as a salt water buffer between Miraflores Locks and Pedro Miguel Locks and damps off the salt concentration variations in Pedro Miguel Locks. This damping effect will not occur in the future Post-Panamax Locks.

2.3 Important phases in view of salt water intrusion

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 leveling 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 leveled up than at uplockage when a ship is in the lower lock chamber, and (ii) when after leveling 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.

2.4 Mitigation measures (general)

In the previous Report E 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. In practice it appears that the mitigation of salt water intrusion is a delicate matter. The effects 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 favorable 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 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. Existing mitigation systems have been developed for single lift locks, but are generally also applicable to multiple lift locks. They have been designed for water-level differences between salt water tailbay and fresh water forebay up to about 4 m, which is considerably smaller than the total lift of about 26 m at the Panama Canal. Consequently, flow velocities in these lock chambers are generally also smaller than in the Panama Canal Locks (unless Post-Panamax Locks are

provided with water saving basins). Higher flow velocities cause a stronger turbulence and generally a stronger mixing of salt and fresh water, which is unfavourable in view of a mitigation of salt water intrusion.

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

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

1. Operational measures: minimize the number of lockages (optimize the number of ships in the lock chamber); minimize the period that lock gates are open; limit lockages to the low tide period; minimize the gate opening (partly open the gates); reduce the water volume of the lock chamber that is involved in the exchange of salt and fresh water (apply intermediate gates in the case of small ships); apply an alternate mode of operation (alternate uplockage and downlockage; this mode of operation is only feasible with 1-lift locks).
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 (air bubble screens) in combination with short open times of lock gates.
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 bottom.

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 (feasible at Gaillard Cut).
2. Drain the salt tongue through a slit in the bottom 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 bottom 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. Another option is the application of desalination plants; some attention will be paid to these systems in Chapter 3.

Afore mentioned salt intrusion mitigation measures have been discussed in Report E and have broadly been compared on the next items:

1. Effectiveness (to what extent is the salt water intrusion reduced?)
2. Extra water loss (how much water, salt water + fresh water, is lost from Gatun Lake as a result of the measure?)
3. Delay for shipping
4. Hindrance for shipping

5. Complexity of the system and ease of operation

Next table presents an overview of measures and the score on the above five items (0 = effect of measure is neutral or no effect, + = moderate positive effect, ++ strong positive effect, - = moderate negative effect, -- = strong negative effect).

	Mitigation measure	*1*	*2*	*3*	*4*	*5*	*Remarks*
A	1 Operational measures	0/+	0	-	0	-/0	
	2 Pneumatic barriers	+	0	0	-/0	0	
	3 Adjustable sill	0/+	0	0	0	-	
B	1 Flush the canal	0/+	--	0	-	0	feasible for Gaillard Cut
	2 Drain salt tongue	+	--	-/0	-/0	-	
	3 Flush from pit	+/++	-/--	0	-/0	0	
C	1 Keep salt water in the lock chamber	++	0	--[1)]	-/0	-	measure suited to 1-lift locks
	2 Remove salt water from lower lock	++	--	--	-/0	--	suited to 3-lift locks, 2-lift locks

[1]) delay may be acceptable when compared to 3-lift locks

Table 2.1 Comparison of mitigation measures

Discussion

As can be read from the table, *measure A1* (operational measures such as: minimize number of lockages, reduce open times of lock gates, etc) is expected to be at the best only moderate effective, while delay for shipping may occur and an efficient handling of ships is not promoted.

Measure A2 (pneumatic barriers) is much more effective, but the expected upper limit of salt water intrusion reduction is about 30% (compared to the situation that no barriers are applied), which may not be sufficient. The relative small effectiveness is also caused by the fact that the salt water intrusion bound up to the water displacement of the ship, is not prevented. The pneumatic barriers do neither cause a delay for shipping nor an extra water loss. Small ships (yachts) can not safely pass the pneumatic barriers. This measure can be combined with other measures to improve the overall effectiveness.

Measure A3 (adjustable sill to heighten the step in the bottom to higher locks) has a relatively small effectiveness (only a small part of the salt exchange caused by density currents is prevented, while the ship-bound salt water intrusion is not prevented). This measure does not cause extra water losses, and shipping is not delayed. The sill has carefully to be positioned; in the case of malfunctioning of the sill there is a risk of a collision.

Measure B1 (flush the canal) is expected to be not very effective since the required large amount of fresh flushing water may not be available throughout the year and flushing of the area in Gatun Lake at the Atlantic side is almost not possible. Some hindrance may occur for shipping when the water is discharged into the tailbay.

Measure B2 (drain the salt tongue through a slit in the bottom at the upstream side of the locks) may be effective in reducing the salt water intrusion (expected upper limit of salt

intrusion reduction 30% – 60%), but the outflow of salt water is difficult to control, which in practice will mean that a lot of fresh water is spilled together with the salt water, while also salt water may escape to the forebay. Sailing ships have an adverse effect on the effectiveness. When directly spilled into the tailbay, some hindrance for shipping may occur.

Measure B3 (catch the intruded salt water in a deep pit and flush) is a measure that offers a better control of the salt water drainage than measure B2, resulting in a lesser fresh water loss and a higher effectiveness (expected upper limit of salt intrusion reduction 60% - 90%). However, the total loss of water from the lake is still considerable. The salt water is continuously spilled at low discharge into the tailbay. A serious hindrance for sailing ships is not expected so that a delay for shipping is not likely. The loss of fresh water can for the greater part be prevented when a perforated floor is constructed in the pit that enables an equally distributed outflow of salt water (similar as in the existing locks), without carrying along too much fresh water.

Measure C1 (keep the salt water in the lock chamber) is expected to be a highly effective measure to reduce the salt water intrusion (expected upper limit 90%), while no extra loss of water from the lake occurs. This measure requires the construction of a combined wall and bottom filling/emptying system and can be applied to a 1-lift lock configuration with water saving basins. The openings in the lock walls have to be provided at both side of the lock chamber, to ensure a symmetrical inflow of fresh water. Salt water is discharged through openings in the bottom into the tailbay. The system is rather complex and needs a balanced design and careful operation in view of obtaining an optimal efficiency and preventing transverse forces on the ship in the lock chamber. The careful operation is the reason that a delay of shipping will occur, but the total lockage time may still be smaller than the total lockage time of a normal 3-lift lock configuration or even a 2-lift lock configuration.

Measure C2 (partly remove the salt water from the lower lock chamber) is a measure comparable with measure C1, but is suited for 2-lift and 3-lift lock configurations. The initial salt water in the lower lock chamber is partly exchanged with fresh water from the forebay. The effectiveness can be as high as with measure C1 for the 1-lift locks, but a considerable quantity of fresh water is required and is lost. The operation of the system is even more complex and a delay of shipping is inevitable. The loss of fresh water can be prevented by application of separate water storage basins, but this reduces the effectiveness.

The measures of group A require the lowest investments, but are least effective. Measures of group C are most expensive and require most studies, but are also are most effective.

Promising mitigation measures

In summary, promising, highly effective mitigation measures may be:

- *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.

2.5 Mitigation systems appropriate for Post-Panamax Locks

In this section we present the basic characteristics of a ten mitigation systems, which are suited – from the hydraulic point of view – for application at the Post-Panamax Locks. The system described in Section 2.4 under measure C1 (measure suited to 1-lift locks) is not longer considered since we concentrate on 3-lift locks.

Measure C2 is a promising measure but requires a careful operation and thus a longer operation time. Possibly this measure, hereafter called system 6, can successfully be applied at downlockage operations (this phase is the most critical phase from the view point of salt water intrusion). Variants of this system, in which the salt content of a lock chamber is reduced by supplying water with a lesser salt content, are the subject of Section 2.5.1. They all have in common that water is transferred without the use of pumps.
Systems that flush back the intruded salt water (like measure B3) or partly prevent the intrusion of salt water (like Measure A2) are the subject of Section 2.5.2.

The estimated effectiveness of the mitigation systems presented in next sections is preliminary classified as low (0 – 30%), moderate (30 – 60%) or high (60 – 90%).

Each uplockage or downlockage operation with a 3-lift lock system causes a 'normal' water loss of 1/3 of the total water level difference (25.7 m on average) between Gatun Lake and both oceans multiplied by the area of the lock chamber (see also Figure 3.2). In next sections, the extra water loss caused by the operation of a mitigation system is expressed as a percentage of the 'normal' water loss. In general, the effectiveness versus the water loss can be optimized.
When water saving basins are applied the lockage loss is reduced: in the case of 2 wsb's per lift the lockage loss is equal to 50% of the 'normal' water loss, in the case of 3 wsb's per lift the lockage loss equals 40% of the 'normal' water loss.
An uplockage operation causes an additional loss of water equal to the submerged volume of the ship, but this loss is recovered when the ship sails down, resulting in a zero total loss for this component.

Next technical demands can be made on mitigation systems:
- appropriate for 3-lift lock systems with water saving basins

- maximum effectiveness at a minimum of water loss or at a minimum of energy consumption (the latter implies: preferably no use of pumps, transfer of water by means of gravity)
- as less as possible impact on ship handling (no or limited delay; no hindrance for shipping)
- safe operation (no strong flow forces on ships in locks; exchange flows between basins stop automatically when water levels have been equalized; preferably no closure of conduit valves when water is flowing at high speed).

The delay for shipping caused by operation of a mitigation system is in particular of importance, since delays may effect the capacity of the new shipping lane. Post-Panamax ships are most probably not allowed to pass the canal at night, which means that the daylight window has to be used to handle the ships. The capacity of the new lane is thus constraint by the length of the daylight window, but is also depending on lock operation times and on the way that ships are guided. In the so-called 'relay mode' of operation locomotives guide the ship halfway and return to their original position. The ship is taken over by other locomotives, which guide the ship further through the locks. This 'relay mode' has been developed for the existing locks with a 'locomotive on single track system', and has the advantage that a second ship can already been handled before the first ship has left the last chamber of the 3-lift lock system. A similar time-saving effect can be obtained in the new locks when tugboats assist the Post-Panamax vessels all the way through the locks.
When the operation of a mitigation system requires some extra time between two subsequent lockages, the capacity of the locks is effected, in particular when a 'relay mode' of operation (or similar) is applied. The maximum number of Post-Panamax ships that can be handled per day may then be reduced. This will result in a considerable loss of revenues for the Panama Canal. From this point of view, systems which cause no delay for shipping are highly attractive.

2.5.1 Mitigation systems based on the principle of reducing the salt water content of a lock chamber by means of dilution or exchange of the salt water by fresh water

Next systems 1 through 6 have in common that the salt content of one or more lock chambers is reduced by a supply of water with lesser salt content or a replacement of salt water with fresh water.

System 1: stepwise flushing of all lock chambers ('dummy' lockage)

Features:
- no special provisions required; standard operation between each two lockages
- wsb's are not in use during operation of the mitigation system, but can be used in the normal way during ship lockages
- extra water loss: up to 100% both at uplockage and downlockage
- effectiveness: moderate to high
- delay for shipping expected in the relay mode of operation

The possible delay for shipping in the relay mode of operation is illustrated by the series of figures shown in Appendix B (source: ACP).

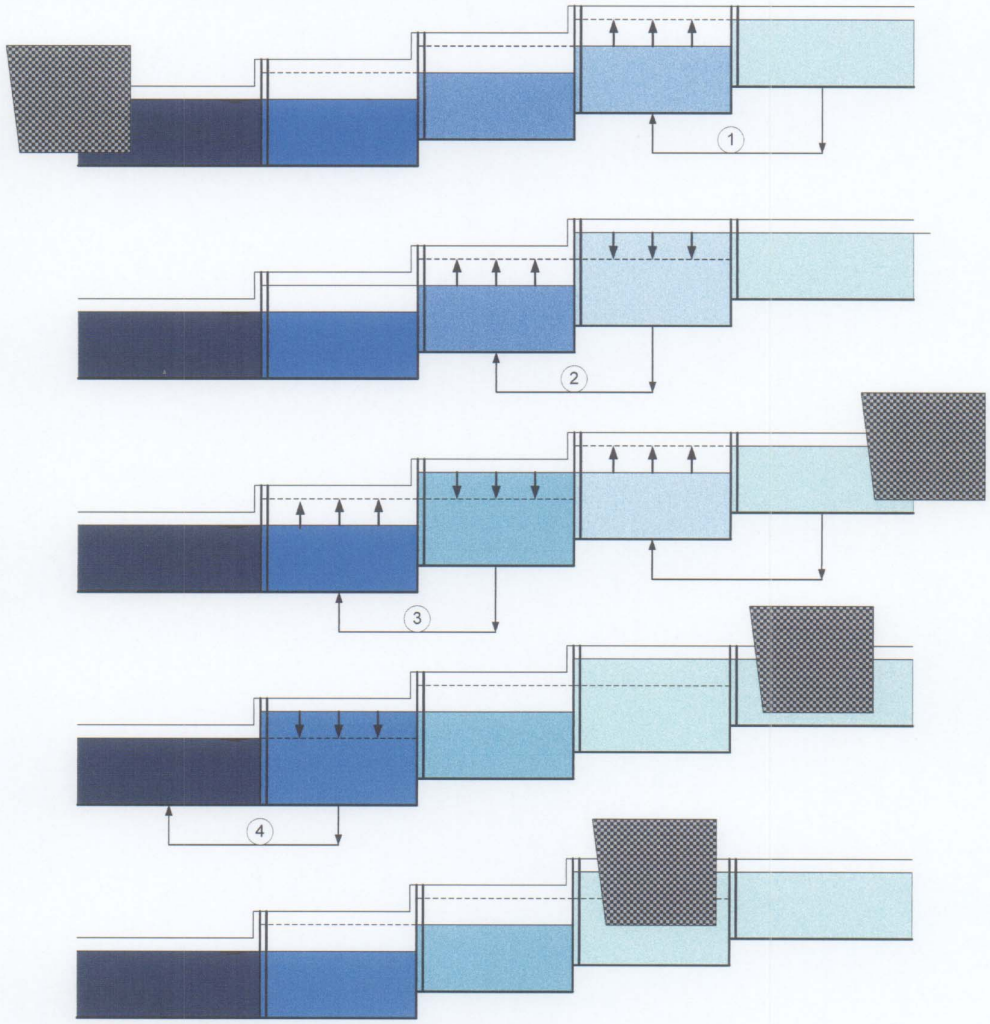


Figure 2.4a Mitigation system 1, downlockage

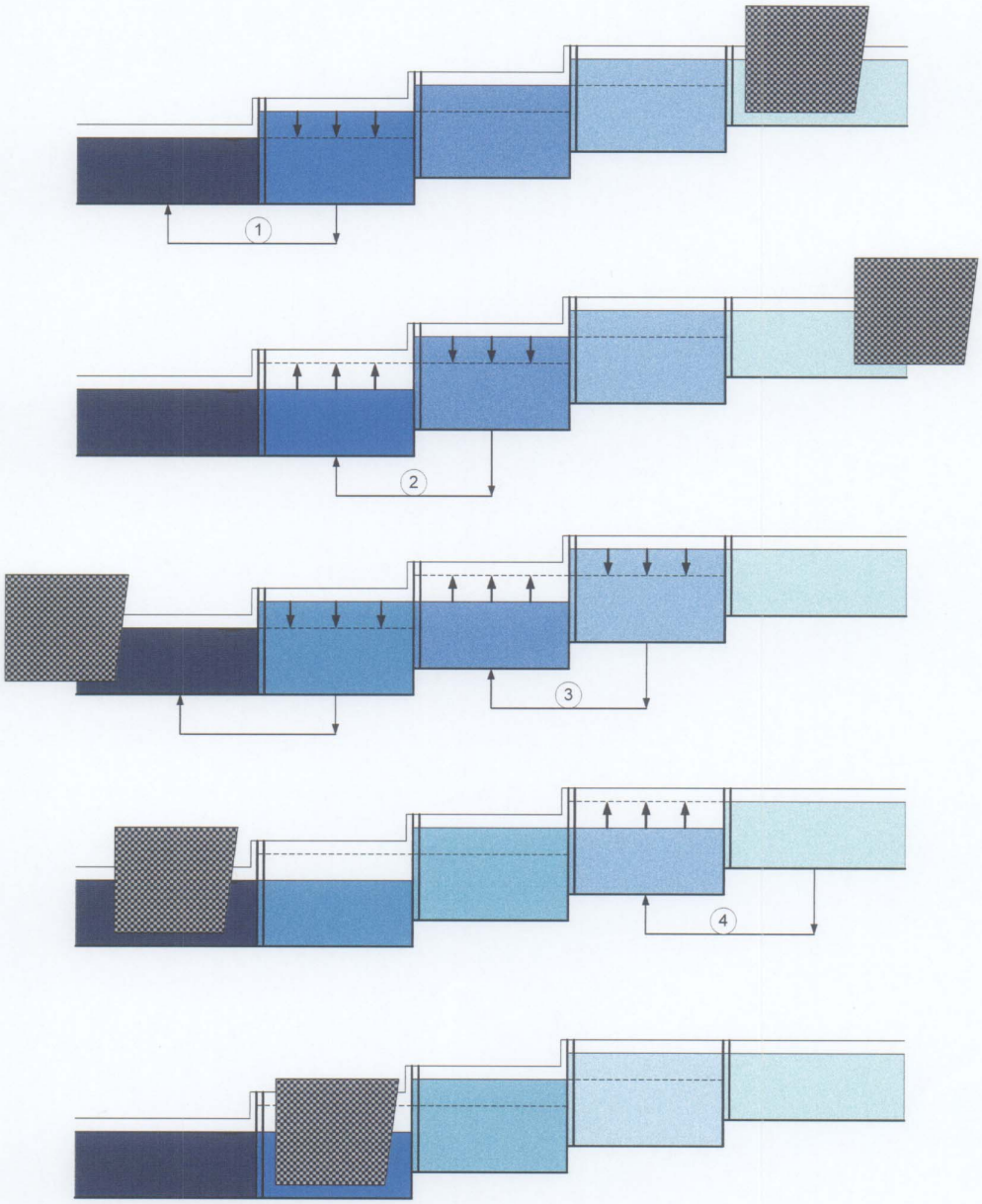


Figure 2.4b Mitigation system 1, uplockage

System 2: flushing of middle and upper lock chamber

Features:

- separate culverts required between middle lock and tailbay with control valves
- at uplockage: valves in culverts have to be closed when the water of the middle lock is at the pre-defined low level, meaning that the valves are closed when conduits are running at full capacity; as an alternative 'system 1 – uplockage' can be combined with 'system 2 – downlockage'
- wsb's are not in use during operation of the mitigation system, but can be used in the normal way during ship lockages
- extra water loss: up to 100% both at uplockage and downlockage
- effectiveness: moderate to high; probably better than with system 1, because the lock chambers are first leveled down before they are leveled up (also at downlockage); this sequence prevents a mixing up of the water in the lock chamber prior to the withdrawal of water; as a result the water with highest salt content near the bottom is evacuated from upper and middle lock chambers; the lower lock chamber is not effected
- delay for shipping expected in the relay mode of operation

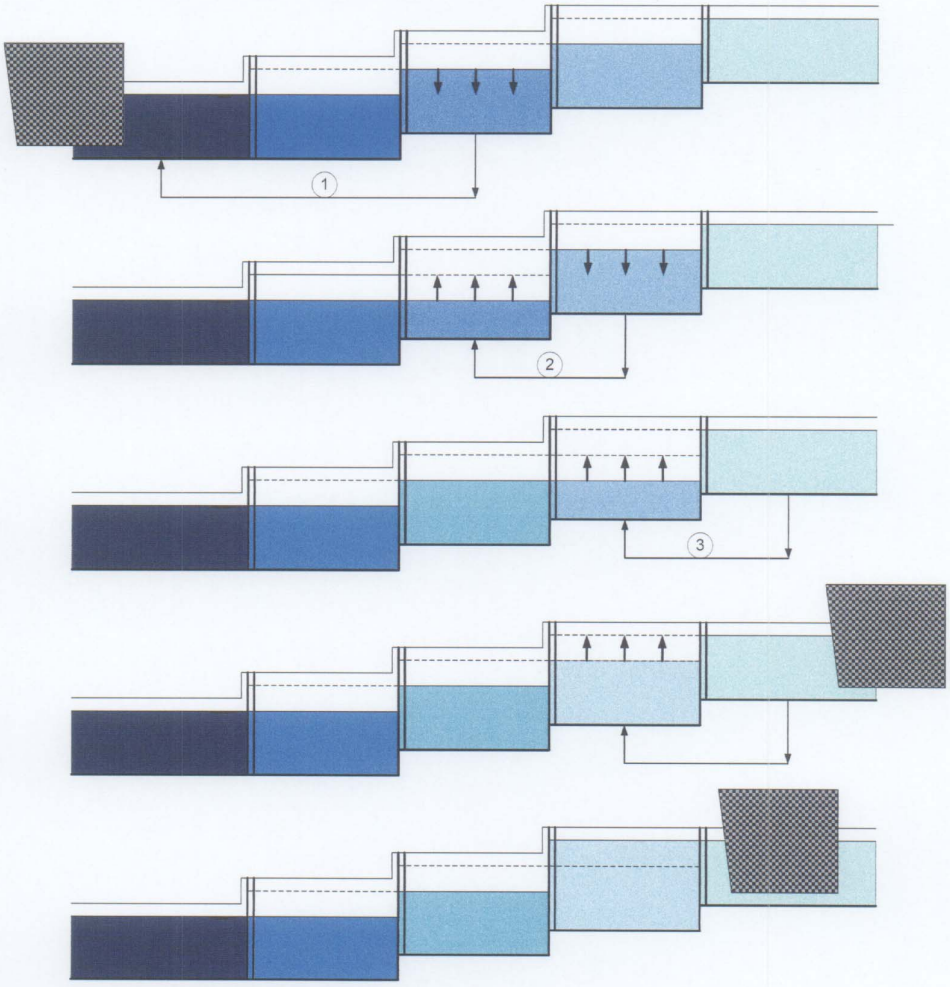


Figure 2.5a Mitigation system 2, downlockage

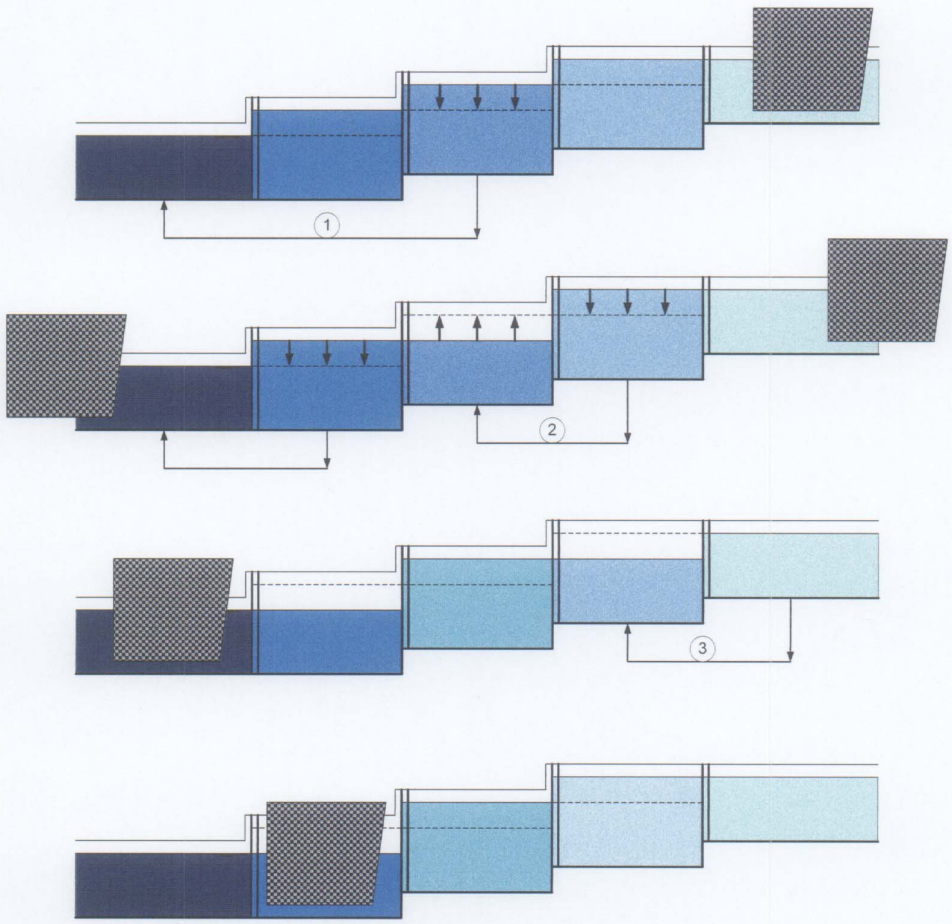


Figure 2.5b Mitigation system 2, uplockage

System 3: flushing of upper and lower lock chamber

Features:

- separate culverts required between upper lock and lower lock with control valves
- at uplockage: valves in culverts have to be closed when the water of the upper lock is at the pre-defined low level, meaning that the valves are closed when conduits are running at full capacity; as an alternative 'system 1 – uplockage' can be combined with 'system 3 – downlockage'
- wsb's are not in use during operation of the mitigation system, but can be used in the normal way during ship lockages (the use of wsb's is separately shown in next figures)
- extra water loss: up to 100% both at uplockage and downlockage
- effectiveness: moderate to high, possibly equal to the effectiveness of system 2
- delay for shipping expected in the relay mode of operation

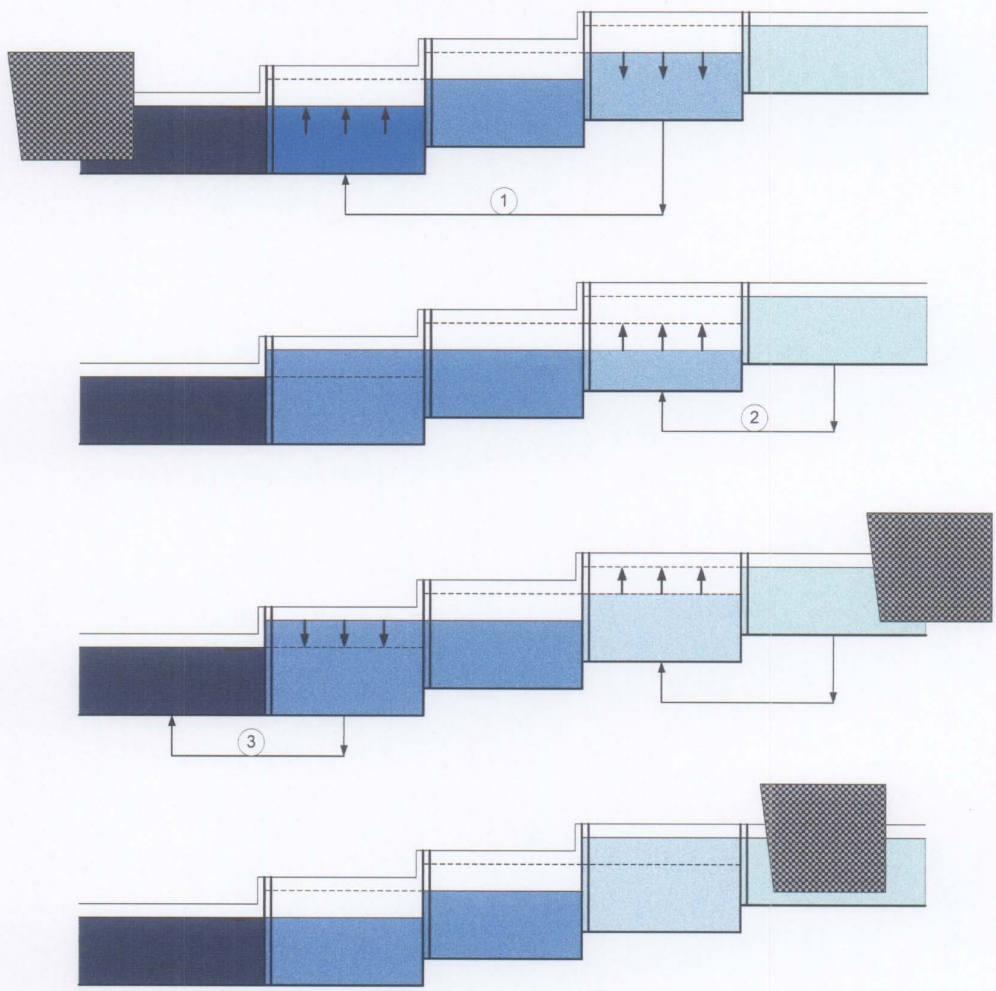


Figure 2.6a Mitigation system 3, downlockage

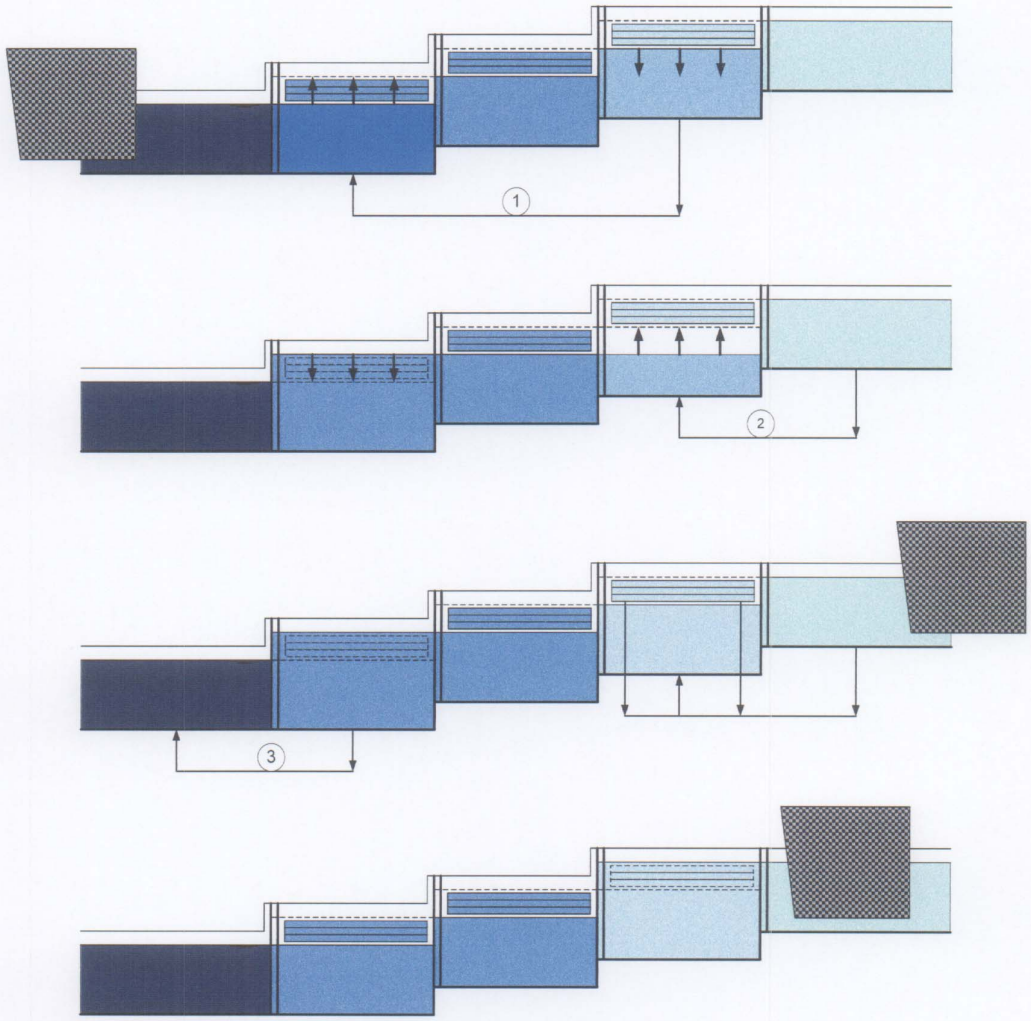


Figure 2.6b Mitigation system 3, downlockage, use of wsb's during lockage of a ship

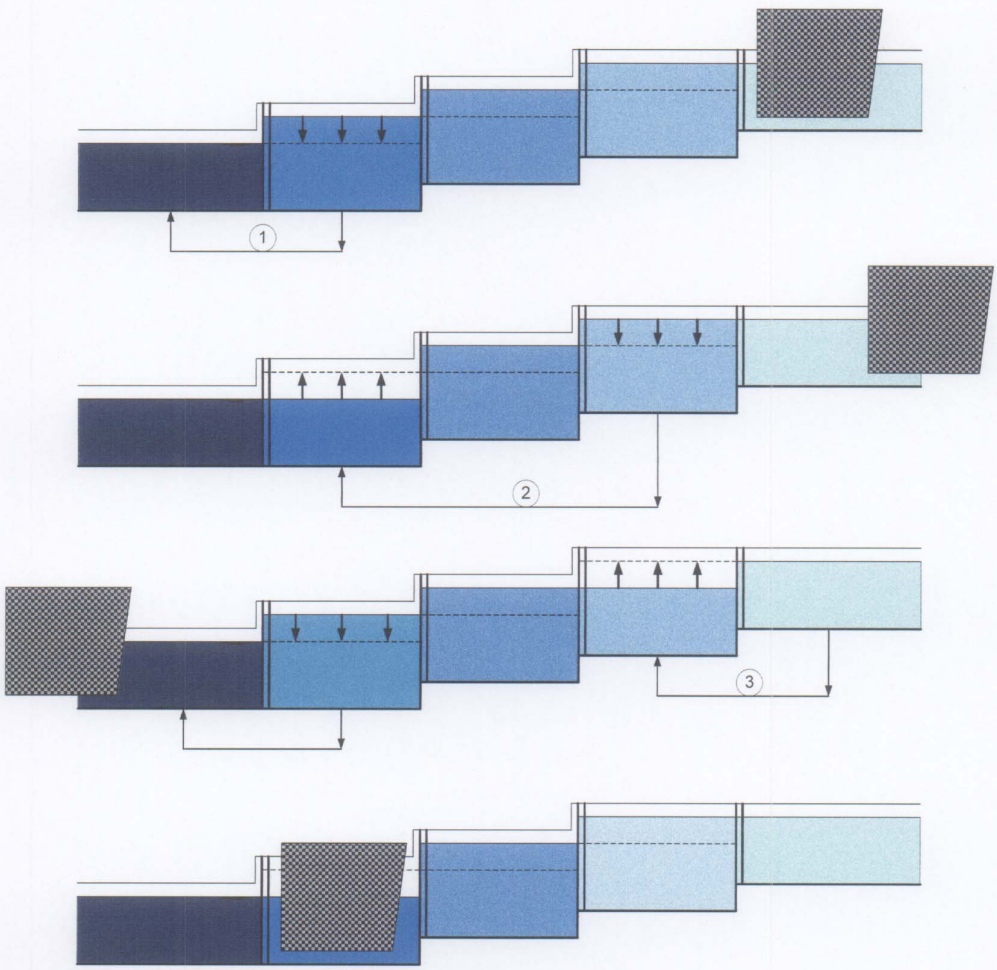


Figure 2.6c Mitigation system 3, uplockage

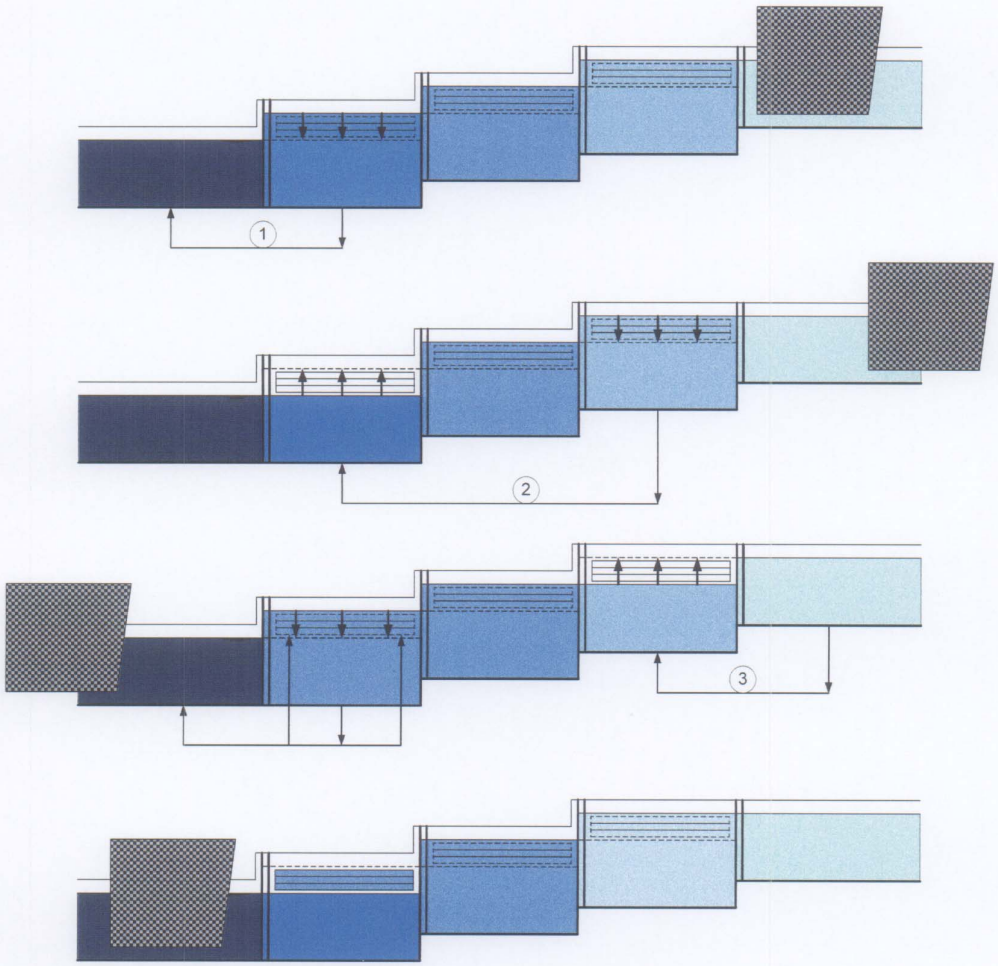


Figure 2.6d Mitigation system 3, uplockage, use of wsb's during lockage of a ship

System 4: enhanced flushing of upper and lower lock chamber

Features:

- separate culverts required between upper lock and lower lock and between upper lock and tailbay; culverts provided with control valves
- at uplockage: valves in culverts have to be closed when the water of the upper lock is at the pre-defined level, meaning that the valves are closed when conduits are running at full capacity; as an alternative 'system 1 – uplockage' can be combined with 'system 4 – downlockage'
- negative water level difference across gates of upper lock
- wsb's are not in use during operation of the mitigation system, but can be used in the normal way during ship lockages (the use of wsb's is separately shown in next figures)
- extra water loss: up to 200% both at uplockage and downlockage (this depends on the quantity of water that is directly spilled from the upper lock into the tailbay)
- effectiveness: high at downlockage, moderate at uplockage
- delay for shipping expected in the relay mode of operation

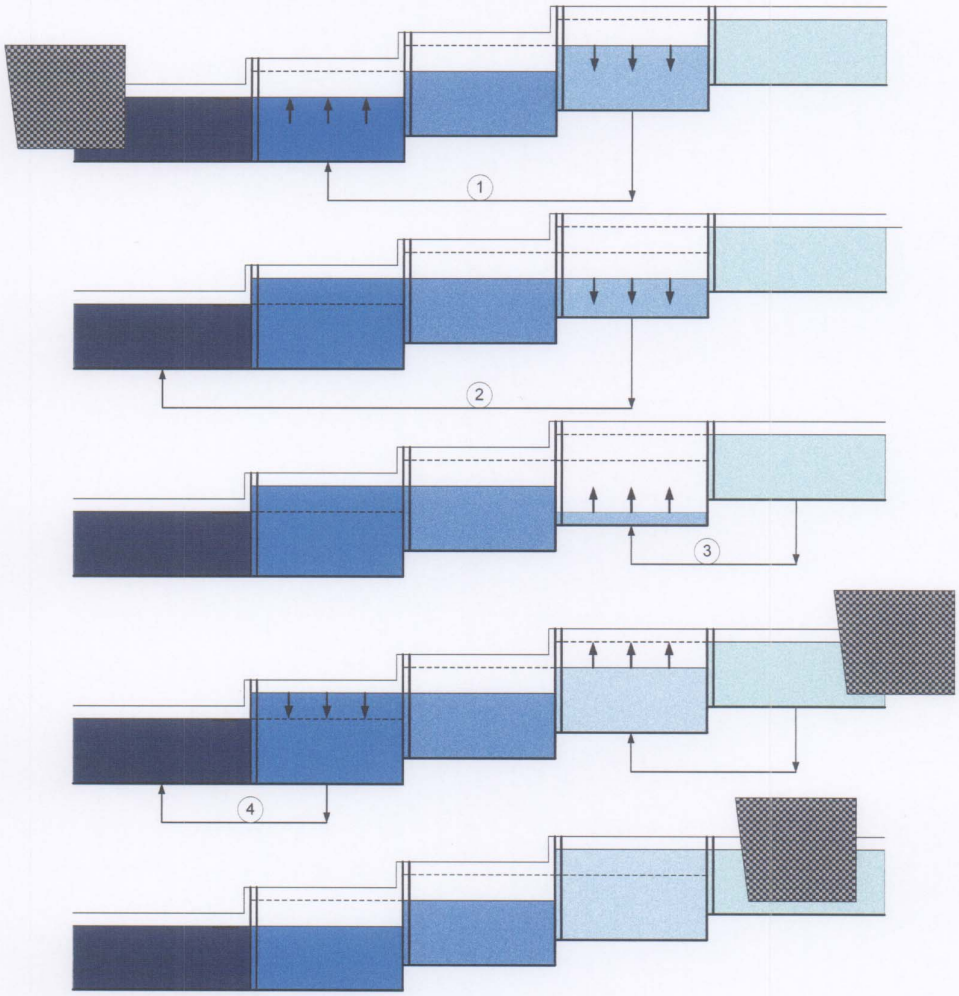


Figure 2.7a Mitigation system 4, downlockage

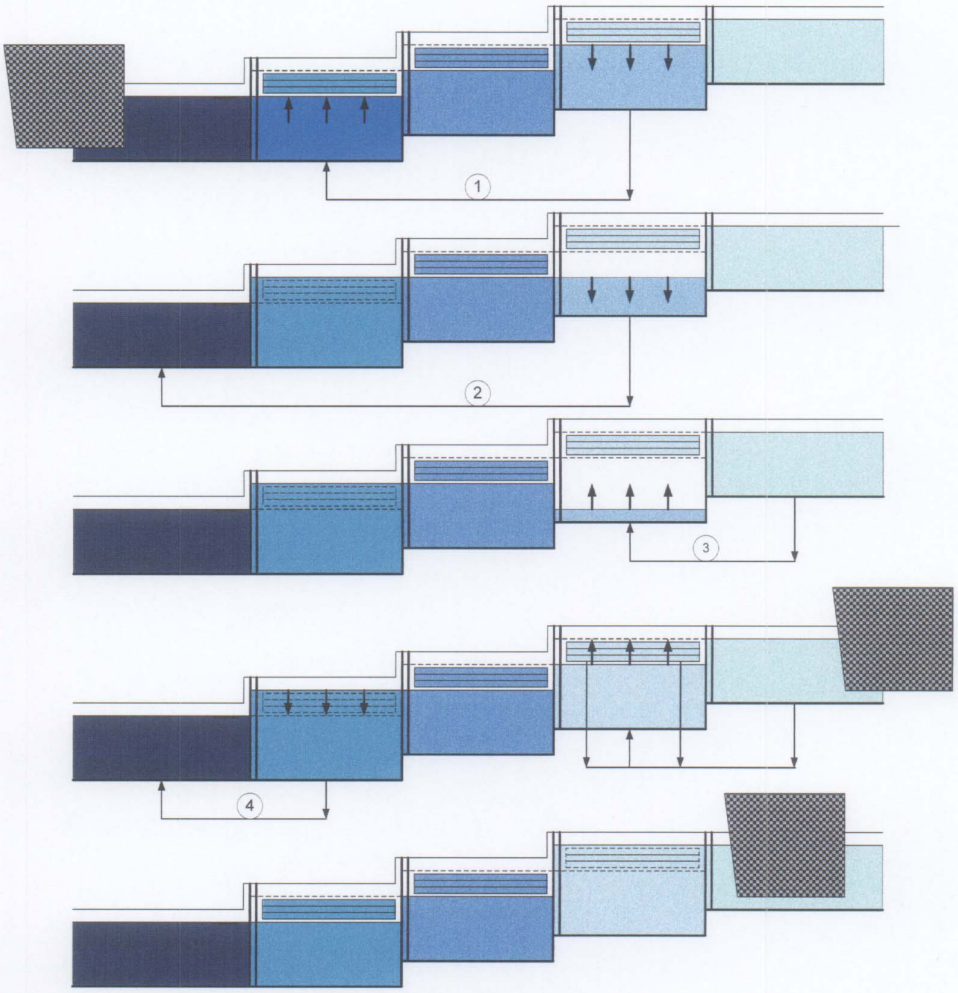


Figure 2.7b Mitigation system 4, downlockage, use of wsb's during lockage of a ship

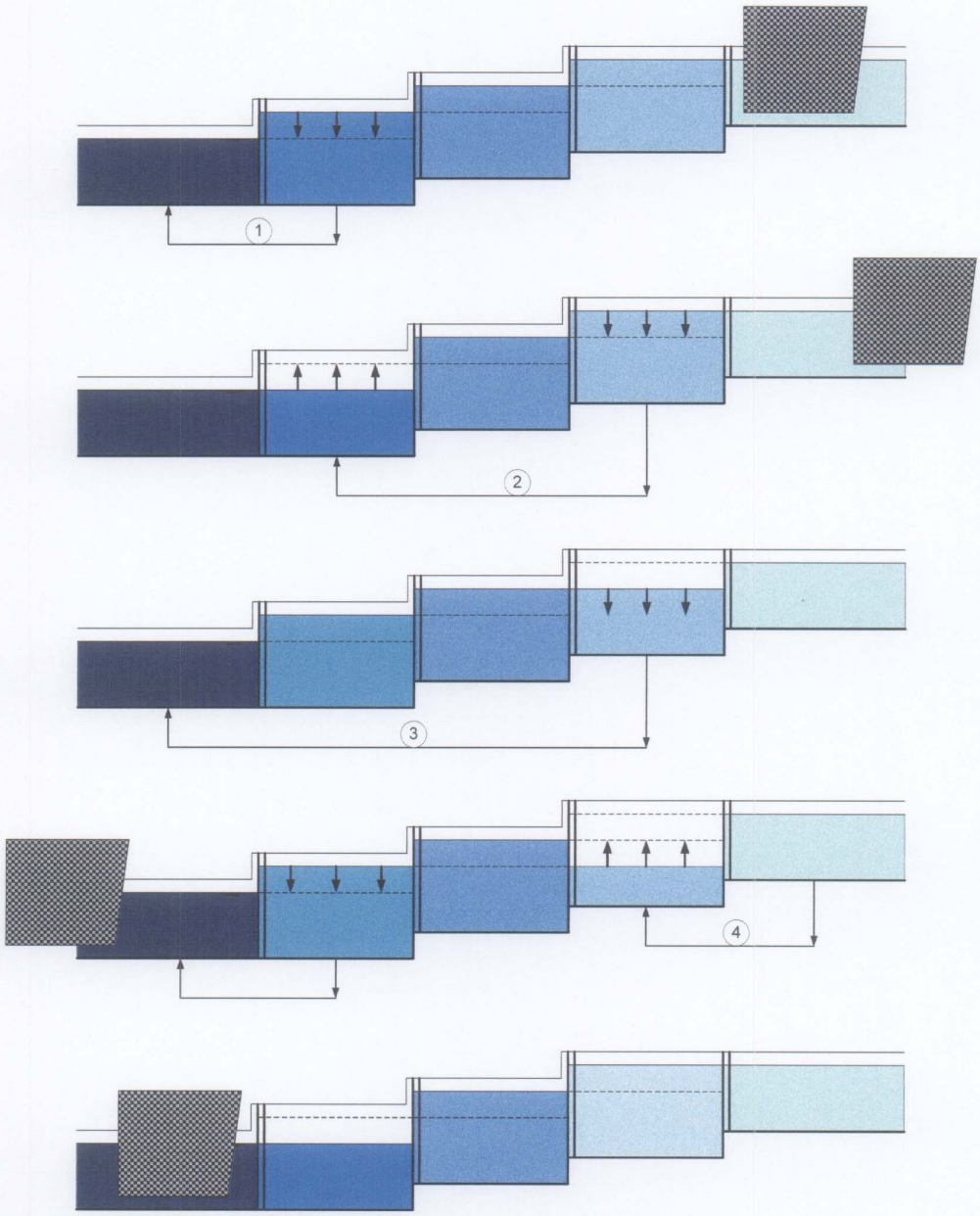


Figure 2.7c Mitigation system 4, uplockage

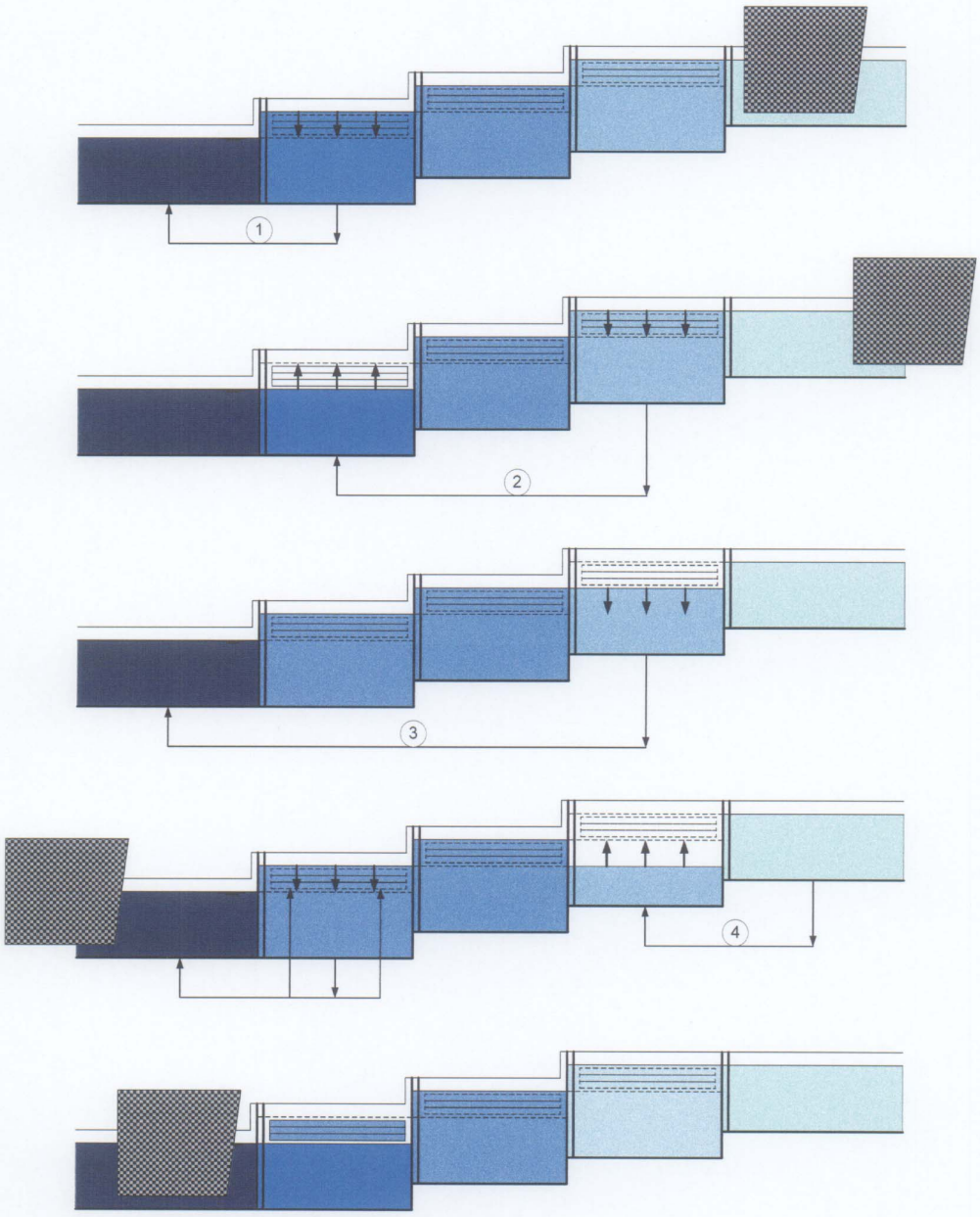


Figure 2.7d Mitigation system 4, uplockage, use of wsb's during lockage of a ship

System 5: intensive flushing of upper lock chamber

Features:

- separate culverts required between upper lock and tailbay with control valves
- no closure of valves when conduits are running at full capacity
- negative water level difference across gates of upper lock
- wsb's are not in use during operation of the mitigation system, but can be used in the normal way during ship lockages (the use of wsb's is separately shown in next figures)
- extra water loss: up to 200% at downlockage, up to 300% at uplockage
- effectiveness: high at downlockage, moderate to high at uplockage
- delay for shipping expected in the relay mode of operation

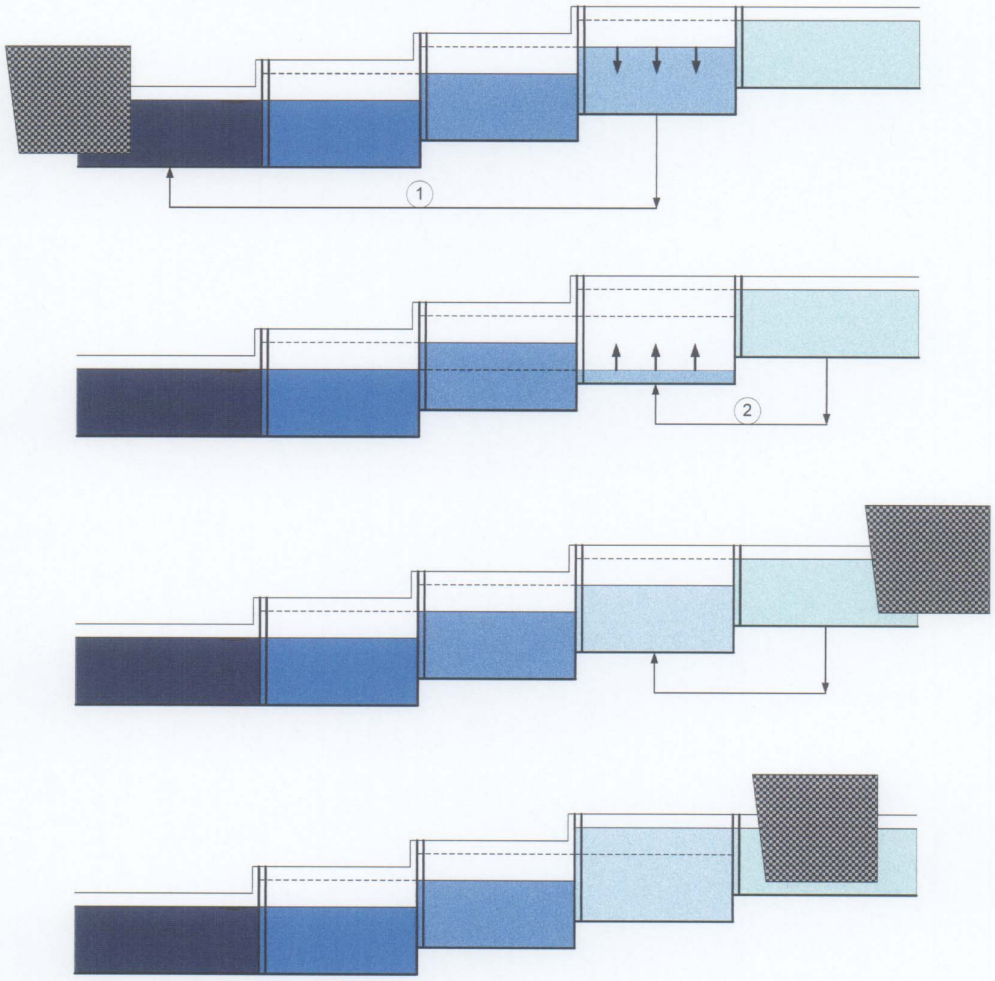


Figure 2.8a Mitigation system 5, downlockage

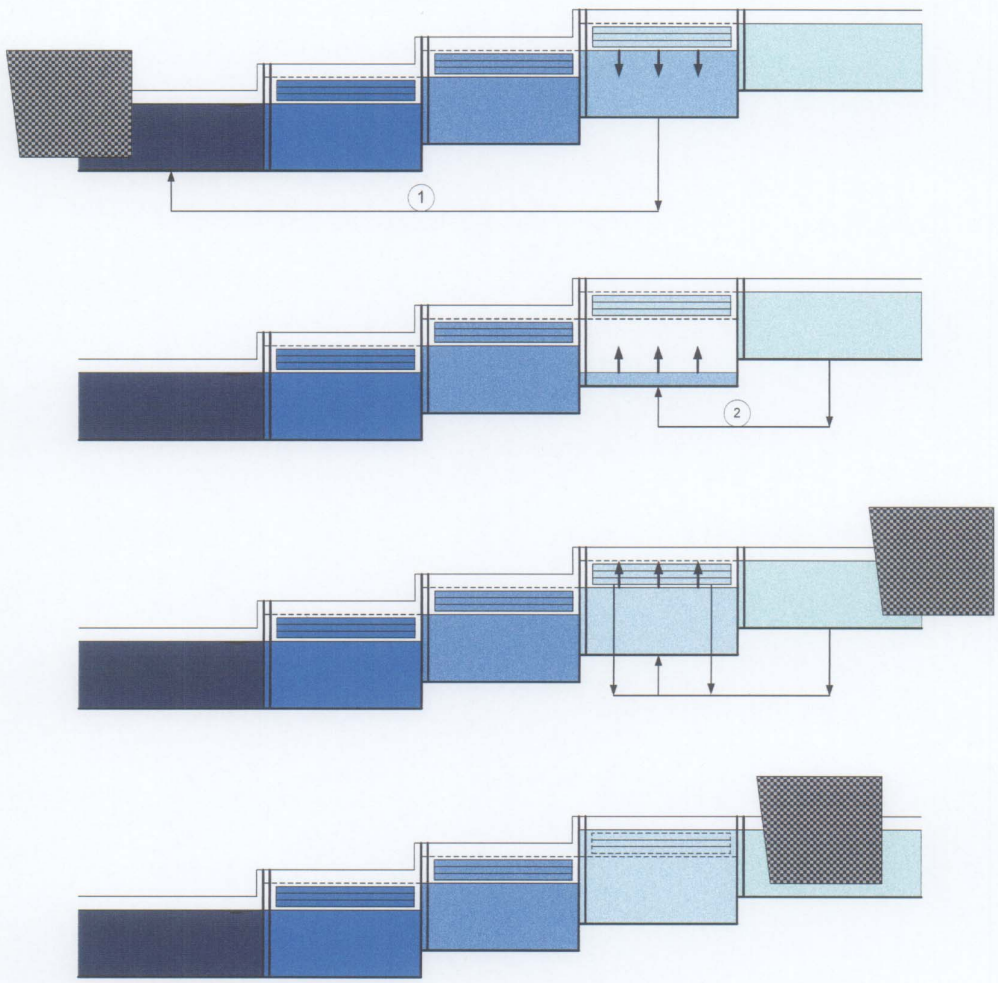


Figure 2.8b Mitigation system 5, downlockage, use of wsb's during lockage of a ship

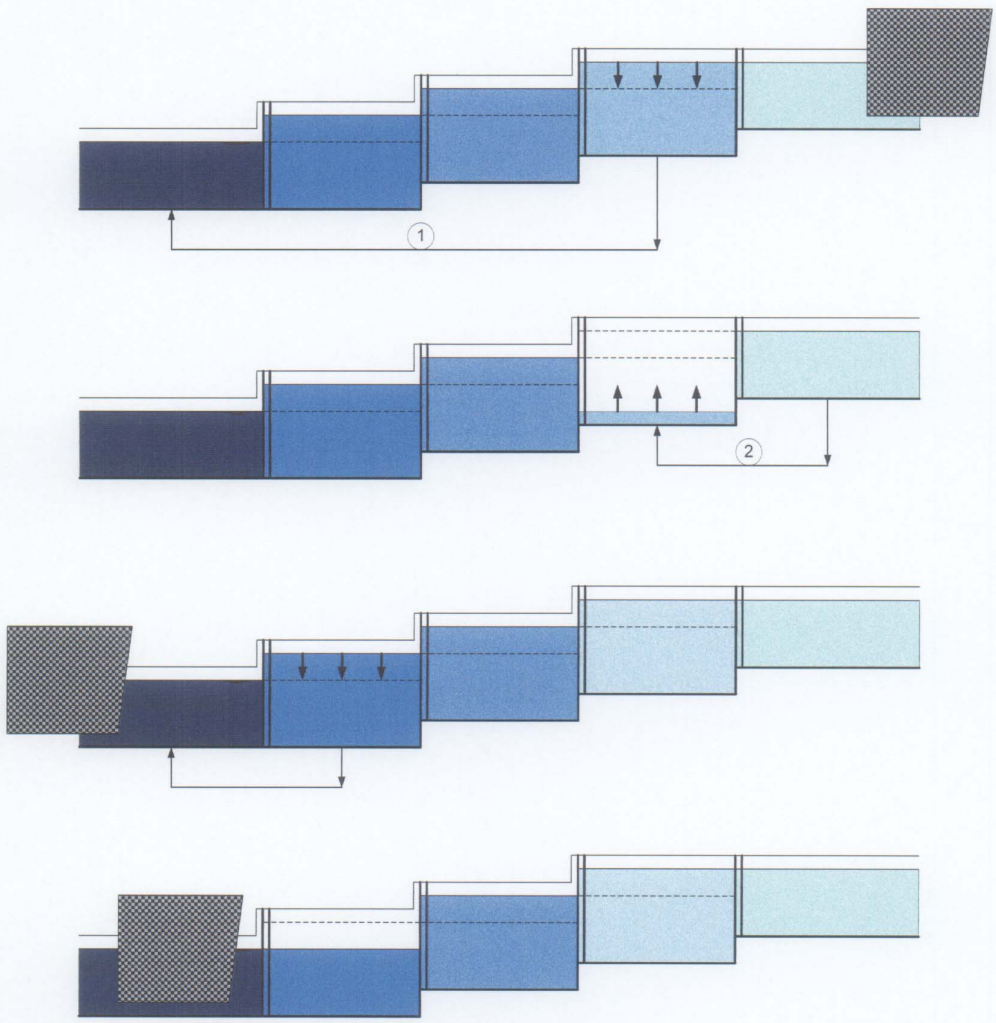


Figure 2.8c Mitigation system 5, uplockage

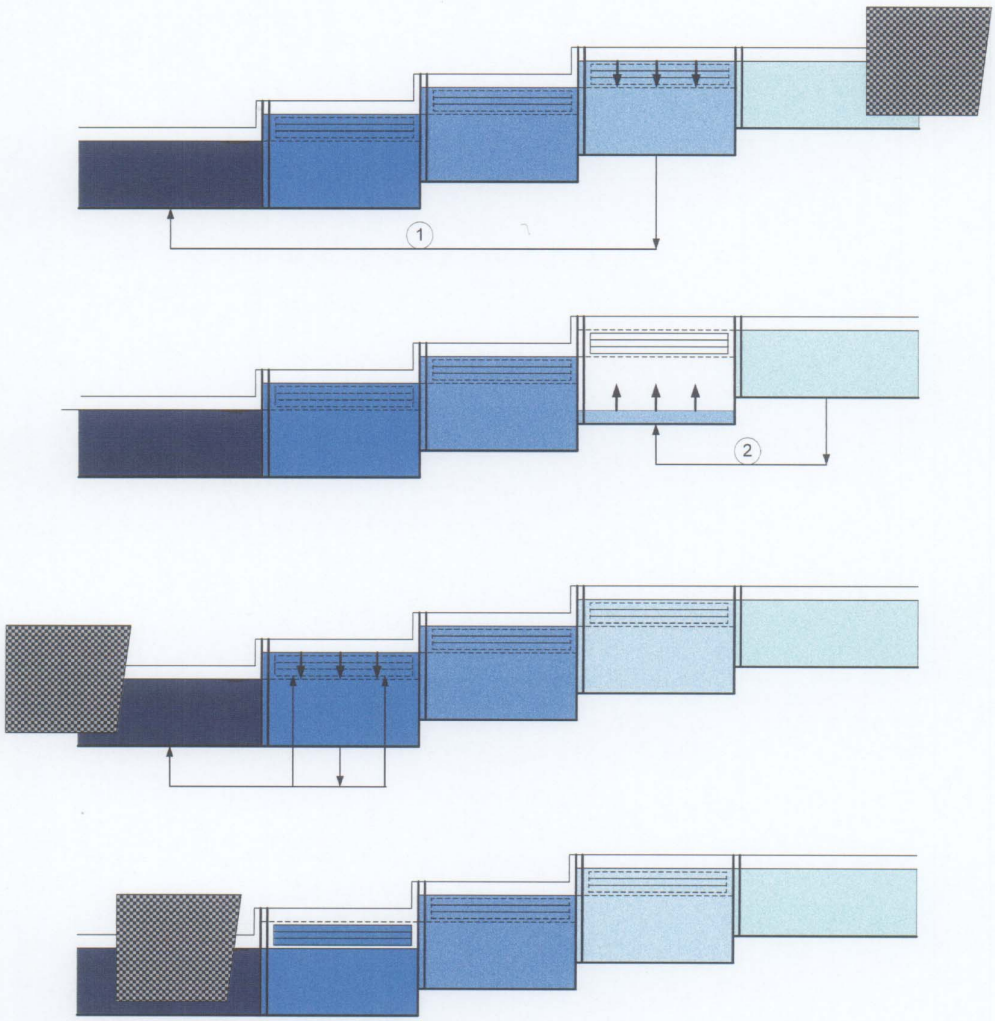


Figure 2.8d Mitigation system 5, uplockage, use of wsb's during lockage of a ship

System 6: exchange of salt water with fresh water in lower lock chamber (see also measure C2 in Report E)

Features:

- separate culverts with control valves required between forebay and lower lock; separated filling and emptying systems required in lower lock chamber: filling through openings in the lock walls (openings are situated at the level of low water), emptying through openings in the lock chamber bottom; complex operation
- fully controled flow in lower lock chamber required; downlockage: operations in the lower lock chamber can start as soon as the ship has left the lower lock; uplockage: the exchange of salt water with fresh water must be executed when the ship is in the lower lock chamber
- wsb's can be used in the operation of the mitigation system; the use of wsb's is separately shown in next figures
- extra water loss: 150% at downlockage, 50% at uplockage
- effectiveness: high
- considerable delay for shipping expected, mainly at uplockage

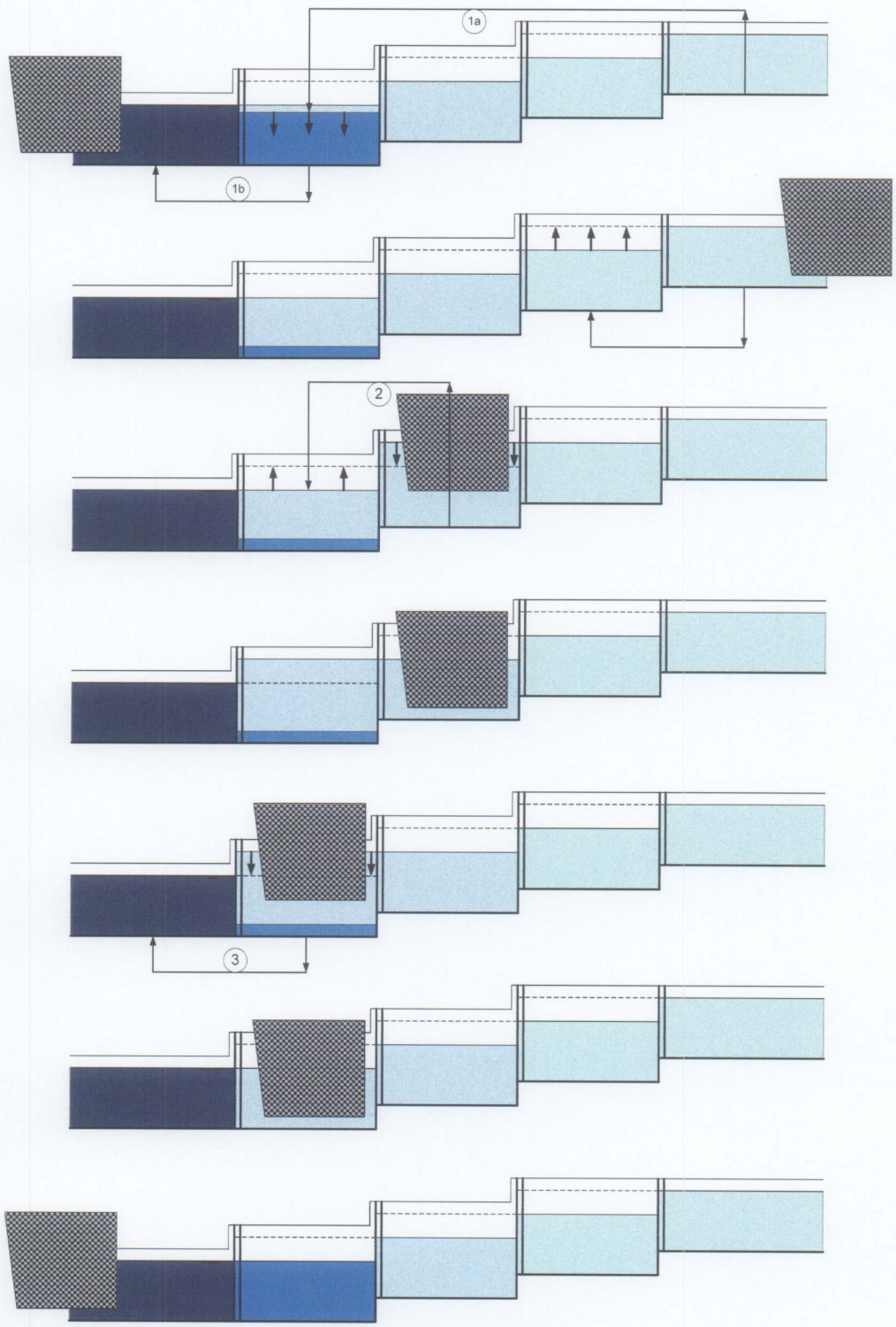
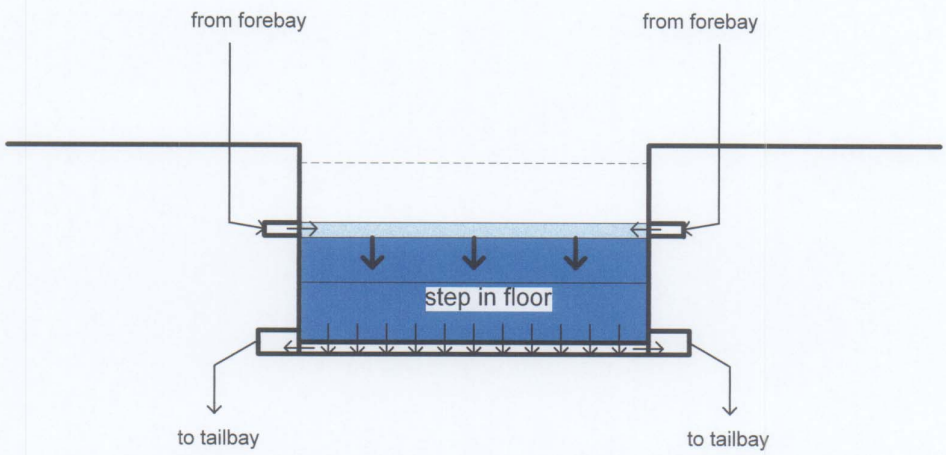
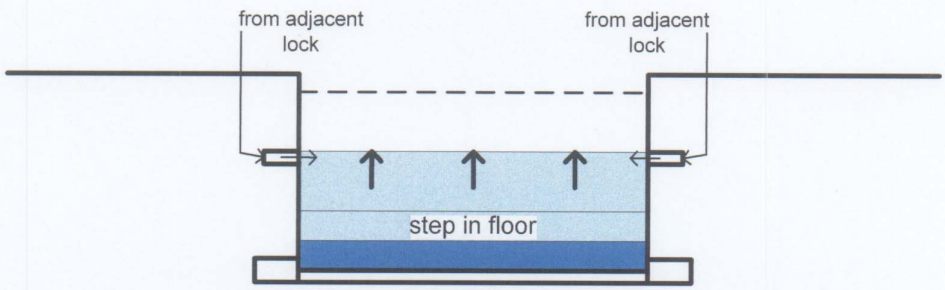


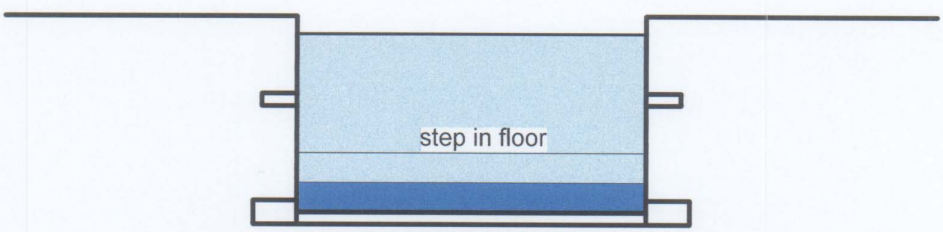
Figure 2.9a Mitigation system 6, downlockage



Exchange of water in lower lock chamber

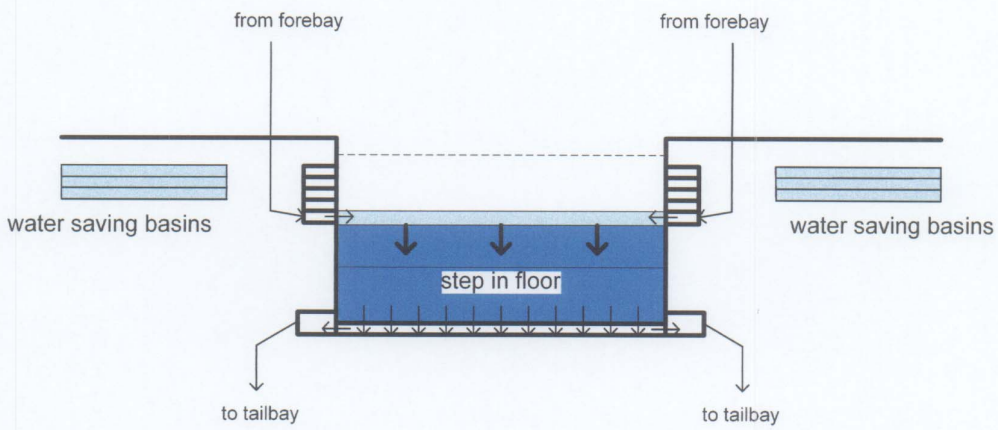


Leveling of water with adjacent lock chamber

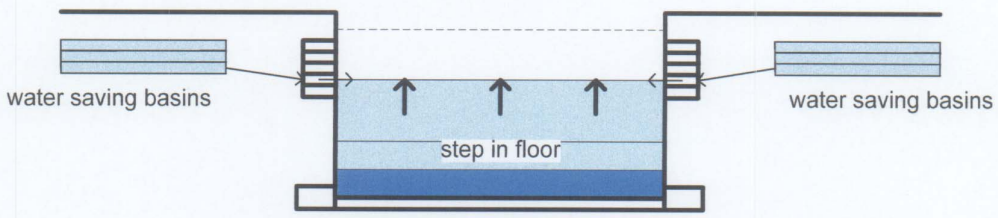


End of leveling process

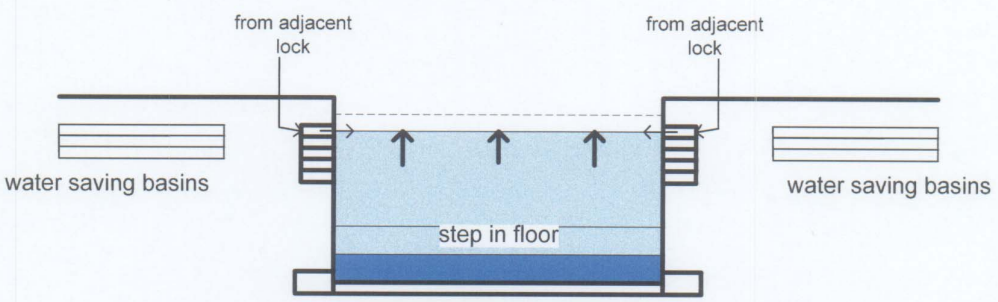
Figure 2.9b Mitigation system 6, downlockage; water exchange and leveling of lower lock chamber; wsb's not in use



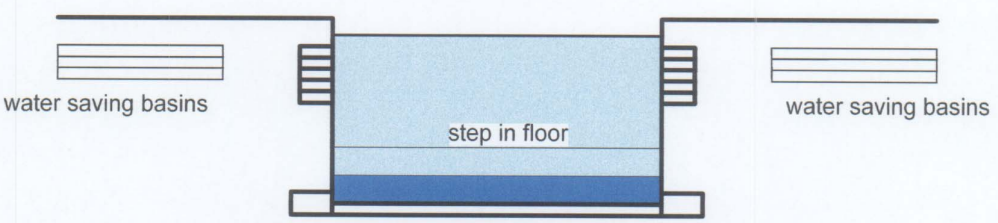
Exchange of water in lower lock chamber



Emptying of wsb's into lower lock chamber



Leveling of water with adjacent lock chamber



End of leveling process

Figure 2.9c Mitigation system 6, downlockage; water exchange and leveling of lower lock chamber; wsb's in use

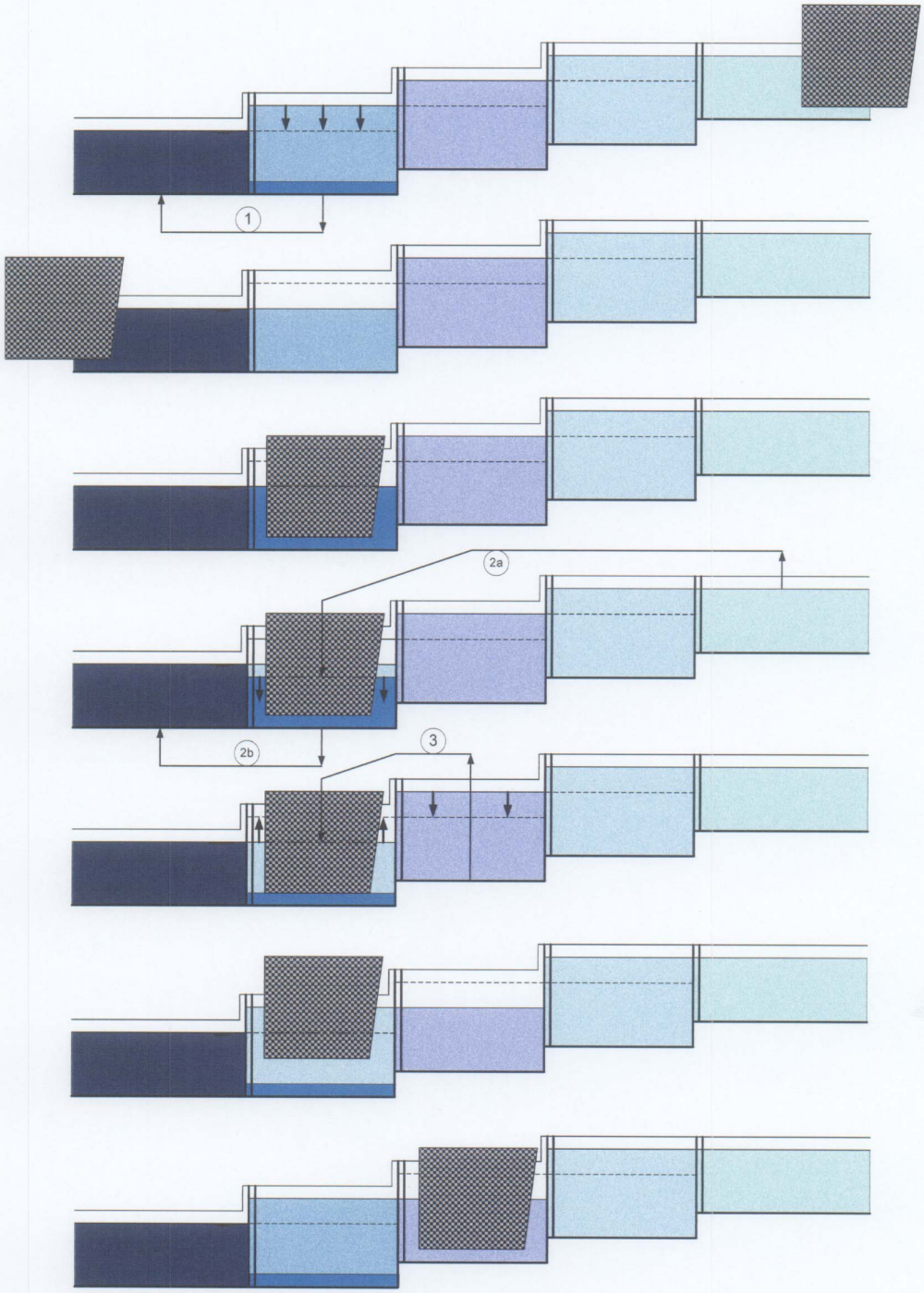
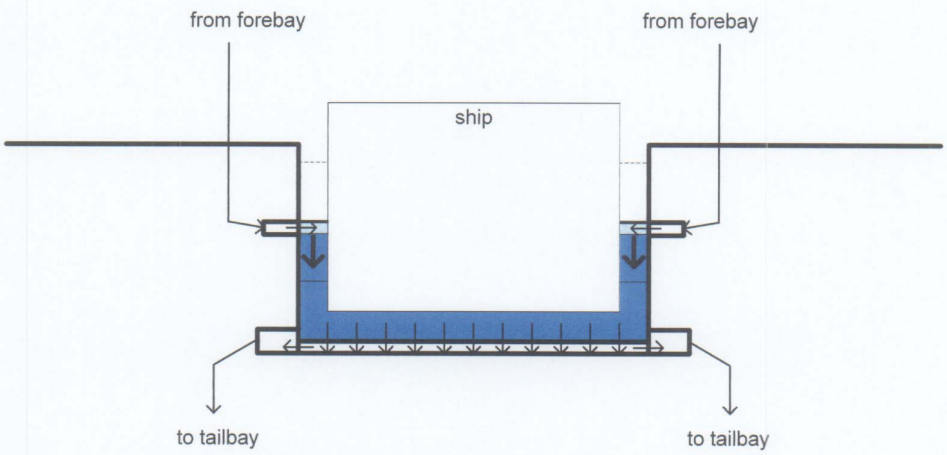
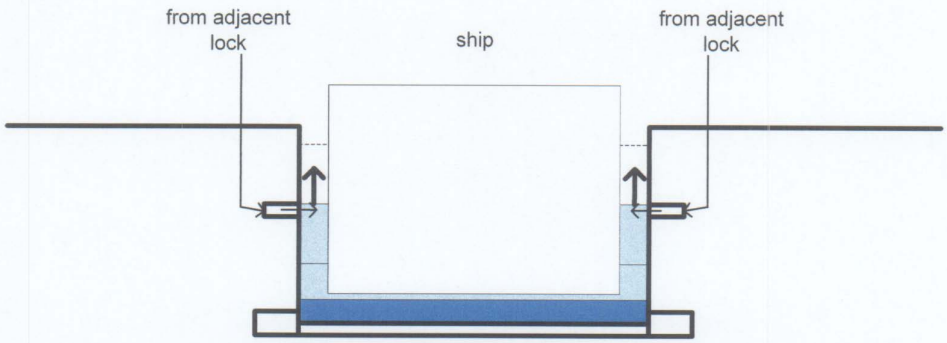


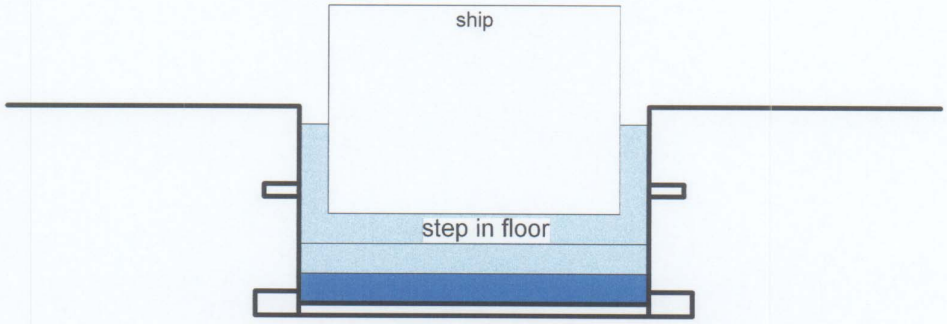
Figure 2.9d Mitigation system 6, uplockage



Exchange of water in lower lock chamber

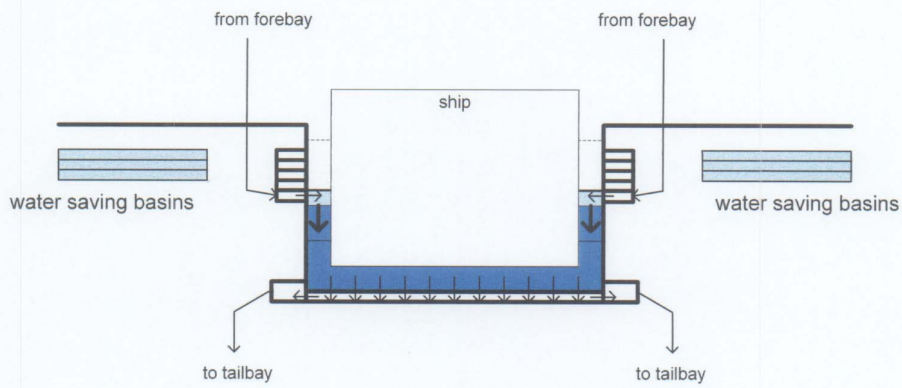


Leveling of water with adjacent lock chamber

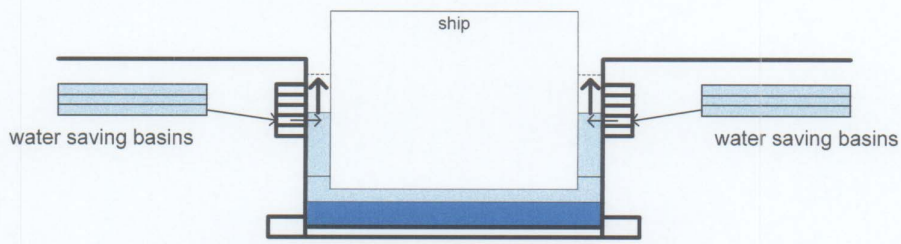


End of leveling process

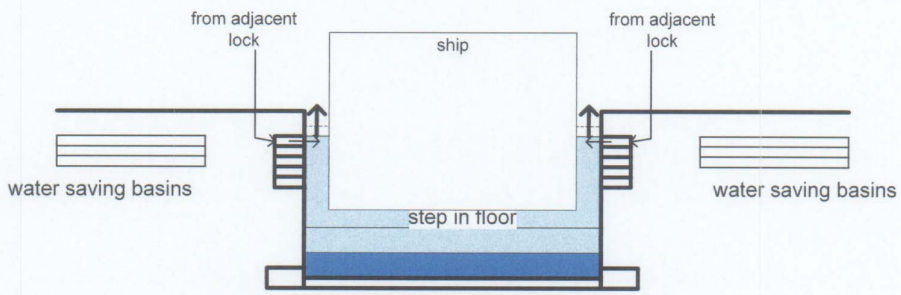
Figure 2.9e Mitigation system 6, uplockage; water exchange and leveling of lower lock chamber; wsb's not in use



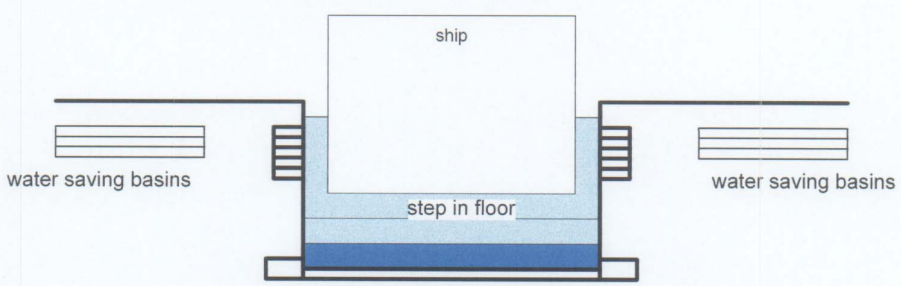
Exchange of water in lower lock chamber



Emptying of wsb's into lower lock chamber



Leveling of water with adjacent lock chamber



End of leveling process

Figure 2.9f Mitigation system 6, uplockage; water exchange and leveling of lower lock chamber; wsb's in use

2.5.2 Systems that flush back the intruded salt water or partly prevent the intrusion of salt water

Next systems 7 through 10 are meant to flush back the intruded salt water or to reduce the salt water intrusion.

System 7: drainage of salt tongue through slit in bottom (see also measure B2 in Report E)

features:

- slit in bottom at upstream side of upper lock required with separate culverts and control valves to tailbay; process of drainage of salt water is difficult to control
- wsb's can be used in the normal way
- extra water loss: 100% - 200% at downlockage, smaller loss at uplockage (water loss depends also on the time that gates of upper lock are open)
- effectiveness: moderate
- no delay for shipping expected

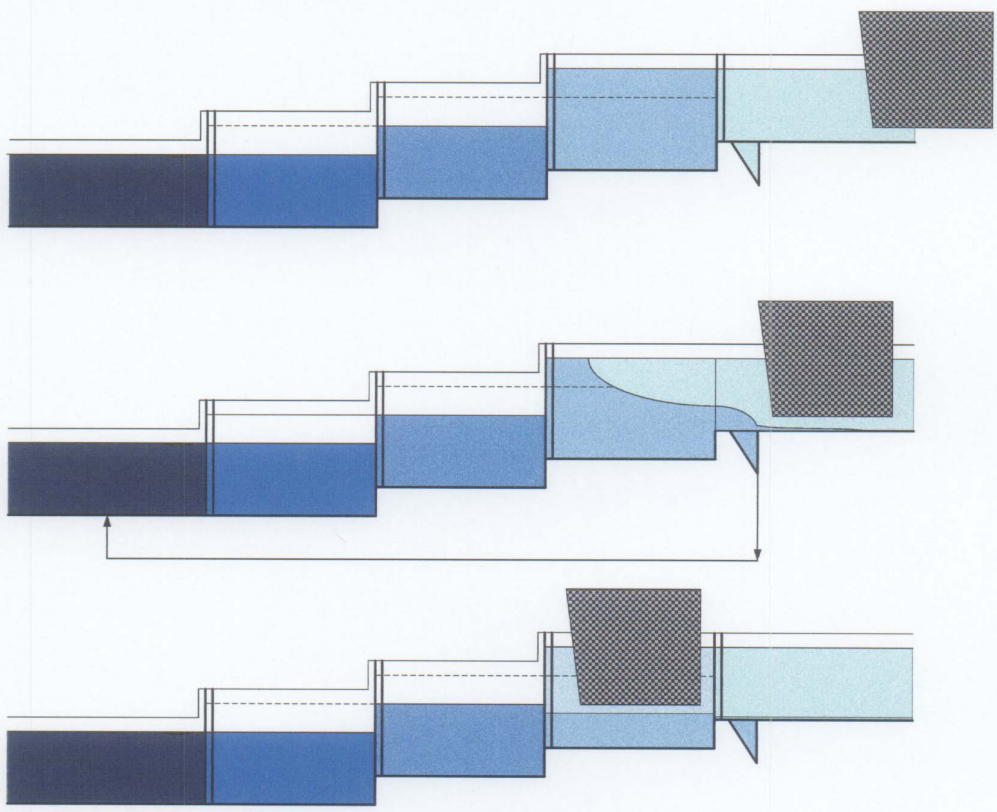


Figure 2.10 Mitigation system 7, drainage of salt tongue through slit in bottom

System 8: flushing of salt water from pit (see also measure B3 in Report E)

features:

- pit at upstream side of upper lock required with separate culverts and control valves to tailbay; process of drainage of salt water can better be controled than with system 7; to this aim the salt concentration in the pit should be measured
- wsb's can be used in the normal way
- extra water loss: 100% - 200% at downlockage, smaller loss at uplockage (water loss depends also on the time that gates of upper lock are open)
- effectiveness: high
- no delay for shipping expected

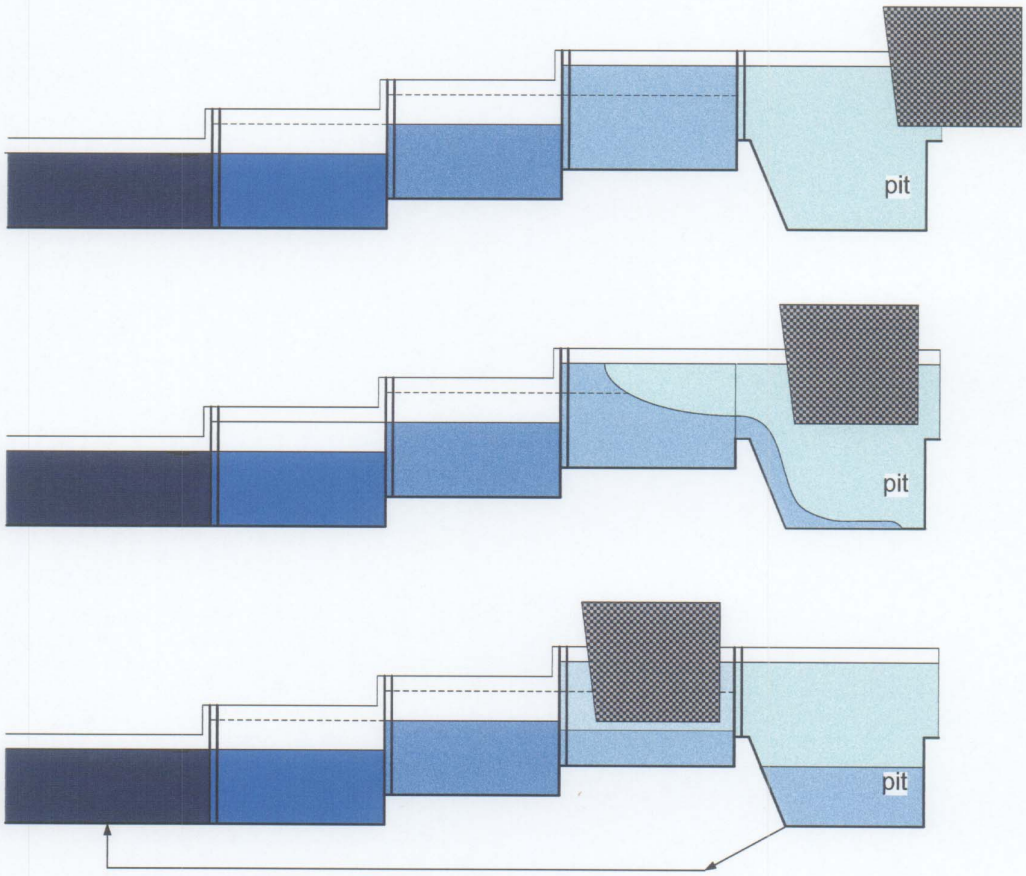


Figure 2.11 Mitigation system 8, flushing of salt water from pit

System 9: flushing of salt water from pit with perforated floor (see also measure B3 in Report E)

features:

- pit at upstream side of upper lock required with perforated floor and drainage system; separate culverts and control valves required to tailbay; less fresh water loss than with system 8
- wsb's can be used in the normal way
- extra water loss: 100% - 150% at downlockage, smaller loss at uplockage (water loss depends also on the time that gates of upper lock are open)
- effectiveness: high, better than system 8
- no delay for shipping expected

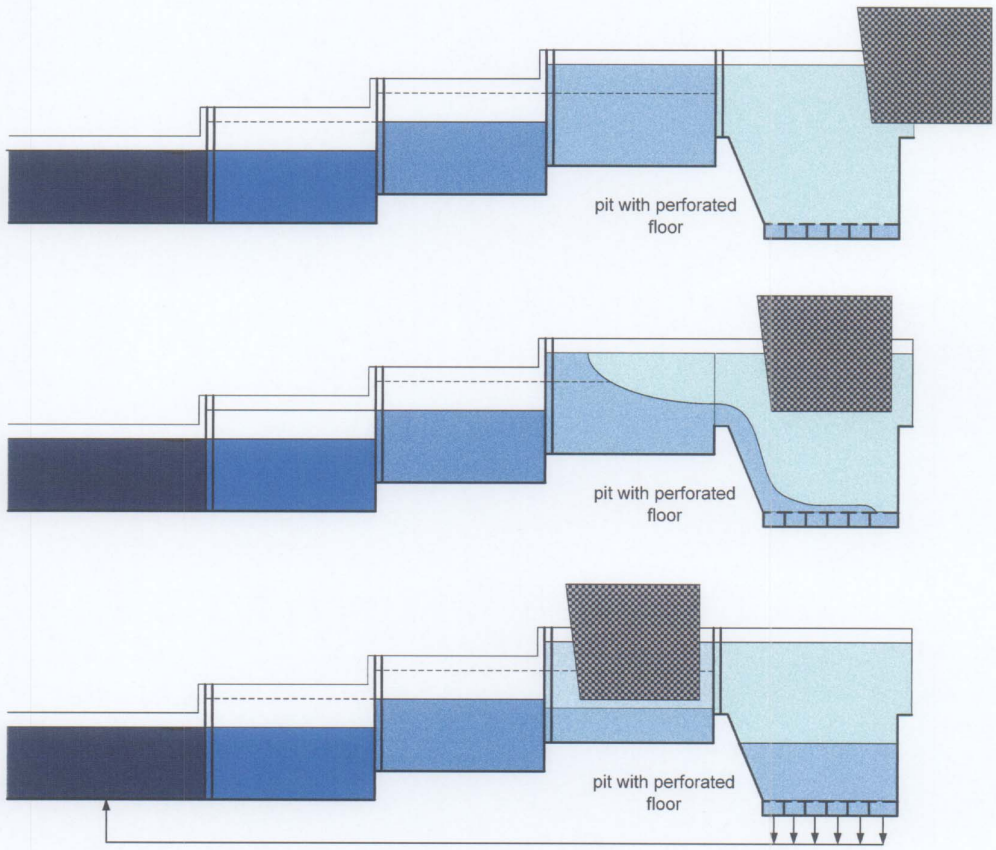


Figure 2.12 Mitigation system 9, flushing of salt water from a pit with perforated floor

System 10: pneumatic barrier at the entrance to the lower lock (see also measure A2 in Report E)

features:

- air bubble screen at entrance to lower lock required (air compressors needed); second screen can be applied at upstream side of upper lock
- the ship-bound exchange of water is not prevented
- wsb's can be used in the normal way
- extra water loss: 0%
- effectiveness: low; better at uplockage than at downlockage
- no delay for shipping expected; hindrance may be expected for small yachts

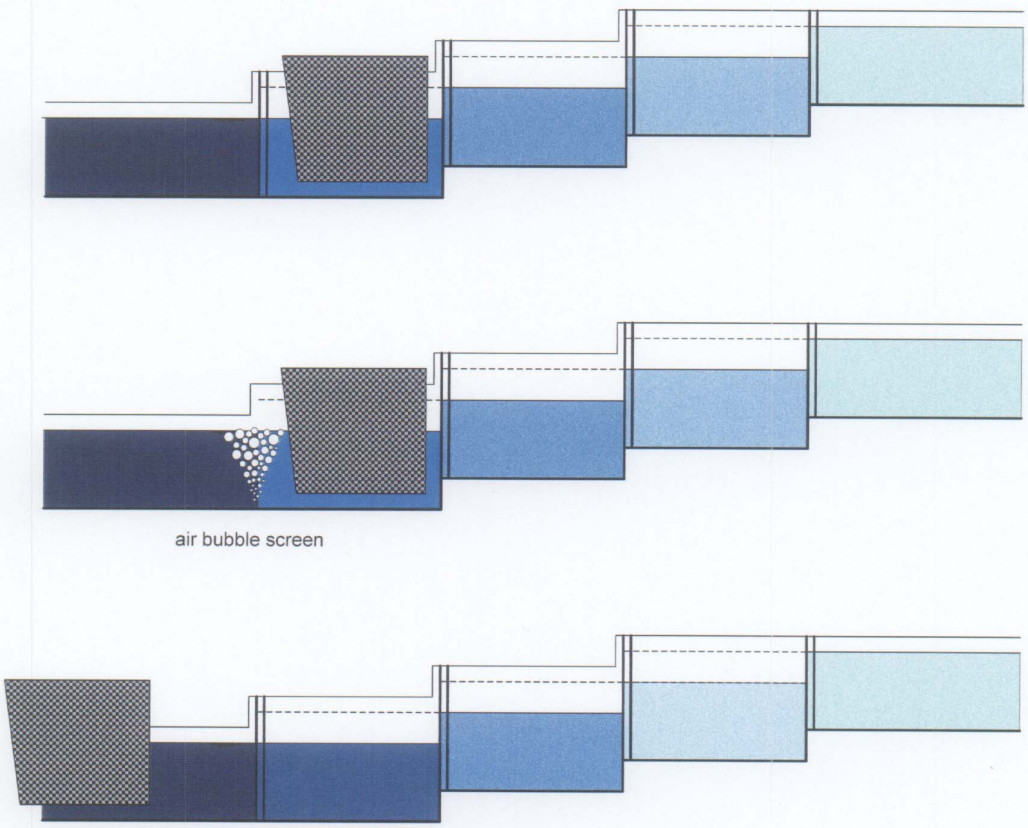


Figure 2.13 Mitigation system 10, pneumatic barrier at the entrance to the lower lock

2.6 Mitigation systems selected for a further evaluation

At the kick off meeting of 12 July 2004 six of above ten mitigation systems have been selected for a further analysis. The selected mitigation systems represent a broad spectrum of combinations of effectiveness, water loss, complexity of system and ease of operation.

Selected systems:

- System 1 (no special provision required, no special operation procedures, moderate to high effectiveness and moderate water loss)
- System 2 (one set of extra culverts and control gates required between middle lock and tailbay, moderate to high effectiveness, better than system 1, moderate water loss)
- System 4 (one set of extra culverts and control gates required between upper lock and lower lock and between upper lock and tailbay, high effectiveness but high water loss)
- System 6 (one set of extra culverts and control gates required between forebay and lower lock, separate wall filling and bottom emptying system required in lower lock, delay for shipping in particular at uplockage, high effectiveness, moderate water loss, complicated system)
- System 9 (pit with perforated floor and drainage system, extra set of culverts with control gates required between pit and tailbay, no delay for shipping, high effectiveness at moderate to high water loss)
- System 10 (pneumatic barrier, no special operation procedures, low effectiveness).

The results of the analysis for the selected mitigation systems are discussed in next chapter. Some attention will also be paid to the option of desalination of the intruded salt water.

3 Evaluation of mitigation systems

This chapter deals with the six salt intrusion mitigation systems which have been selected at the kick off meeting of 12 July 2004 for a further evaluation. In addition, some attention will be paid to the option of desalination of the intruded salt water.

The evaluation concentrates on next questions:

- what is the expected effectiveness of the mitigation system (to what extent is the salt water intrusion reduced)?
- what is the extra loss of water from Gatun Lake (salt water and fresh water) when the mitigation system is in operation, and how is the effectiveness affected when a lesser water quantity is used?
- does the mitigation system cause any hindrance for shipping or delays in ship transits?

A summary of advantages and disadvantages of the selected mitigation systems will be presented at the end of this chapter.

In support to this evaluation case studies of salt water intrusion mitigation systems which are used in shipping locks in the Netherlands, have been executed. These case studies pay attention to next items:

- a description of the system including system dimensions and drawings
- the purpose of the system
- hydraulic (scale) model studies executed in the pre-design and design stage
- effectiveness of the system and extra water loss caused by the system
- an estimate of the construction cost (cost amplifier)
- experiences with the system and conclusions from in situ measurements, if any
- system modifications, if any

The Ministry of Transport and Public Works of the Netherlands has contributed to these case studies. The construction cost concern the cost of the mitigation systems which have been realised in the Netherlands. On the basis of these data a cost amplifier has been derived, which may be used by ACP to assess the cost of a mitigation system for the 3-lift Post-Panamax Locks. The presented cost amplifier can also be used to compare different mitigation systems in order to get insight in relative price levels.

In next sections the expected effectiveness of a mitigation system is defined as the reduction of the salt load on Gatun Lake in comparison to the situation that no mitigation system is in operation (salt load: the quantity of dissolved salts that enters Gatun Lake through lockage operations). Only the salt load caused by the revised 3-lift locks is considered.

The inflow (salt load) and outflow (salt discharge) of salt water is schematically shown in Figure 3.1 for the Panama Canal system. The numerical program SWINLOCKS, that is used to study the salt water intrusion, simulates both the salt load of existing locks and future Post-Panamax Locks and the outflow of salt water at Gatun Dam and Miraflores Dam in a

step by step salt balance and water balance approach. The dispersion of salt water in Gatun Lake is not computed; this can be done with the help of a full 3-dimensional flow model.

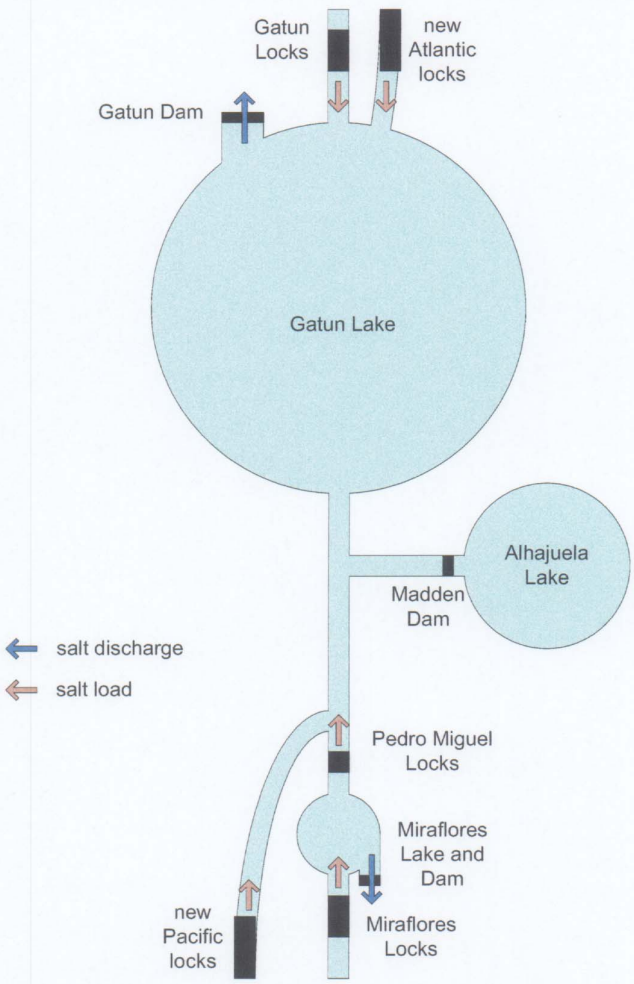


Figure 3.1 Salt load and salt discharge, Panama Canal system

The extra water loss caused by the operation of the mitigation system is expressed as a percentage of the 'normal' water loss of the revised 3-lift locks without water saving basins; this loss occurs at each uplockage and downlockage operation at either side of the canal. The 'normal' water loss is defined as the product of Δh, see Figure 3.2, and the area of the lock chamber (including two gate recesses). The quantity Δh is about 1/3 of the water level difference between Gatun Lake and the oceans, the latter being 25.7 m on average. The normal water loss is indicated as the shaded area in Figure 3.2.

The so defined 'normal' water loss amounts to 0.23×10^6 m^3 for the revised 3-lift locks (0.46×10^6 m^3 for each ship transfer). The water loss of the revised 3-lift locks with 2 wsb's per lift is 50% of the 'normal' water loss, the water loss of the revised 3-lift locks with 3 wsb's per lift is 40% of the 'normal' water loss.

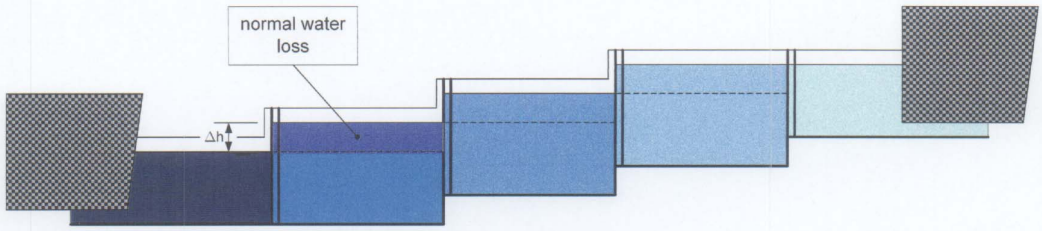


Figure 3.2 Definition of 'normal' water loss of revised 3-lift locks

In next sections the total water loss per lock operation is presented, being the summation of the lock loss and the loss caused by the mitigation system. When the mitigation system is only used during a downlockage operation the presented total loss is the mean value of the downlockage loss and the uplockage loss.

In the present analysis we assume that the lock chambers of the revised 3-lift Post-Panamax Locks are filled and emptied through a multiport system, consisting of gated culverts along both sides of the lock chamber with openings distributed over the entire length of the chamber and located in the lock walls just above the chamber bottom.

3.1 Mitigation system 1

3.1.1 Features of the system

An overview of the features of mitigation system 1 has been presented in Section 2.5.1. The subsequent operational steps of mitigation system 1 are shown in Figure 2.4a for downlockage of ships and in Figure 2.4b for uplockage of ships. The operation can be regarded as a 'dummy lockage', but the gates between the lock chambers are not opened. At downlockage the operation starts at the forebay side. Water is withdrawn from the forebay and supplied to the upper lock. The water in the upper lock is mixed up and diluted. In the next step the same quantity of water is withdrawn from the upper lock and supplied to the middle lock. Then water is drawn from middle lock and supplied to lower lock and in the last step water is drawn from the lower lock and spilled into the tailbay. The overall effect is a reduction of the salt content of all three lock chambers and a mixing up of the water in the lock chambers (causing a more or less uniform salt distribution after leveling up). At uplockage the operation starts at the tailbay side with a spillage of water from the lower lock chamber into the tailbay. Then the reverse sequence is followed and the operation is concluded by a supply of water from the forebay to the upper lock.

The mitigation system does neither require special additional provisions, nor special operational procedures; the filling and emptying system of the revised 3-lift lock configuration can be used in the operation of the mitigation system. The water saving basins of the locks can be applied in the normal way during uplockage and downlockage of ships, but are not in use when the mitigation system is in operation.

Since a greater amount of salt water intrudes at downlockage of ships than at uplockage, the mitigation system should preferably be used after each downlockage operation. At the cost

of a greater water loss the salt water intrusion may further be reduced when the mitigation system is also used after each uplockage operation.
It is not strictly necessary to use a quantity of flushing water corresponding to a layer thickness Δh (see Figure 3.2); also a smaller quantity of water will help to reduce the salt water intrusion. The latter option has the disadvantage that the valves in the culverts have to be closed when water levels in adjoining lock chambers have not yet been equalized and consequently the flow in the culverts has not yet come at rest.

The operation of the mitigation system can already start when the ship is in the middle lock chamber (both at uplockage and downlockage). Despite of this, delays for shipping may be expected when the relay mode of operation is practised. At uplockage the spillage of water into the tailbay may cause some hindrance for the next approaching ship, mainly when it is already in the tailbay.

3.1.2 Expected effectiveness and water loss of mitigation system 1

The effectiveness of mitigation system 1 has been assessed on the basis of a spreadsheet computation of the uplockage – downlockage cycle in the revised 3-lift lock configuration on a single day. Water saving basins have not been applied in this computation. The formulas of the simulation model SWINLOCKS which describe the water balance and the salt balance of the lock chambers after each operational change, have been implemented in the spreadsheet. Salt exchange coefficients in the formulas have been selected as indicated in Report C for a 3-lift lock configuration; these coefficients can – after some modification, see Section 4.5 – also be used for 'dummy' lockages.

The simulated shipping cycle consisted of a series of 7 uplocking ships, a turn around (uplockage → downlockage), a series of 7 downlocking ships, and a second turn around (downlockage → uplockage). The shipping cycle was repeated until stable salt concentration values in the lock chambers were obtained. A 'standard' Post-Panamax vessel with water displacement of 215000 m^3 was applied.

The water levels of the seaside tailbay and the forebay in the lake were kept constant, as well as the salt concentrations. The salt concentration of the tailbay was set to 30 ppt; the salt concentration of the forebay was set to 0 ppt. The flush quantity Δh, see Figure 3.2, was selected as 8.7 m (1/3 of the overall water level difference between Gatun Lake and tailbay). To reduce the loss of water also flushing quantities of 1/3.Δh and 2/3.Δh were applied. In addition, the effect of using the mitigation system during downlockage operations only was examined. Next cases were analysed:

- Mitigation system not in operation
- Reduced flushing quantity 1/3.Δh, after each uplockage and downlockage operation
- Reduced flushing quantity 2/3.Δh, after each uplockage and downlockage operation
- Full flushing quantity Δh, after each uplockage and downlockage operation
- Reduced flushing quantity 1/3.Δh, after each downlockage operation
- Reduced flushing quantity 2/3.Δh, after each downlockage operation
- Full flushing quantity Δh, after each downlockage operation

For each of these cases the volume-averaged salt concentration of the lock chambers was computed at specific moments of time during uplockage and downlockage. The salt load on Gatun Lake is directly depending on the salt concentration of the upper lock chamber in the situation just before exit of the ship (uplockage) or entry of the ship (downlockage). The salt concentration values at these moments of time have been compared with the salt concentration values in the upper lock chamber when no mitigation system is in operation. The reduction of the salt concentration caused by the mitigation system corresponds to the expected effectiveness of the mitigation system.

Next Figure 3.3 shows the computed concentration values of the upper lock chamber just before exit of the ship (uplockage) and entry of the ship (downlockage), and after a turn around. The values are valid for operation of the mitigation system after each uplocking and downlocking ship. Slightly higher values are found when the mitigation system is merely used after each downlockage operation.

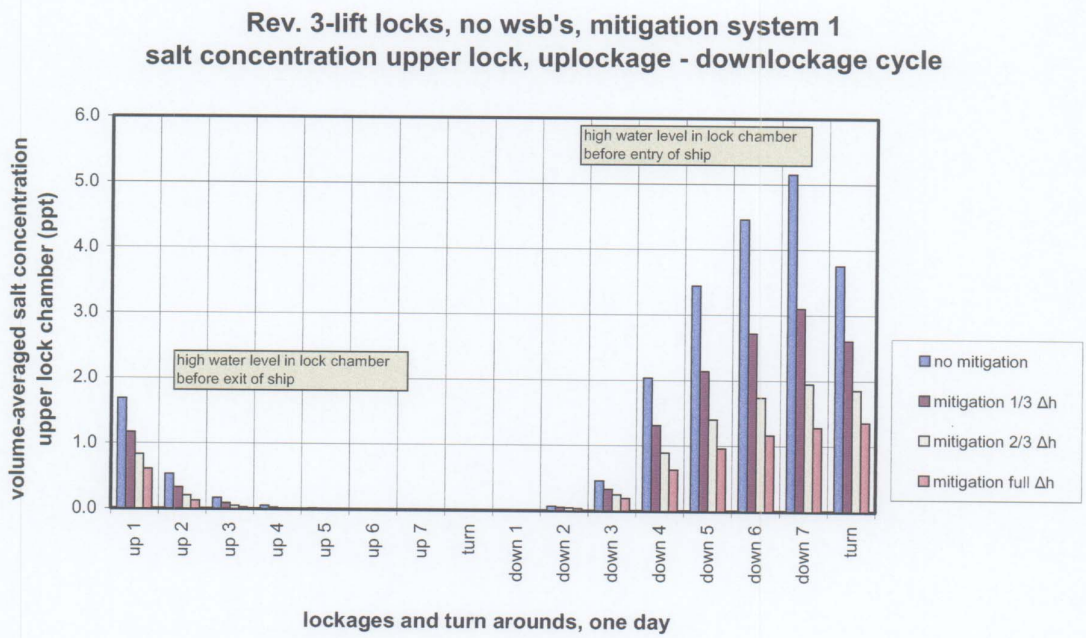


Figure 3.3 Volume-averaged salt concentration of upper lock chamber, mitigation system 1

It can be seen that the salt concentration in the upper lock chamber builds up with each downlocking ship, and diminishes again with each uplocking ship. The building up is reduced when the mitigation system is in operation. The strongest effect is obtained when the full flushing quantity Δh is applied, but a smaller flushing quantity of for example 1/3.Δh has already a considerably favourable effect.

Figure 3.4 presents the expected effectiveness of mitigation system 1. The figure is derived from the results of above cases (with traffic cycle of 14 ships a day) but can also be used for a traffic intensity of 15 Post-Panamax vessels a day (expected high traffic intensity level in the future). The expected effectiveness is defined as the reduction of the salt load on Gatun Lake as a result of the mitigation system.

From Figure 3.4 it appears that when the mitigation operations are limited to the phase with downlocking ships, an almost as good effectiveness may be expected as when the mitigation system is operated in both uplockage and downlockage phase. In both cases the effectiveness is about 70% at a full flushing quantity Δh. Clearly, the downlockage phase is the most important phase in view of salt water intrusion, and attempts to reduce the salt water intrusion should therefore preferably be focused on this phase. When the mitigation efforts are limited to the downlockage phase a considerable saving of water can be obtained.

Spreadsheet computations have not been executed for the revised 3-lift locks with wsb's in operation, but it can be argued that the effectiveness is approximately the same. In the case of wsb's, however, the salt load level is higher, which implies that after mitigation also a higher salt load has to be expected.

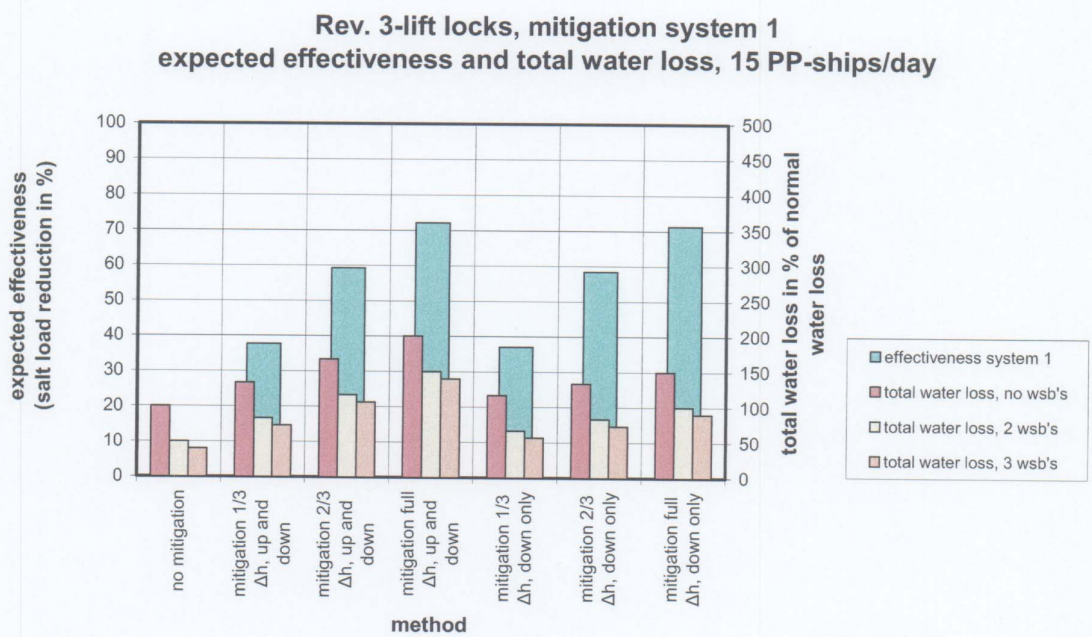


Figure 3.4 Expected effectiveness of mitigation system 1 and total water loss per lockage

The total loss of water for each uplocking or downlocking ship is also shown in Figure 3.4. The total loss (sum of lock loss and loss caused by the mitigation system) is expressed as a percentage of the 'normal' loss. With a full mitigation, that is limited to the downlockage phase, an effectiveness of about 70% is obtained at a total water loss of 150% (average value of a loss of 200% at downlockage and a loss of 100% at uplockage). More or less the same effectiveness can be obtained when the water saving basins are in operation during lockages. In the case of a full mitigation at downlockage operations and 2 wsb's per lift the total water loss amounts to 100% and with 3 wsb's per lift the total water loss is 80%.

The effect of a smaller ship with a water displacement of 90000 m^3 (Panamax vessel) instead of 213000 m^3 has been checked through separate spreadsheet computations. It appeared that the effectiveness of the mitigation system to be expected was slightly higher.

3.2 Mitigation system 2

3.2.1 Features of the system

The subsequent operational steps of mitigation system 2 are shown in Figure 2.5a for downlockage of ships and in Figure 2.5b for uplockage of ships. Contrary to mitigation system 1 the operation can not be regarded as a 'dummy lockage'. The lower lock chamber is not involved in the operation and the sequence of filling and emptying is different. At downlockage the operation starts with the withdrawal of water from the middle lock and spillage of this water into the tailbay. Since the water in the middle lock is not yet leveled up, there still exists a lower layer with higher density and salt concentration near the bottom. The water is withdrawn from the region near the bottom, and as a result water with relatively high salt concentration is evacuated from the middle lock. In the next step water is withdrawn from the upper lock and supplied to the middle lock. Finally water is withdrawn from the forebay and supplied to the upper lock. The overall effect is a reduction of the salt content of middle lock and upper lock and a mixing up of the water in these lock chambers (causing a more or less uniform salt distribution after leveling up). At uplockage the same sequence is applied, but in this case water levels are high in middle lock and upper lock at the start of the operation. As a consequence, when spilling water from the middle lock into the tailbay, the water flow in the culverts does not stop automatically and the transfer of water has to be stopped by closing the valves at the moment that the conduits are running at full capacity.

The filling and emptying system of the 3-lift lock configuration can be applied to transfer water from upper lock to middle lock and from forebay to upper lock. However, extra separate culverts with valves are required between middle lock and tailbay. Alternatively, to spill water from the middle lock into the tailbay, the culverts of the filling and emptying system may be applied, but in that case all fill openings to the lower lock chamber have to be closed off with valves.
The operation of the mitigation system is easy and does not require special operational procedures, but closure of the valves in the separate culverts from middle lock to tailbay requires attention, since a rapid closure causes high pressures at the upstream side and low pressures at the downstream side of the valves (inertia forces), air suction through valve shafts and transient flow phenomena in the culverts.
The water saving basins of the locks can be applied in the normal way during uplockage and downlockage of ships, but are not in use when the mitigation system is in operation.

The mitigation operations start with the spillage of water from the middle lock to the tailbay. At downlockage, spillage of water can begin when the ship has left the lower lock and is in the tailbay. The next downlocking ship has to wait in the forebay until the mitigation operations in the middle lock and upper lock are ready. This will cause a delay. Alternatively, the spillage of water from the middle lock to the tailbay can be executed immediately after the lower lock has leveled down, but prior to the exit of the ship. In that case a smoother operation of the locks is possible causing a somewhat lesser delay.
At uplockage, the spillage of water from the middle lock to the tailbay can begin when the ship is in the upper lock. When this action is executed prior to leveling down the water in

the lower lock, the next uplockage operation can be executed rather smoothly. However, a delay will occur.
At uplockage the spillage of water into the tailbay may cause some hindrance for the next approaching ship.

3.2.2 Expected effectiveness and water loss of mitigation system 2

The effectiveness of mitigation system 2 has been assessed on the basis of a spreadsheet computation, similar as for mitigation system 1. The subsequent steps when operating the mitigation system were modeled in the spreadsheet, and the model was run for the uplockage – downlockage cycle on a single day, consisting of a series of 7 uplocking ships, a turn around (uplockage → downlockage), a series of 7 downlocking ships, and a second turn around (downlockage → uplockage). The shipping cycle was repeated until stable salt concentration values in the lock chambers were obtained. A 'standard' Post-Panamax vessel with water displacement of 215000 m^3 was applied. The hydraulic boundary conditions were the same as for mitigation system 1 and a similar set of cases was analysed.

Next Figure 3.5 shows the computed salt concentration values of the upper lock chamber just before exit of the ship (uplockage) and entry of the ship (downlockage), and after a turn around. The concentration values are valid for operation of the mitigation system after each uplocking and downlocking ship. The concentration values are slightly higher when the operation of the mitigation system is limited to the phase with downlocking ships.

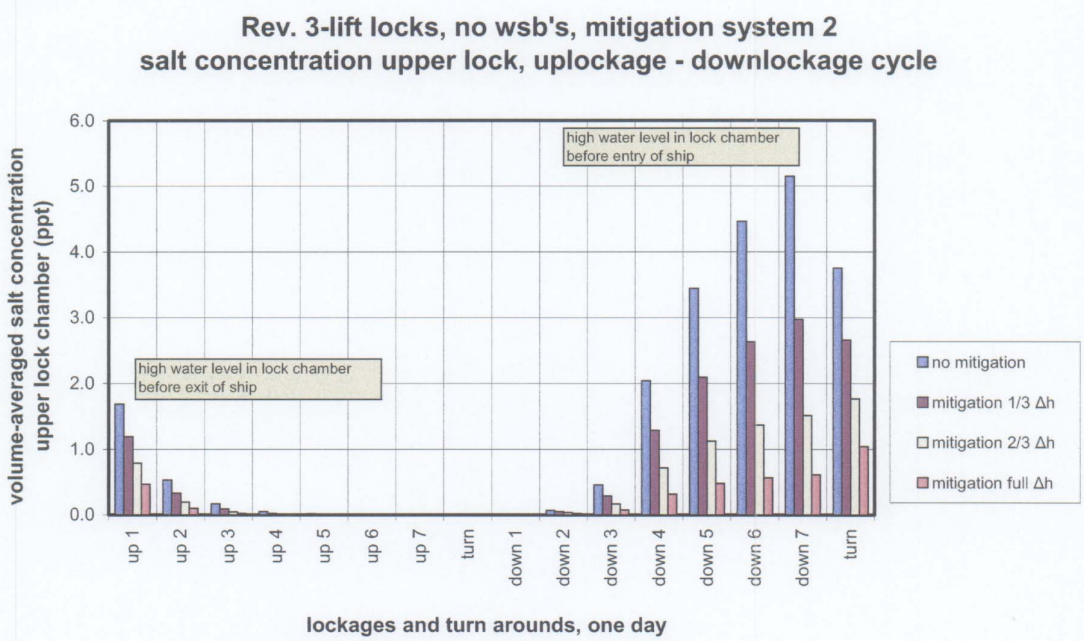


Figure 3.5 Volume-averaged salt concentration of upper lock chamber, mitigation system 2

As can be seen the salt concentration of the upper lock builds up with each downlocking ship and reduces again with each uplocking ship. As a result of operation of the mitigation system the salt concentration in the upper lock attains a less high value.

Figure 3.6 presents the expected effectiveness of mitigation system 2 and the total loss of water at each downlockage and uplockage operation. The expected effectiveness is higher than with mitigation system 1 and is about 85% at full mitigation; the total water loss is the same. The higher effectiveness is obtained thanks to the more efficient spillage of salt water from middle lock and upper lock in the important downlockage phase.

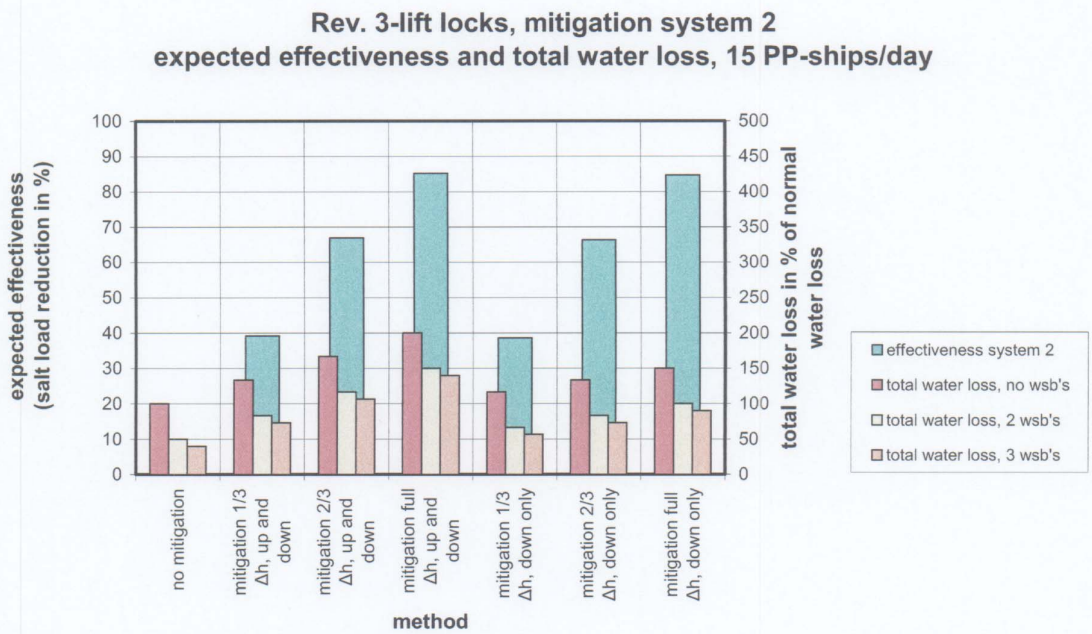


Figure 3.6 Expected effectiveness of mitigation system 2 and total water loss per lockage

3.3 Mitigation system 4

3.3.1 Features of the system

The subsequent operational steps of mitigation system 4 are shown in Figure 2.7a for downlockage of ships and in Figure 2.7c for uplockage of ships. The middle lock chamber is not involved in the operations. At downlockage the operation starts with the withdrawal of water from the upper lock and supply of this water to the lower lock. When the water levels of these two lock chambers have been equalized, more water from the upper lock is spilled into the tailbay. The water level in the upper lock drops until it equalizes with the tailbay water level. Only a thin water layer remains in the upper lock and a negative head occurs at the gates between upper lock and middle lock. Then water is supplied from the forebay to the upper lock, and the original water level in the upper lock restored. Simultaneously water from the lower lock is spilled into the tailbay. The overall effect is a reduction of the salt content of the lower lock and an almost full replacement of the water in the upper lock by fresh water from the forebay.

The first step at uplockage is the spillage of water from the lower lock into the tailbay. Then the same sequence of steps is applied as at downlockage, but in this case the water level of the upper lock is high at the start of leveling down. This means that the water transfer from upper lock to lower lock and subsequently from upper lock to tailbay does not automatically stop when the water of the upper lock is at the pre-defined level. The water flow is stopped by closing the valves, at the moment that the conduits are running at full capacity. When water is spilled from the upper lock into the tailbay a negative head occurs at the gates between upper lock and middle lock.

Separate culverts with valves are required between upper lock and lower lock and next to the tailbay. Alternatively, to transfer water from the upper lock to the lower lock, the culverts of the filling and emptying system may be applied, but in that case all fill openings to the middle lock chamber have to be closed off with valves. The same holds when water is transferred from upper lock to tailbay; in that case also the fill openings of the lower lock chamber have to be closed off with valves.
Since the downstream gates of the upper lock are loaded with a negative head when the mitigation system is operated, attention is required for a proper sealing at the gate edges to prevent leakage flows. When mitre gates are applied, the gates and the gate supports have to be designed on both pull and push forces, and a system has to be provided that firmly clamps the gates together when negatively loaded.
The operation of the mitigation system does not require special operational procedures, but closure of the valves when conduits are running at full capacity requires attention, in view of possible high inertia forces on the valves, air suction through valve shafts and transient flow phenomena in the conduits.
The water saving basins of the locks can be applied in the normal way during uplockage and downlockage of ships, but are not in use when the mitigation system is in operation. The use of wsb's during downlockage and uplockage operations is shown in Figures 2.7b and 2.7d. Wsb's are not in use when the mitigation system is operated.

At downlockage mitigation operations can start as soon as the ship has left the lower lock. The next downlocking ship has to wait until the mitigation operations in the upper lock are ready. This will cause a delay. A delay will also occur at uplockage, since the next uplocking ship has to wait until the mitigation operations in the lower lock are ready. At uplockage the spillage of water into the tailbay may cause some hindrance for the next approaching ship.

3.3.2 Expected effectiveness and water loss of mitigation system 4

The effectiveness of mitigation system 4 has been assessed on the basis of a spreadsheet computation, similar as for mitigation system 1. The subsequent steps when operating the mitigation system were modeled in the spreadsheet, and the model was run for the uplockage – downlockage cycle on a single day, consisting of a series of 7 uplocking ships, a turn around (uplockage → downlockage), a series of 7 downlocking ships, and a second turn around (downlockage → uplockage). The shipping cycle was repeated until stable salt concentration values in the lock chambers were obtained. A 'standard' Post-Panamax vessel with water displacement of 215000 m^3 was applied. The hydraulic boundary conditions were the same as for mitigation system 1 and a similar set of cases was analysed.
Next Figure 3.7 shows the computed salt concentration values of the upper lock chamber just before exit of the ship (uplockage) and entry of the ship (downlockage), and after a turn

around. The concentration values are valid for operation of the mitigation system after each uplocking and downlocking ship. The concentration values are slightly higher when the operation of the mitigation system is limited to the phase with downlocking ships.

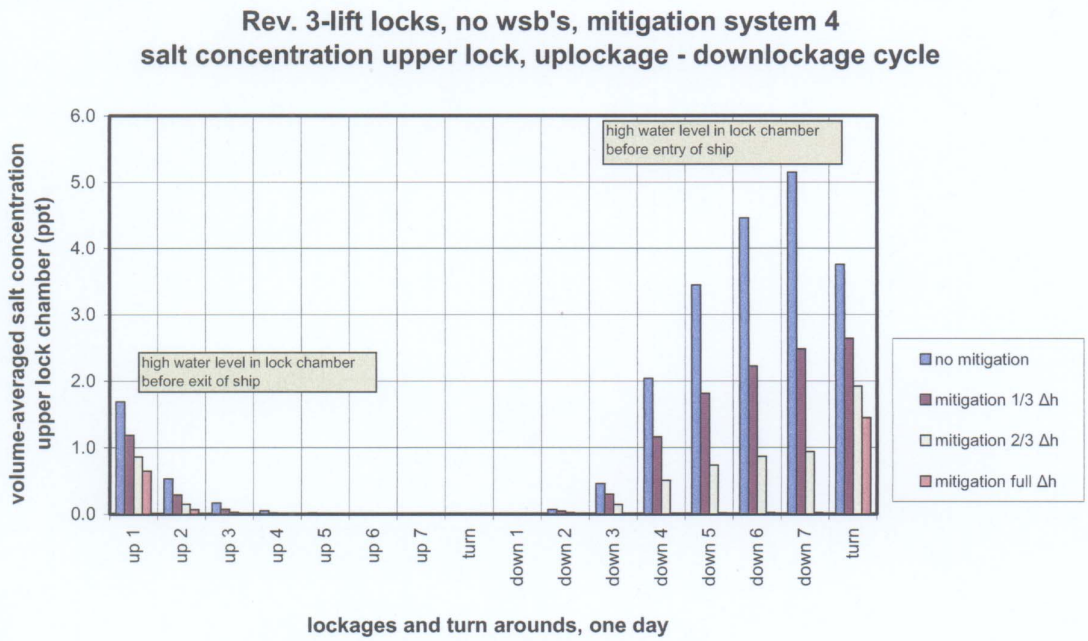


Figure 3.7 Volume-averaged salt concentration of upper lock chamber, mitigation system 4

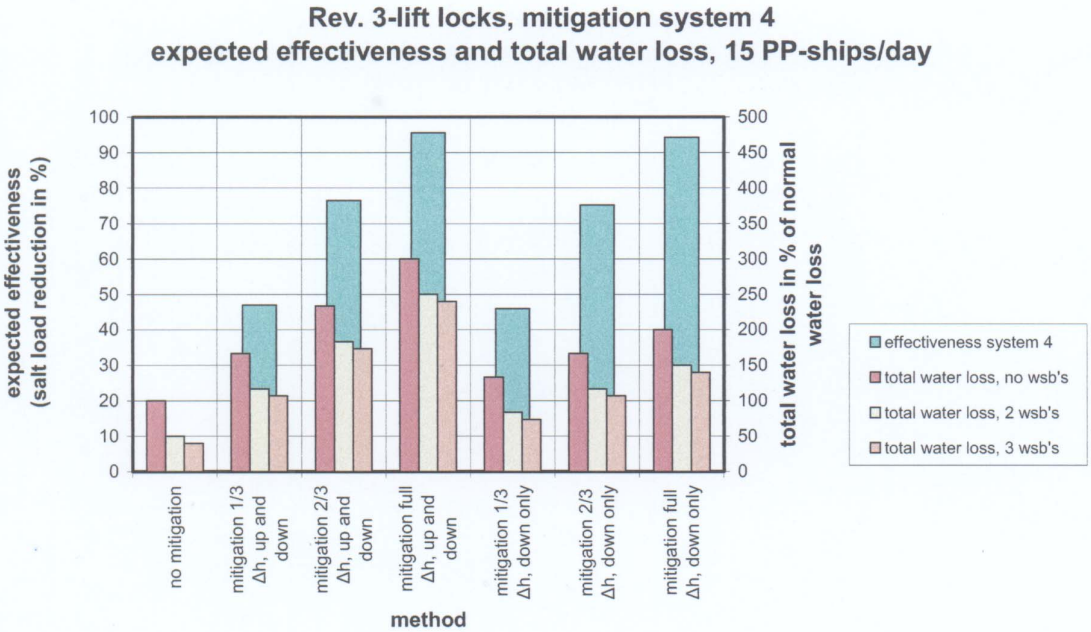


Figure 3.8 Expected effectiveness of mitigation system 4 and total water loss per lockage

Figure 3.8 presents the expected effectiveness of mitigation system 4 and the total loss of water at each downlockage and uplockage operation.
The expected effectiveness is high, about 95% at full mitigation, and is higher than with mitigation system 1 or mitigation system 2. This is caused by the almost full replacement of water in the upper lock with fresh water from the forebay in the important downlockage phase. The higher effectiveness is at the cost of a higher water loss. When the operation of the mitigation system is limited to the downlocking phase, an effectiveness of about 90% – 95% (full mitigation) is obtained at a total water loss per lockage of 200% (average value of a loss of 300% at downlockage and a loss of 100% at uplockage). When a smaller flushing water quantity is applied the expected effectiveness is still relatively high.
We expect that more or less the same effectiveness can be obtained when the water saving basins are in operation (but the resulting salt load level is higher when wsb's are in operation). In the case of a full mitigation at downlockage operations and 2 wsb's per lift the total water loss amounts to 150% and with 3 wsb's per lift the total water loss is 140%.

3.4 Mitigation system 6

3.4.1 Features of the system

Mitigation system 6 is a rather complex system; the system is aimed to replace a part of the salt water in the lower lock chamber with fresh water from the forebay in the course of which is tried to keep the remaining salt water as much as possible separated from the supplied fresh water. The more salt and fresh water get mixed up, the lesser the effectiveness.
Contrary to the previous discussed systems 1, 2 and 4, which are all activated after a ship has passed the locks, mitigation system 6 forms an integral part of the ship lockage operation. The subsequent operational steps are shown in Figures 2.9a/b/c (downlockage) and Figures 2.9d/e/f (uplockage).

At downlockage, when the ship has left the lower lock, the next downlockage - mitigation operation starts with a partial replacement of the salt water in the lower lock chamber with fresh water from the forebay. Salt water is withdrawn through openings in the bottom (or openings in the side walls just above the bottom) and spilled into the tailbay. Simultaneously fresh water from the forebay is supplied through openings in the side walls, which are located at the level of low water in the lock. The replacement of salt water with fresh water is a delicate process: the fresh water must carefully be supplied so that it can flow on top of the salt water without mixing up too much with the salt water, and form a separate fresh water layer. Moreover, at each moment of time the inflow of fresh water has to balance with the outflow of salt water. When the salt water – fresh water interface has amply dropped below the level of the step in the bottom, the downward exchange of water is stopped. This is also the end of the mitigation action in the downlockage process. The step in the bottom prevents an escape of salt water to the adjacent middle lock in the phase that lock gates are open, provided that the ship moves slowly and don't use too much it's engine.
Downlockage can now proceed as in a normal lockage operation, but all the time fill water is supplied carefully to the lower lock chamber through the high-elevated openings in the side walls. Water saving basins can be used in the normal way but they are also filled and emptied through these openings in the side walls.

At uplockage the mitigation action starts when the ship has entered the lower lock chamber. Similarly as at downlockage the salt water in the lower lock chamber is replaced with fresh water from the forebay. The quantity of exchanged water, however, is smaller since the ship occupies a part of the lock chamber volume To prevent transverse forces on the ship the filling discharge at both sides of the ship must be equal and the ship should preferably be positioned in the centre line of the lock chamber. The downward exchange of water is stopped when the salt water – fresh water interface is amply below the level of the step in the bottom. Then the uplockage operation can proceed in the normal way, but fill water is always supplied carefully through the high-elevated openings in the side walls.

The system requires extra culverts with control valves between forebay and lower lock, and separated filling and emptying systems in the lower lock chamber with control valves. Fill water (also from the wsb's) is supplied through openings in the lock walls (openings are situated at the level of low water), salt water is spilled through openings in or near to the lock chamber bottom, but water that is saved in the wsb's is evacuated through the high-elevated wall openings. The water quantity that is exchanged in the downward exchange process and is spilled into the tailbay forms a loss of the mitigation system.

The exchange process in the lower lock chamber requires a careful operation in order not to mix up fresh water and salt water and to prevent transverse forces on the ship. This process is in particular complex at the Pacific side, where large tidal fluctuations occur. Probably adjustable overflow gates are required in all inflow openings in the side walls to adjust the level of the openings to the low water level in the lock chamber. The ship has to sail slowly into or out of the lock chamber and should minimize its propeller action in order not to disturb too much the salt water – fresh water interface. These are reasons that a delay for shipping is inevitable, in particular at uplockage (at downlockage the downward exchange of water can already start when the previous ship has left the lower lock chamber).

3.4.2 Reduction of water loss by means of storage basins

The loss of water caused by the downward exchange of salt water with fresh water from the forebay can be prevented when a separate storage basin is applied at either side of the lower lock, in which temporarily the fresh water quantity is stored that is involved in the exchange process. Apart from the storage basins also pumps are required, which are needed to return the fresh water from the lower lock chamber to the high situated storage basins. These pumps must have a sufficient capacity, so that the leveling times remain acceptable.
As an alternative two storage basins at either side of the lower lock may be applied: the first one is at a high elevation and is used to supply fresh water to the lower lock chamber, the second, low situated storage basin is used to receive the fresh water from the lower lock chamber. A pumping station returns continuously (at low speed) water from the lower storage basin to the higher storage basin. The water saving basins of the lower lock can be omitted when one or two storage basins in combination with pumps are applied at either side of the lower lock, since the storage basins can also act as water saving basins.
The concept with two storage basins at either side of the lower lock is shown in next figures for a downlocking ship. The storage basins are used in this concept as water saving basins.

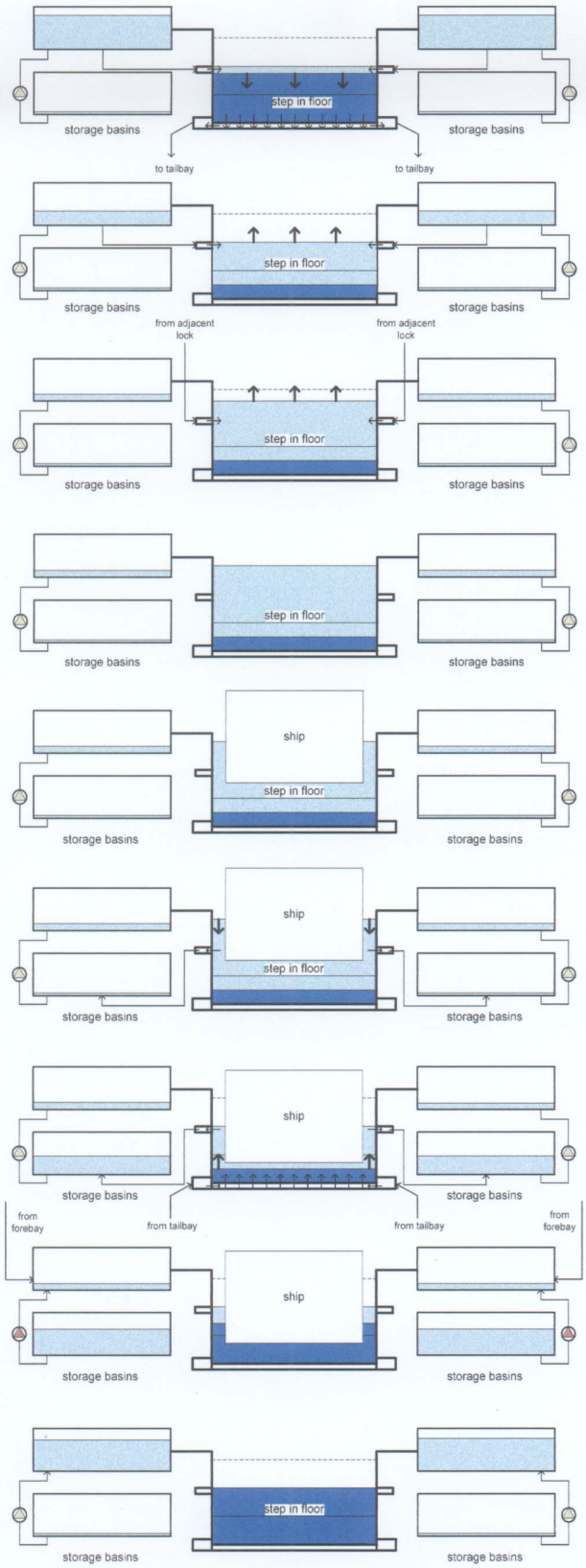


Figure 3.9 Mitigation system 6 with storage basins at either side of lower lock; downlockage

The operation in the lower lock starts with a downward exchange of salt water and fresh water. Fresh water is supplied from the upper storage basins (instead of the forebay) through the openings in the side walls and salt water is spilled into the tailbay through the openings in the lock chamber bottom (or openings in the side walls just above the bottom). Then the valves in the culverts to the tailbay are closed and more water is supplied from the upper storage basins. Simultaneously the water in the middle lock is leveled down (water is transferred to the water saving basins of the middle lock). Finally the water levels in middle lock and lower lock are equalized (water is transferred from middle lock to lower lock), the gates are opened and the ship sails from middle lock to lower lock.

Now, the ship is in the lower lock and fresh water is evacuated through the openings in the side walls to the lower storage basins. When the water mirror in the lock chamber arrives at the level of low water, the upward exchange of fresh water with salt water can be started. The valves of the culverts to the tailbay are opened and salt water from the tailbay flows through the openings in the bottom (or the openings in the side walls just above the bottom) into the lock chamber. As a result fresh water flows through the openings in the side walls to the lower storage basins. This upward exchange process must carefully be executed in order not to mix up salt and fresh water. However, some mixing up of salt water and fresh water is inevitable, and when too a large quantity of water is exchanged, salt water will enter the storage basins and accumulate in subsequent lockages. The accumulation of salt in the storage basins is the reason that the effectiveness of the mitigation system strongly reduces. The upward exchange of water must, therefore, timely be stopped, leaving the fresh water portion that is most contaminated with salt water in the lower lock chamber. As a separate action water is pumped from the lower storage basins to the upper storage basins.

At uplockage, the operation in the lower lock chamber is more or less the same as at downlockage. After leveling down fresh water is recovered through an upward exchange of water. Then the ship enters the lock chamber and in a downward exchange of water salt water is drained to the tailbay. Subsequently the water of the lower lock is leveled up and the ship exits to the middle lock.

The difference between the quantity of water that is drained through the openings in the bottom to the tailbay in the downward exchange phase and the quantity of water that flows back in the upward exchange phase corresponds to the total loss of water. This total loss of water is the sum of the lockage loss (with 2 wsb's per lift equal to 50% of the 'normal' loss and with 3 wsb's per lift equal to 40% of the 'normal' loss) and the extra loss caused by the mitigation system.
The extra loss of water is related to the question how much fresh water has to be kept in the lower lock chamber during the upward exchange of water to prevent the penetration of salt water in the lower storage basins. The more fresh water is kept in the lower lock, the higher the water loss caused by the mitigation system, but the higher the effectiveness of the mitigation system.

The extra water loss has to be compensated by a supply of fresh water to the upper storage basins; separate culverts with valves are required between the forebay and the storage basins to facilitate this water supply.
The inflow and outflow of fresh water through the openings in the side walls has to be controled by valves in the culverts to upper and lower storage basins. Probably, also adjustable overflow valves are required in the side wall openings. The outflow and inflow of

salt water trough the openings in the bottom (or openings in the side walls just above the bottom) has to be controled by valves in the culverts to the tailbay. Since the inflow and outflow of water of the lower lock chamber occurs simultaneously during the upward and downward exchange of water, the operation of the lock is rather complicated.

When storage basins are applied to reduce the loss of water, the effectiveness decreases. The operational procedure of the lower lock is extended with an upward exchange of water in addition to the downward exchange of water. The operation time will therefore increase, causing an extra delay for shipping and a further reduction of the capacity of the locks.

3.4.3 Case study Krammer locks / Kreekrak locks / Bergsediep lock

Mitigation system 6 has similarities with salt water intrusion mitigation systems which are in operation in the south-western delta area of the Netherlands. In this section we present the results of a case study for the locks in the Zoommeer area.

Zoommeer area

Figure 3.10 presents a map of the delta area and shows the different water basins, which have been formed after the construction of dams. The basin called Zoommeer or Zoom Lake is situated at the eastern side of the area (right side of map). It has been designed as a fresh water border lake along an area with agricultural activities. It prevents the penetration of salt water through the subsoil and acts as a fresh water reservoir in dry periods of the year. The border lake developed after the construction of several dams that separated the basin from salt sea arms. The water level is maintained at NAP (average sea level); surplus water is spilled to the salt sea arm Westerschelde by way of the sluice near Bath.

The border lake functions also as the main inland fairway between the ports of Antwerp and Rotterdam. For that reason shipping locks have been constructed at several locations in the area. The locks in the south, called Kreekrak locks, connect the border lake with the brackish water of the docks of Antwerp (water level NAP +1.85 m); the locks in the north, called Volkerak locks, connect the border lake with the fresh water basin Hollands Diep. The water level of Hollands Diep varies with the discharge of the river Rhine, but is regulated between NAP +0.7 m and NAP + 0.4 m with the help of the sluices at Haringvliet dam. The total length of the fairway between Kreekrak locks and Volkerak locks is 35 km.

Shipping locks have also been constructed to connect the border lake directly with the salt sea arm Oosterschelde. These locks are called Krammer locks, in the north, with tidal movement at the seaside between NAP +1.63 m and NAP – 1.45 m (on average), and Bergsediep lock, in the south, with tidal movement at the seaside between NAP +1.86 m and NAP – 1.6 m (on average). At high tide the sea water level is considerable higher than the level of Zoommeer, which is very unfavorable in view of a prevention of salt water intrusion. Note: the water mirror of the Panama Canal is always far above sea level, which is a great advantage.

In order to keep the salt concentration of the water of the border lake below acceptable limits for agriculture, the Krammer locks, the Bergsediep lock and the Kreekrak locks have been provided with a salt water intrusion mitigation system.

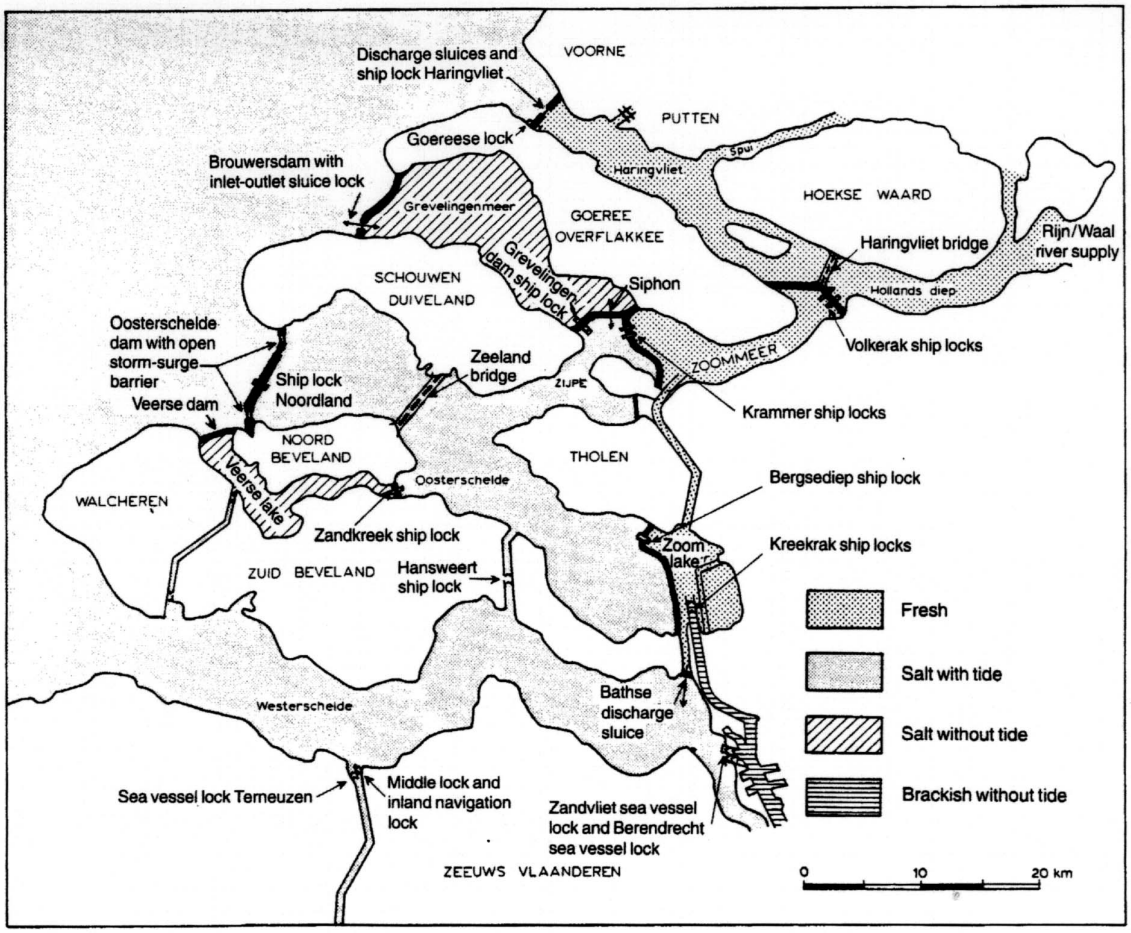


Figure 3.10 Delta areas in the south-western part of the Netherlands

General description of salt water intrusion mitigation systems

The Krammer locks complex consists of two parallel locks for cargo boats, each lock being 280 m long and 24 m wide, and two parallel locks for yachts, each with a lock chamber area of 75.9 m^2. The Kreekrak locks complex consists of two parallel locks for cargo boats, each lock with a length of 320 m and a width of 24 m. The salt water intrusion mitigation systems of the locks for cargo ships are more or less similar: facilities have been provided that enable the upward and downward exchange of salt water and fresh water in the lock chamber during uplockage or downlockage of ships. The exchange of water is realized through fresh water openings in the side walls, near the water surface, and salt water openings in the floor.

The exchange of water in the smaller Bergsediep lock (lock chamber dimensions 34 m long and 6.5 m wide) is different. Only a downward exchange of salt water with fresh water is possible; as a consequence the fresh water loss of this lock is higher, but since the lock chamber dimensions are relatively small this is acceptable. The fresh water is supplied to the lock chamber through the lock head at the fresh water side (water flows over the crest of a

movable weir) and the salt water is spilled through openings near the bottom in one side wall. The two locks for pleasure yachts of the Krammer locks complex have a more or less similar mitigation system as the Bergsediep lock. Only a downward exchange of water is possible. The fresh water is supplied through openings in one side wall near the water surface, and salt water is spilled through an opening underneath the lock head at the salt water side. These locks have a deepened bottom.

The mitigation system of the Krammer locks for cargo boats has a great similarity with mitigation system 6, in particular the variant with water storage basins, and is discussed more into detail.

Mitigation system of Krammer locks for cargo boats

Figure 3.11 presents a top view of the Krammer locks complex. The seaside is left on the picture. The gated fresh-water openings in the side walls of the cargo boat locks are in connection with the fresh water basins at either side of the lock chambers, which in turn are in open connection with the fresh water of Zoommeer. The salt-water openings in the bottom are in connection with separate salt water reservoirs at the seaside of the locks through a system of gated culverts. The water level of one reservoir is kept high (by means of pumps or utilizing high tide) and is used during the upward exchange of water; the water level of the second basin is kept low (again by means of pumps or utilizing low tide) and this basin is used during the downward exchange of water.

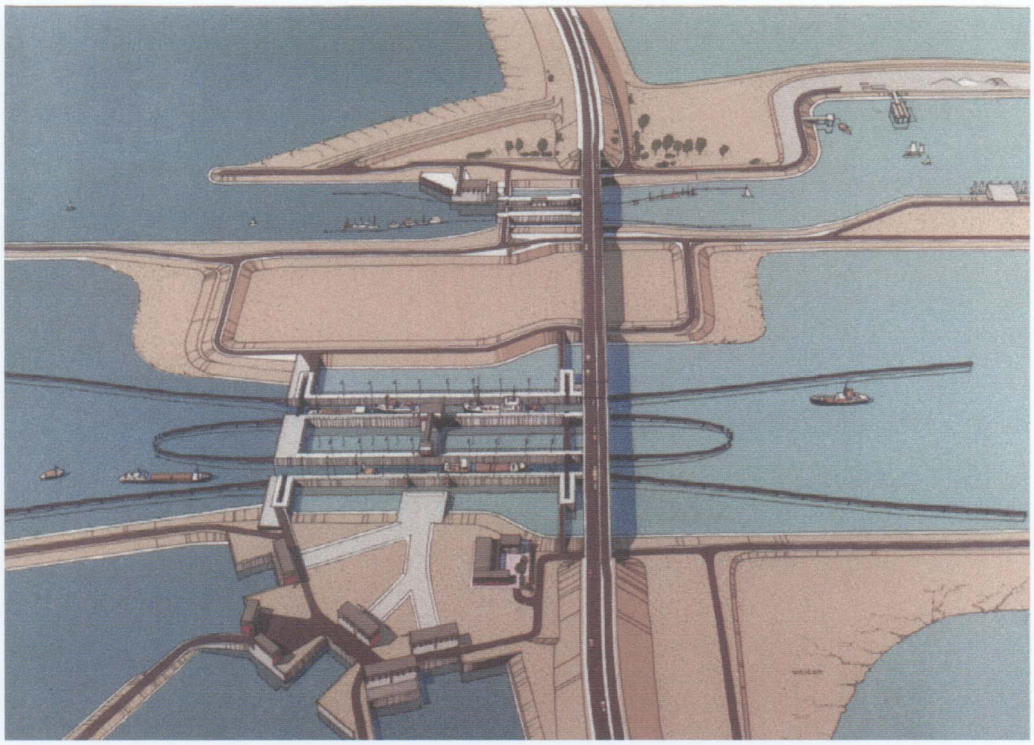


Figure 3.11 Krammer locks (in foreground: cargo ship locks, in background: yacht locks)

Figure 3.12 shows the downward exchange of salt water with fresh water. The salt water is evacuated through openings in the perforated floor and simultaneously fresh water is

supplied through the openings in the side walls. These openings can be closed off by valves and the inflow of water regulated by vertically adjustable sliding valves.
The salt water – fresh water interface is drawn below the perforated floor. The perforated floor covers the deepened part of the lock chamber and has been provided to protect the salt water – fresh water interface against the disturbing action of the ships when they sail into and out of the lock chamber.

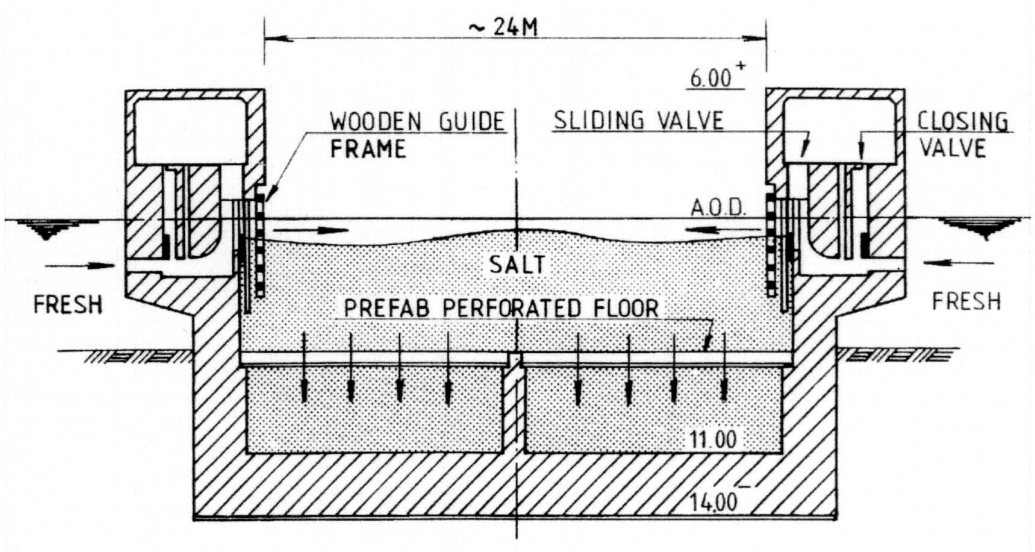


Figure 3.12 Krammer cargo boat locks: cross section, downward exchange of water

Note that the deepened part of the lock chamber can be compared with the step in the bottom of the Panama Canal locks. But the salt water – fresh water interface in the Panama Canal locks can not be protected with a perforated floor.

Studies executed for Krammer locks

In the pre-design and design stage of the Krammer locks many studies have been undertaken. These studies focused on:

- The feasibility of various mitigation systems.
- The general lay out of a lock provided with a salt water intrusion mitigation system.
- The process of downward and upward exchanging of salt water and fresh water in the lock chamber, mixing during the exchange of water, effect of the ship in the lock chamber on the exchange of water.
- The inflow / outflow of fresh water through openings in the side walls and the operation of adjustable overflow gates in the fill openings.
- The outflow / inflow of salt water through the perforated floor and the mixing effect of turbulence caused by the flow through the confined openings.
- The effect of a moving ship and propeller on the salt water – fresh water interface and the mixing effect caused by the ship-induced turbulence.
- Optimization of the detailed design of filling openings in lock walls and perforations in lock floor.

- Transverse forces on the ship caused by inflow/outflow of water and density differences.

The technical studies were for the greater part executed at WL | Delft Hydraulics and included both desk studies (based on analytical models) and scale model studies on specific aspects and phases of the lockage process. These studies are described in study reports (in Dutch language) and culminated in various publications in leading journals. A full list of publications and reports has been given in Report E, part II.

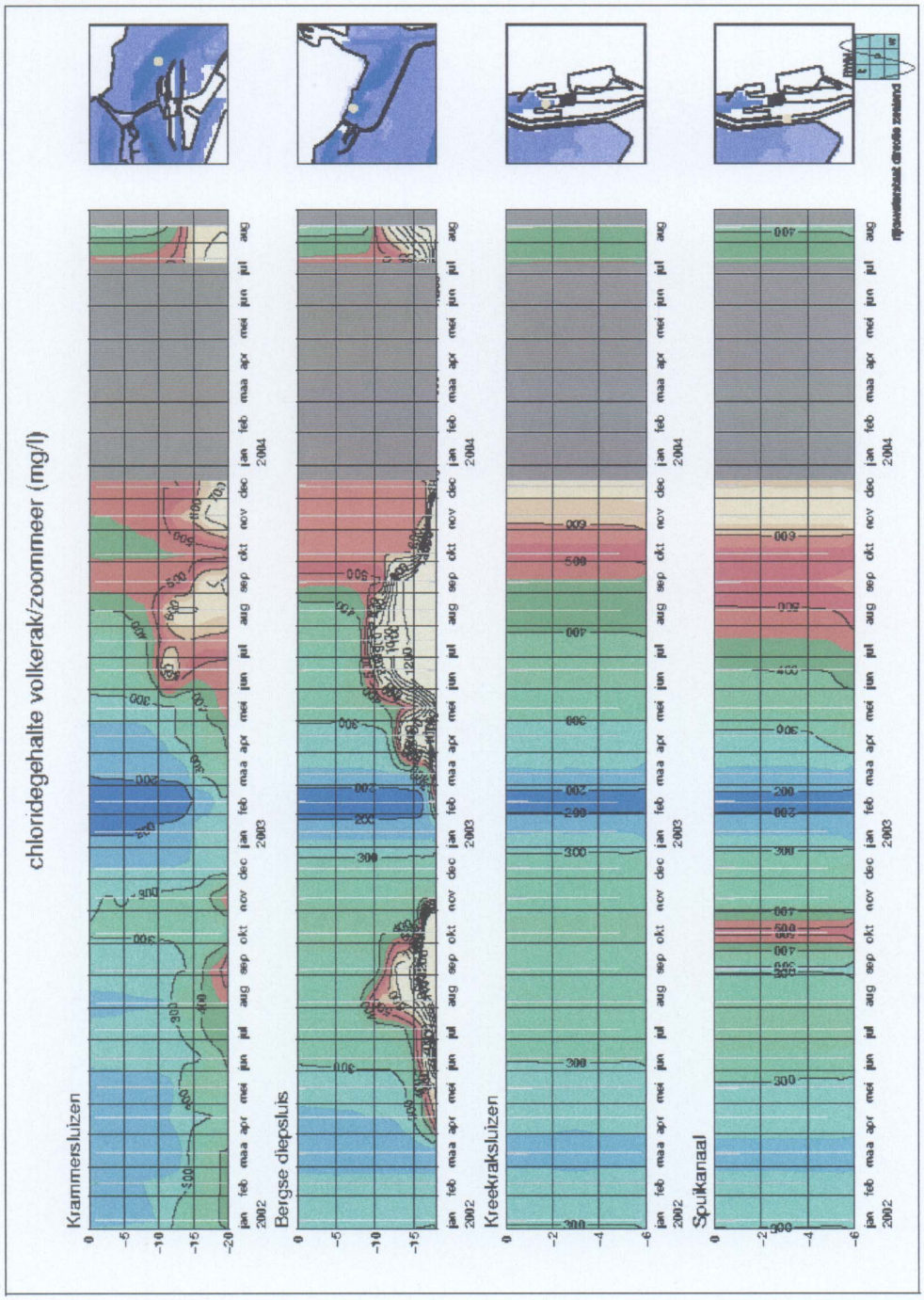
Effectiveness and water loss of mitigation systems Zoommeer locks

After the construction of the locks of the Zoommeer the effectiveness of the mitigation systems of the locks under real operational conditions has been verified. The evaluation was made on the basis of in-situ measurements, and revealed the following findings:

- The mitigation system as applied in the Krammer locks for cargo ships has a high effectiveness. Maximum, a salt water quantity with volume equal to 5% of the lock chamber volume enters the fresh water basin Zoommeer. When no mitigation system had been installed, the quantity of salt water that, on average, would enter Zoommeer each lockage, may be estimated as 60% - 70% of the lock chamber volume. The achieved reduction of the salt load (= effectiveness of mitigation system) is thus better than 90%. The fresh water loss is on average 30% of the lock chamber volume. Fresh water is lost when the water level at the seaside is lower than the level of Zoommeer (when the sea level is higher than the Zoommeer level there is no fresh water loss; instead, salt water is returned to the seaside during leveling down). Fresh water is also lost during the upward exchange process.
- The mitigation system as applied in the small Bergsediep lock has a somewhat lesser effectiveness. Maximum, a salt water quantity of 15% of the lock chamber volume enters Zoommeer; this corresponds to an effectiveness of about 75%.

The mitigation system of the Kreekrak locks in the south, that connects the fresh Zoommeer with the light brackish water of the docks of Antwerp, is not active anymore. Instead, the pumps of the locks are used to bring water from the Zoommeer into the canal; in this way the water at the upstream side of the locks is diluted and the chloride concentration kept below about 0.4 ppt (corresponding to a salt concentration of about 0.75 ppt), which is sufficient to adequately reduce the salt load on Zoommeer. As a result of the adapted strategy, lockage operation times are strongly reduced and long waiting times and delays for shipping are prevented.

In addition to the salt intrusion mitigation systems of the locks the full Zoommeer is regularly flushed; the flushing water enters Zoommeer through the sluice of the Volkerak locks complex in the north and is spilled at Bath in the south. All measures together result in salt concentration values of Zoommeer, which are acceptable for agriculture: the chloride concentration in the growing season April - September is kept below 0.45 ppt (corresponding to a salt concentration of about 0.8 ppt). This is illustrated by next figure that is provided by the Ministry of Transport and Public Works; it shows the results of salt measurements (chloride concentration versus water depth) at four locations in Zoommeer in the period January 2002 – August 2004. Locations: near Krammer locks, near Bergsediep lock, near Kreekrak locks and in separate channel to the sluice of Bath.


chloridegehalte volkerak/zoommeer (mg/l)
Krammersluizen
Bergse diepsluis
Kreekraksluizen
Spijkenaal
jan feb maa apr mei jun jul aug sep okt nov dec jan feb maa apr mei jun jul aug
2002
2003
2004

3.4.4 Expected effectiveness and water loss of mitigation system 6

To achieve a high effectiveness with mitigation system 6 (Figures 2.9a – 2.9f) it is essential that the fresh water and salt water in the lower lock chamber are kept apart in all phases of the lockage process. Any mixing of fresh water and salt water during the downward exchange of water and leveling up reduces the effectiveness. Besides mixing, also the generation of internal waves by sailing ships may be the reason of a reduction of the effectiveness.

Next actions are most critical:

- the downward exchange of water, and
- movement of the ship over the unprotected salt water – fresh water interface.

Experimental data on the downward exchange do not exist for locks with the dimensions of the revised 3-lift Post-Panamax Locks. All experiments in scale models and in-situ measurements are done for less wider and shallower locks. Tests have been executed for ships sailing over an unprotected salt water – fresh water interface, but also with lesser dimensions of lock chamber and ship. To a certain extent the test results can be scaled up and general conclusions drawn.

Conclusions with respect to the downward exchange of water:

- The inflow of water through the openings in the side walls must be controled in such a way that in particular in the initial phase of the downward exchange of water no salt water escapes through the openings to the water saving basins; the inflow of water can be controled by adjustable overflow valves.
- The simultaneous inflow and outflow of water can best be controled so that the downward velocity of the salt water – fresh water interface is typically about 0.01 m/s. The mixing of water increases as the downward velocity is higher. For the lower locks of the Panama Canal a downward velocity of 0.01 m/s means that the exchange of water will take 20 – 25 minutes.
- Due to mixing a sharp salt water – fresh water interface does not occur; both the density and the salt concentration increase gradually going down in the salt water – fresh water interface

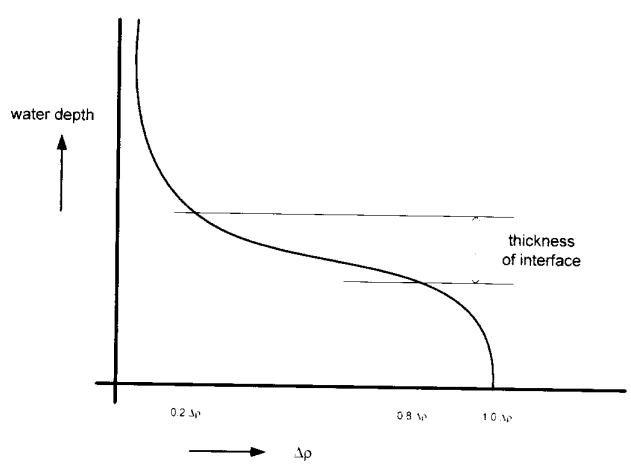


Figure 3.13 Definition of interface thickness

- The thickness of the interface is typically 1 – 3 m (in case of a density difference $\Delta\rho$ of 20 kg/m^3 as in the lower locks of the Panama Canal); see above figure for a definition of the interface thickness.

Conclusions with respect to the movement of the ship:

- The moving ship causes an internal wave in longitudinal direction of the lock, that slowly travels from one side to the other side of the lock chamber and reflects on the closed boundaries; when the salt water – fresh water interface is not far enough below the level of the step in the bottom, the internal wave may overtop the step and enter the adjacent higher lock.

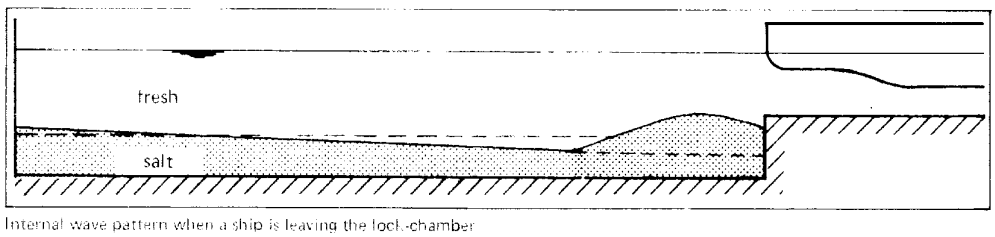


Figure 3.14 Internal wave when ship leaves lock chamber.

- The wave effect is stronger as: (1) the ship is bigger and the draught is greater, (2) the ship's speed is higher, (3) the salt water – fresh water interface is at a smaller distance to the ships keel, and (4) the density difference is greater.
- The effect of the propeller is small compared to the effect of the ship itself (valid for a big ship).
- The sailing direction is of lesser importance for the generation of internal waves: both at uplockage and downlockage internal waves develop with a more or les equal wave height.
- The return current of the ship causes a transport of water in counter direction of the ship. This return current is the reason that additional salt water may enter the adjacent lock. The more the water in the lock chamber is mixed up (the thicker the salt water – fresh water interface) the greater the additional salt water transport.

Tests with big ships sailing at low speed indicate that as a result of the internal wave maximum a salt water quantity of about 5% of the lock chamber volume escapes in the case of a position of the salt water – fresh water interface just below the level of the step. When the salt water – fresh water interface is halfway the step height this quantity of water may drop to maximum 1%. These numbers are valid for a density difference of 20 kg/m^3, as is the case in the lower locks of the Panama Canal.

Now we consider the revised 3-lift Post-Panamax Locks with either 2 wsb's per lift or 3 wsb's per lift, but without water storage basins. The effectiveness of mitigation system 6 is estimated starting from a pessimistic and an optimistic approach:
In the pessimistic approach we assume that the salt water – fresh water interface is drawn about 1.5 m below the level of the step in the bottom. However, the downward exchange process and subsequent leveling up are so badly executed that the water in the lower lock

chamber gets fully mixed up. In that case there is no salt water – fresh water interface anymore and internal waves do not occur.
In the optimistic approach the salt water – fresh water interface is drawn down to a level of about 3.5 m above the bottom, far below the level of the step in the bottom. The salt water – fresh water interface is relatively thin and when a ship sails into or out of the lock chamber an internal wave is generated that causes some escape of salt water to the adjacent middle lock chamber.

The pessimistic approach has been modeled using the spreadsheet as explained in Section 3.1.2. The simulated shipping cycle consisted of a series of 7 uplocking ships, a turn around (uplockage → downlockage), a series of 7 downlocking ships, and a second turn around (downlockage → uplockage). The shipping cycle was repeated until stable salt concentration values in the lock chambers were obtained. A 'standard' Post-Panamax vessel with water displacement of 215000 m^3 was applied. The water levels of the seaside tailbay and the forebay in the lake were kept constant, as well as the salt concentrations. The salt concentration of the tailbay was set to 30 ppt; the salt concentration of the forebay was set to 0 ppt. The optimistic approach could not be modeled in the spreadsheet, since the formulas are only valid for computations based on volume-averaged salt concentrations. Instead we estimated the effectiveness starting from the proven effectiveness of Krammer locks and Bergsediep lock, and taking into account the positive effect of downward exchange of water in comparison to downward and upward exchange of water, the positive effect of a water level of the canal that is always higher than the sea level, and the negative effect of the unprotected salt water – fresh water interface.
Next Figure 3.15 shows the expected effectiveness both for the pessimistic and optimistic approach, for the case that the mitigation system is used at uplockage and downlockage and for the case that it is only used during downlockage.

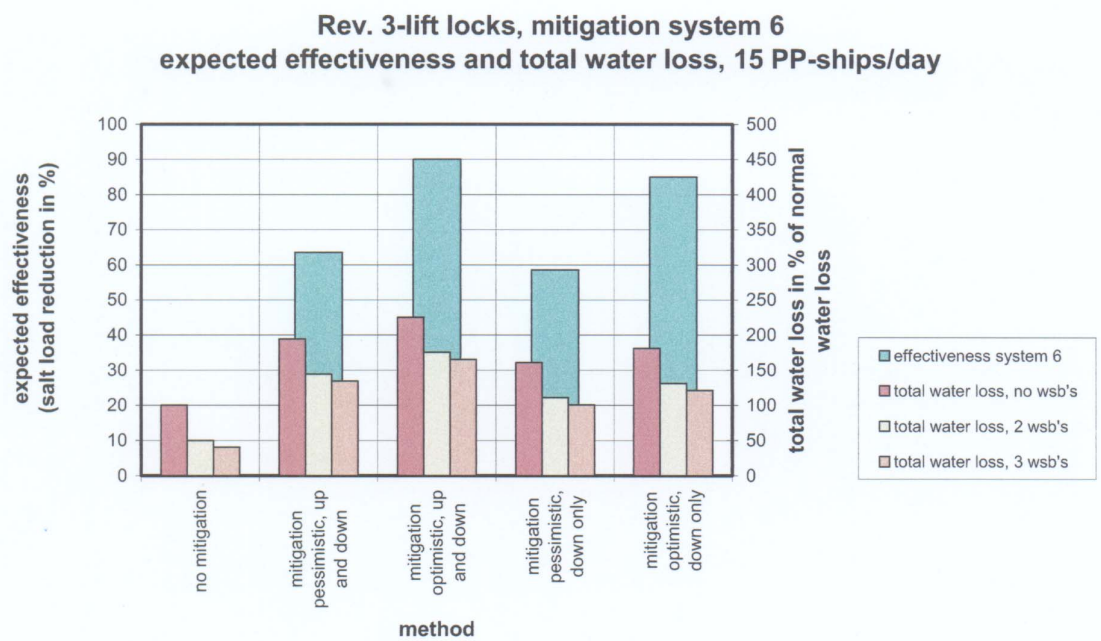


Figure 3.15 Expected effectiveness of mitigation system 6 and total water loss per lockage

We expect that the effectiveness is more or less the same when the water saving basins are applied. However, the salt load will be higher.
The total water loss per lockage (average value of uplockage and downlockage) is also shown in Figure 3.15. This loss is the sum of the lockage loss and the loss caused by the mitigation system.

3.5 Mitigation system 9

3.5.1 Features of the system

Mitigation system 9 is shown in Figure 2.12. The aim of the system 9 is to flush the salt water back that has intruded the forebay of the locks. A salt collecting pit is constructed at the upstream side of the upper locks, which catches the salt water that enters the forebay when the gates of the upper lock are opened. After it has been caught the salt water is slowly discharged into the tailbay through a culvert system with control valves. The salt collecting pit has been provided with a perforated floor and drainage system. The openings in the floor, which are well distributed, enable an equally outflow of salt water. When the drainage of salt water is stopped when the salt water – fresh water interface is just above the floor, the loss of fresh water is for the greater part prevented. A monitoring system that measures the salt concentration at different locations in the pit is therefore required. The drainage of salt water should preferably be completed before the next ship arrives.

The dimensions of the pit should at least be sufficient to collect the salt water that enters the forebay when a ship sails down. This quantity of water depends on the volume of the ship but also on the time that the lock gates are open. The volume of water that has to be stored in the pit can roughly be estimated as 50 – 75% of the volume of the upper lock chamber above the level of the step in the bottom, but some extra storage capacity is strongly advised. In order to prevent a mixing up of the caught salt water with fresh water when a ship sails over the pit, the salt water – fresh water interface in the pit should be kept a few meter (e.g. 3 m) below the bottom level of the forebay. The pit must also be sufficient deep to prevent an overtopping of internal (density) waves at the canal side of the pit. When the pit has horizontal dimensions which are equal to the lock chamber dimensions, the perforated floor of the pit shall therefore preferably be designed at a level that is 15 – 20 m below the bottom level of the forebay. The downward slope from the upper lock to the pit should not be steep in order to avoid high flow velocities of the salt water on the slope. High flow velocities cause a high turbulence level and thus a strong mixing, which should be prevented, since this promotes an escape of salt water to the canal and the drainage of a greater quantity of water from the pit than necessary. The salt pit should at least be drained after each downlockage of a ship, since the salt water load is highest when ships sail down.

The mitigation system does not effect the normal operation of the locks; also the wsb's of the locks can be operated in the normal way. Delays for shipping are not expected. Since the salt water is drained from the pit at a relatively low speed, hindrance for shipping in the tailbay is neither expected.

3.5.2 Case study Terneuzen locks

Mitigation system 9 has similarities with the salt water intrusion mitigation system that is in operation at the Terneuzen locks in the south-western delta area of the Netherlands. The Terneuzen lock complex is situated at the entrance to the canal that connects the city of Gent with the sea arm Westerschelde (see Figure 3.10). In this section we present the results of a case study for the Terneuzen locks.

Description of lock complex and canal area

The canal has a length of about 30 km and is suited to seagoing vessels. The water level is maintained at +2.1 m above mean sea level. The water depth is about 15 m. The canal discharges typically a fresh water quantity of 20 m^3/s throughout the year. The tide on the Westerschelde ranges on average between +2.3 m and -1.9 m.
The lock complex consists of the western lock for seagoing vessels with dimensions 355 m long and 40 m wide, the middle lock with dimensions 184 m long and 24.5 m wide (16 m near lock heads), and the eastern lock with dimensions 280 m long and 24 m wide. Both the western lock and the eastern lock are provided with intermediate gates for lockage of small ships.

Figure 3.16 Lock complex Terneuzen; lock for seagoing vessels at the left of the picture

All locks have been provided with a pneumatic barrier system, which is aimed to mitigate the intrusion of salt water. The air bubble screens are located near the gates at both sides of the lock. Air bubble screens are also provided at the intermediate gate of the western lock for seagoing vessels.
The western lock has an additional mitigation system. This system consists of a deepened pit in the forebay of the lock in which salt water is collected; the salt water is flushed back through a culvert system that is controled by valves. The inlet of this system seen from the pit is shown on Figure 3.17.

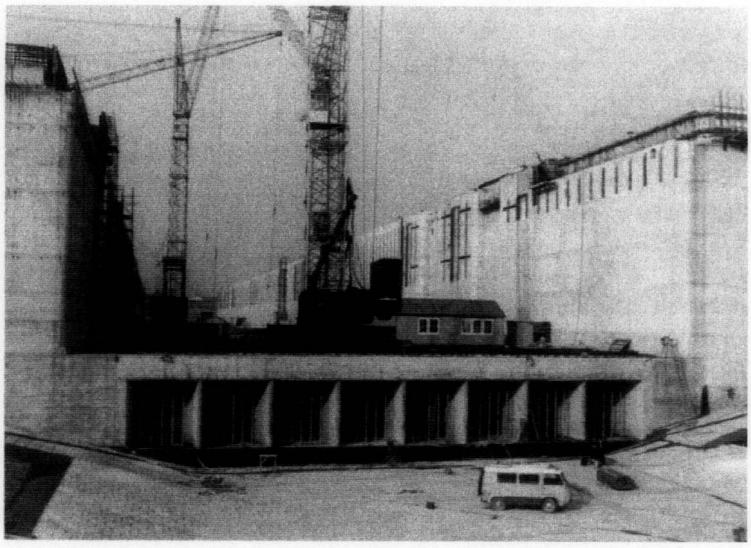


Figure 3.17 Lock complex Terneuzen; inlet of culvert system of lock for seagoing vessels

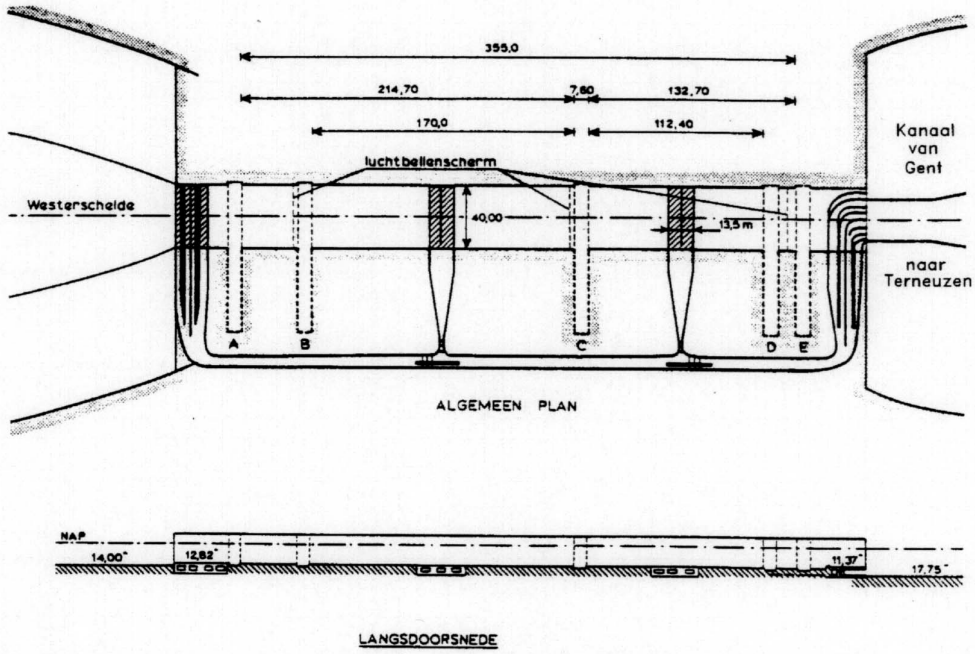


Figure 3.18 Lock complex Terneuzen; plan and longitudinal section of lock for seagoing vessels

Figure 3.19 Lock complex Terneuzen; lock for seagoing vessels: transverse culvert underneath lock chamber with fill openings to chamber

As can be seen in Figure 3.18 the culvert system of the western lock forms an integral part of the lock filling and emptying system. The system is also used to discharge water from the canal, but normally the smaller middle lock is used to sluice the surplus water from the canal and to maintain the water level. Figure 3.19 shows the interior of one of the transverse culverts underneath the chamber of the western lock with fill / empty openings.

Operation of the mitigation systems

The air bubble screens of all locks are activated when the concerned lock gates are opened and switched off as soon as the gates have been closed.
Initially, the additional mitigation system of the western lock (with salt collecting pit) was operated when the gates at the canal side were opened. The valves of the culverts were opened and the salt water that left the lock chamber was withdrawn and immediately discharged to the Westerschelde through the culvert system. The efficiency, however, was not very high since a part of the salt water escaped to the deepened salt collecting pit, while a considerable quantity of fresh water was drawn into the culvert system and discharged together with the salt water. Nowadays the system is operated after passage of a ship, after the lock gates have been closed.

Studies for Terneuzen lock complex

In the pre-design and design stage of the Terneuzen locks, several studies have been undertaken, in particular for the western lock for seagoing vessels. These studies focused on:

- The general lay out of a lock provided with a salt water intrusion mitigation system. Water balance of the canal in relation to the salt load.
- The process of selective withdrawal of salt water immediately after opening of the lock gates at the canal side.
- The process of flushing of salt water from the deepened pit in the forebay.
- The effect of air bubble screens.

- The detailed layout of the inlet of the discharge culverts, the capacity of the culverts, the forces on the valves and pressures in the culverts.
- The stream patterns in the tailbay during flushing
- Rip-rap bed protections.
- Wave forces on the rolling gates of the lock.
- Filling and emptying process and forces on the ship in the lock chamber during uplockage and downlockage.

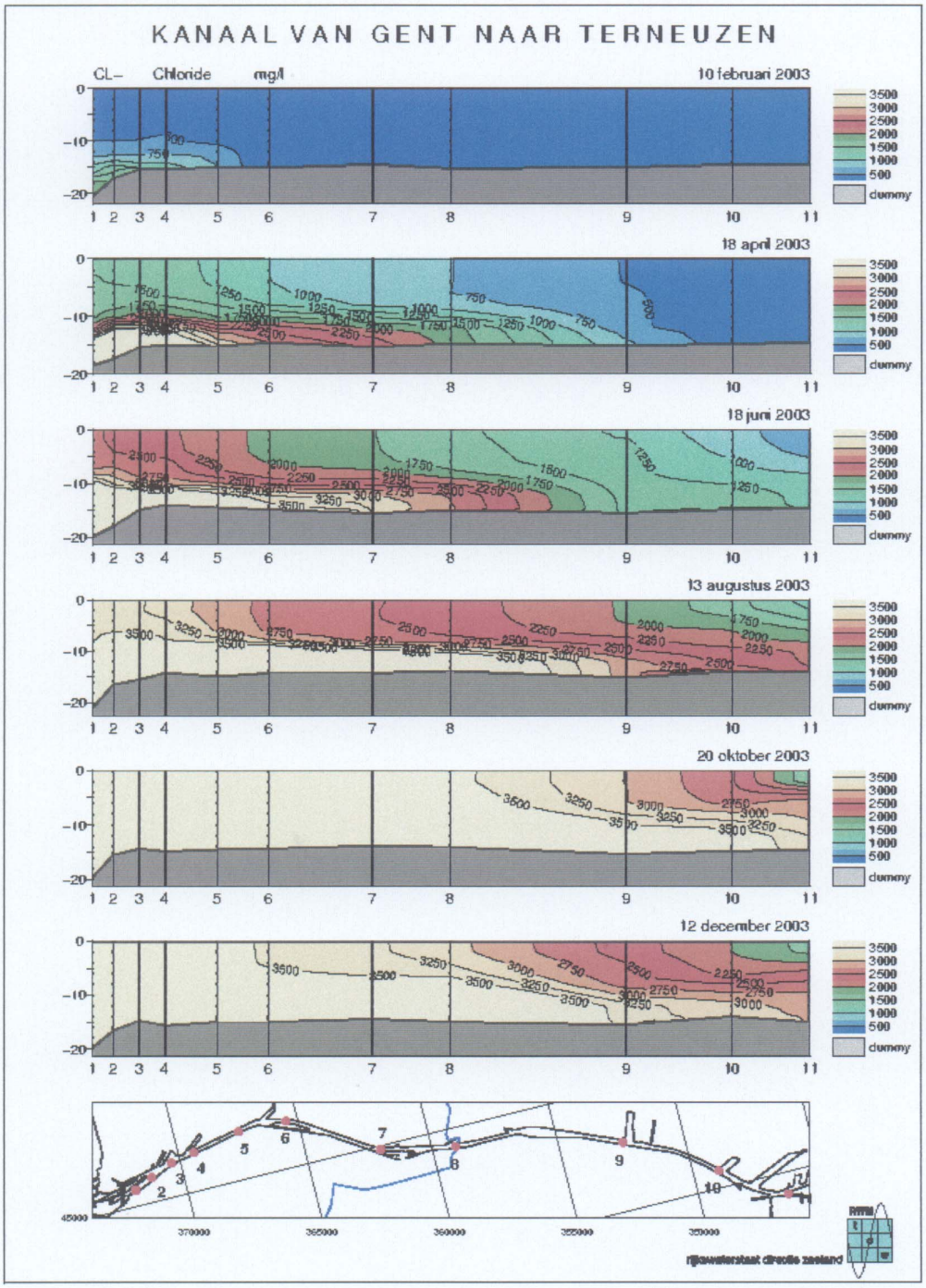
Again, the technical studies were for the greater part executed at WL | Delft Hydraulics and included both desk studies (based on analytical models) and scale model studies on specific aspects and phases of the lockage process. These studies are described in study reports (in Dutch language). A full list of publications and reports has been given in Report E, part II.

Effectiveness of mitigation systems of Terneuzen locks

In-situ measurements have been executed which revealed the following:

- The air bubble screens of the middle lock and eastern lock are able to reduce the salt load of the concerned lock on the canal with 50%. This is however only true when the lock gates are opened shortly before the entry / exit of the ship and closed immediately. In practice the salt load reduction is much smaller; this is caused by the fact that the opening time of the lock gates is greater (because of safety rules, efficient handling of ships etc.). The upper effectiveness limit seems to be 30% in practice.
- The effectiveness of the air bubble screens in the western lock for seagoing vessels is even considerable smaller, which is attributed to the deeper water in the locks (13 m on average) and the long opening time of the lock gates.
- The salt water pit in the forebay of the sea lock is flushed after the lock gates have been closed; selective withdrawal of salt water during entry or exit of the ship is not longer practiced. This adapted operation of the flushing system is the reason that the volume of the salt water pit, with a depth of about 5 m below the canal bottom, is too small. As a result salt water escapes to the canal. Sailing ships cause internal waves in the pit; this phenomenon contributes to the escape of salt water. In addition, the outlet of the pit to the flushing culverts is not optimally designed for flushing operations: together with the salt water quite a lot of fresh water is drawn. Finally, the salt pit has been silted up, which is the reason that the effective volume of the pit has been reduced.

The intrusion of salt water caused by all three locks of the Terneuzen lock complex is combated by flushing the entire canal. Flushing is, however, only possible when sufficient fresh water is available. In dry periods the quantity of water that can be used for flushing, is rather small, and the salt water advances over a distance of 25 km from the locks (chloride concentration 2 – 3 ppt). In wet periods when an ample quantity of water is available for flushing, the salt water tongue is forced back to a distance of 5 km from the locks (chloride concentration 0.4 ppt).
The penetration of salt water in the Canal Gent-Terneuzen is illustrated by next figure that is provided by the Ministry of Public Works; it shows the results of salt measurements (chloride concentration versus water depth) at eleven locations along the canal at different moments of time during the year 2003.


KANAAL VAN GENT NAAR TERNEUZEN
CL– Chloride mg/l
10 februari 2003
18 april 2003
18 juni 2003
13 augustus 2003
20 oktober 2003
12 december 2003
3500
3000
2500
2000
1500
1000
500
dummy
rijkswaterstaat directie zeeland

3.5.3 Expected effectiveness and water loss of mitigation system 9

We can learn from the experiences with the salt water pit and flushing system of the sea lock Terneuzen that (i) the volume of the pit must be sufficient to catch all the salt water that enters the forebay, (ii) that the salt water – fresh water interface in the pit must remain amply below the bottom of the forebay, and (iii) that the salt water has to be evacuated from the pit at a low speed and well distributed over the area of the pit. All these requirements can be fulfilled when a sufficient deep pit is constructed, that is provided with a perforated floor with drainage system underneath, as in mitigation system 9. With the perforated floor the drainage of salt water is similar as in the existing locks. Measurements have shown that mainly the water near the bottom is withdrawn when the water level in the locks is lowered; this occurs without disturbing the upper layer with a lesser salt concentration.

An escape of salt water from the salt pit to the canal may take place as a result of mixing of salt water and fresh water and because of internal-wave overtopping; these phenomena adversely affects the effectiveness of the mitigation system. Mixing occurs when salt water flows into the salt water pit (the steeper the slope, the higher the turbulence) and when a ship passes the pit (propeller action). Internal waves occur when salt water flows into the salt pit and when a ship moves over the salt pit. Internal-wave overtopping at the canal side of the pit is likely when the pit is not sufficiently deep.
Though experimental studies have been executed in the past (see case studies for Krammer Locks and Terneuzen Locks in this chapter), experimental data on the escape of salt water to the canal for the specific layout of mitigation system 9 is not available. However, preliminary computations with our Delft3D program show that the escape of salt water to the canal may be limited when the salt water pit has an optimal layout and sufficient depth. In that case a high effectiveness up to 90% is possible, provided that the drainage operation is executed well. As a lower limit value we expect an effectiveness of 60%.

The drainage of salt water from the salt pit can not immediately start after the lock gates have been closed. The salt water that flows from the upper lock into the salt pit propagates at a relatively low speed (0.1 – 0.3 m/s) and it takes time before the salt water has covered the full floor of the salt pit and has come at rest. It is therefore required that the drainage process is carefully programmed. A salt concentration monitoring system with sensors at different locations along the longitudinal axis of the salt pit will be highly useful to plan the drainage actions and to minimize the loss of water.

It is difficult to estimate the extra loss of water caused by the mitigation system, because this loss is dependent of sailing direction, ship size, time that lock gates are open, density difference, and the operation of the salt pit. When the salt pit system is selected as mitigation system for the Post-Panamax Locks, a thorough study has to be undertaken into the extra losses of water in relation to the effectiveness of the system; this study will also focus on the optimal layout of the salt pit and on the most efficient drainage procedures.
For the time being we assume that the loss at downlockage will be of the order of magnitude of 100% - 150 % of the 'normal' water loss; the extra loss at uplockage will be smaller, of the order of magnitude of 25% - 75 % (conservative assumptions).

Next Figure 3.20 reflects the above expectations.

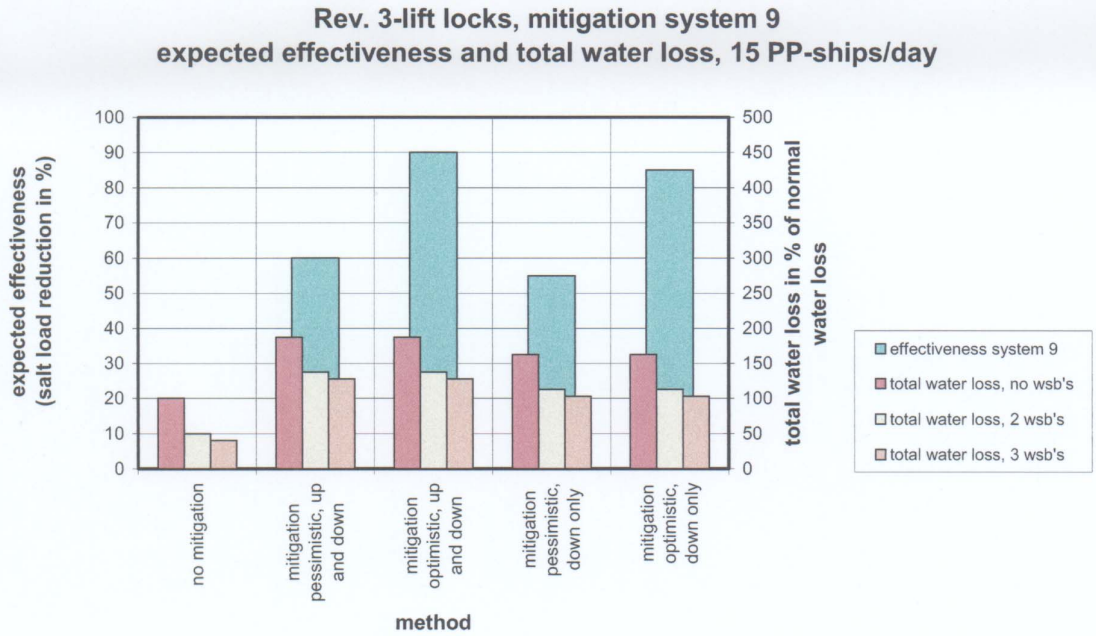


Figure 3.20 Expected effectiveness of mitigation system 9 and total water loss per lockage

When the mitigation system is only applied at downlockage (this will probably not strongly affect the effectiveness), the extra water loss can be reduced to 50% - 75% of the 'normal' water loss (average value for uplockage and downlockage).

The salt water pit at the upstream side of the locks may act as a sand and silt trap. This is especially true when no wsb's are applied, since the average flow velocity towards the lock may then be 0.2 – 0.3 m/s during the time that the upper lock chamber is leveled up. A regular inspection and maintenance of the pit may therefore be required. Alternatively, the intakes of the upper lock chamber may be located at the upstream side of the salt water pit.

3.6 Mitigation system 10

3.6.1 Features of the system

Mitigation system 10 is shown in Figure 2.13. The air bubble screen forms a pneumatic barrier when in operation. The barrier is located near the seaward gates of the lower lock; alternatively a second barrier may be provided near the lake ward gates of the upper lock.

Pneumatic barriers delay and reduce the exchange of salt water and fresh water at the entrance to the lower lock chamber (or at the exit of the upper lock chamber). Eventually, they can not prevent the exchange of water related to density differences and are therefore most effective in combination with short open times of the lock gates. The effectiveness is also strongly dependent on the quantity of air that is blown into the water. The greater the density difference $\Delta\rho$ between lock chamber and tailbay (or forebay) and the larger the water depth, the more air is required to form an effective air bubble screen.

The air bubble screen can not prevent the ship-bound water exchange: the bigger the ship the less effective the air bubble screen. For a full description of pneumatic barriers reference is made to Report E, part II.
The system requires the construction of a perforated pipe across the full width of the lock. The air is supplied through a compressor, which has a sufficient capacity to provide the required air discharge at an overpressure corresponding to the local water depth.

3.6.2 Expected effectiveness and water loss of mitigation system 10

In-situ measurements show that pneumatic barriers have an overall effectiveness that is seldom better than 30%. This conclusion is based on measurements at the Terneuzen lock complex, see Section 3.52, and measurements at the IJmuiden lock complex, see Report E, part II, Appendix A. The main reasons are the exchange of ship bound water and the long opening times of locks for seagoing vessels.

The effectiveness of a pneumatic barrier can be assessed with the help of next Figure 3.21. This figure presents the exchange rate (the ratio of the intruded salt water volume and the total water volume of the lock chamber) as a function of the dimensionless time factor T. The figure is valid for the situation without a ship. Theoretically, when no pneumatic barrier is active, the water of the lock chamber is fully exchanged with salt water of the tailbay after a period T = 1 (dashed line in Figure 3.21). In practice a longer time is required, while also some fresh water will remain in the lock chamber. The other lines shown in Figure 3.21 are based on in-situ measurements at the IJmuiden lock complex and the locks at Kornwerderzand (Lake IJsselmeer, in northern area of Netherlands). The quantity q_l is the air discharge of the pneumatic barrier with a pressure equal to the water pressure at the insertion level (at the bottom of the lock). The quantity q_{lo} represents the theoretical air discharge, which is required to prevent any exchange of salt and fresh water across the air bubble screen.

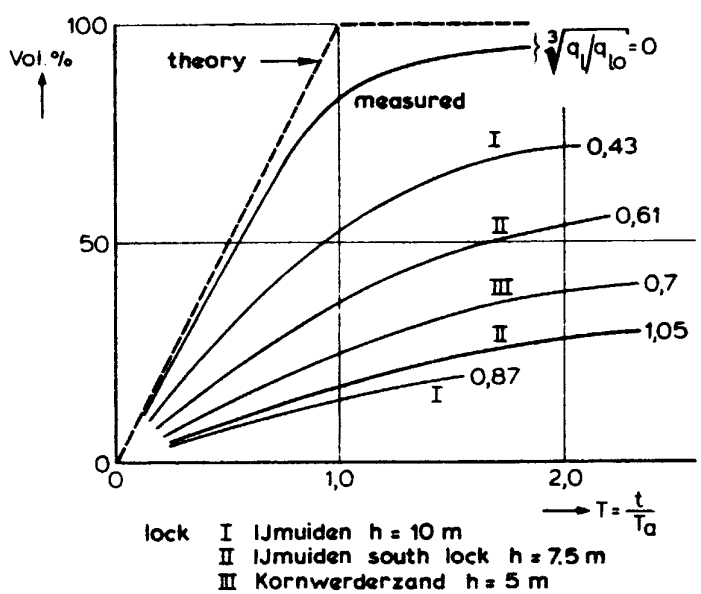


Figure 3.21 Exchange rate (in % volume of lock chamber) versus time factor T

As can be read, the exchange rate is in practice always higher than about 30% when the gates are kept open for a sufficient long time, also when $q_l/q_{lo} > 1$. The latter result proofs that a zero exchange rate (corresponding to a high effectiveness) is not possible under realistic conditions.

The effectiveness of a pneumatic barrier, that is constructed at the seaside of the lower lock of the revised 3-lift Post-Panamax Locks is now considered. In an optimistic approach one may assume that the pneumatic barrier is optimally designed and functions well under the prevailing hydraulic conditions at the Panama Canal. When a sufficient air discharge is supplied one may then assume that the exchange rate is only 10%. In a pessimistic approach one may assume that the pneumatic barrier does not function well, resulting in an exchange rate of say 40%.
Starting from these assumptions the effectiveness of mitigation system 10 has been assessed on the basis of a spreadsheet computation, similar as for mitigation system 1. The reducing effect of the pneumatic barrier has been modeled in the spreadsheet, and the model was run for the uplockage – downlockage cycle on a single day, consisting of a series of 7 uplocking ships, a turn around (uplockage → downlockage), a series of 7 downlocking ships, and a second turn around (downlockage → uplockage). The shipping cycle was repeated until stable salt concentration values in the lock chambers were obtained. A 'standard' Post-Panamax vessel with water displacement of 215000 m^3 was applied. The hydraulic boundary conditions were the same as in the computation for mitigation system 1.

Next Figure 3.22 shows the expected effectiveness both for the pessimistic and optimistic approach, for the case that the pneumatic barrier is used at uplockage and downlockage and for the case that it is only used during downlockage.

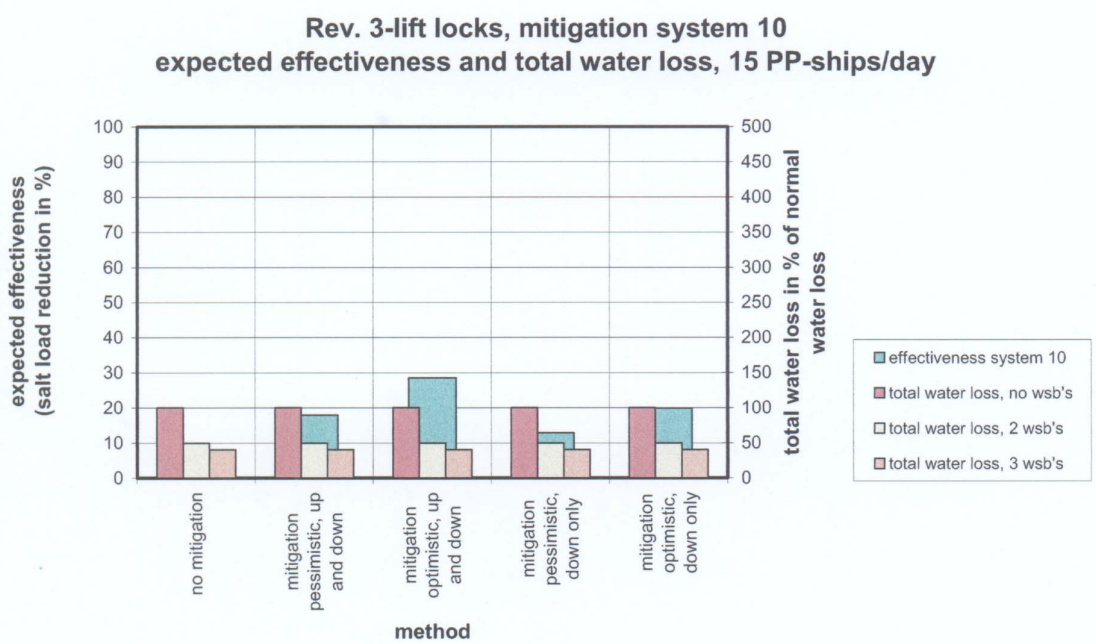


Figure 3.22 Expected effectiveness of mitigation system 10 and total water loss per lockage

For an optimal effectiveness the theoretical air discharge q_a follows from (see Report E, part II, Appendix A):

$$Q = \frac{(q_a g)^{1/3}}{\sqrt{\frac{\Delta\rho}{\rho} gh}} = 1.6$$

where q_a = air discharge per m width at atmospheric pressure.
When we select ρ = 1007 kg/m^3, $\Delta\rho$ = 11 kg/m^3 (corresponding to a salinity of 30 ppt in the tailbay and a salinity of 15 ppt in the lock chamber, 30°C) and h = 20 m for a pneumatic barrier that is installed in the tailbay at the entrance to the lower lock chamber, we find: q_a = 1.3 m^3/s per m' width. With a total width of 54 m the pneumatic barrier requires thus an air discharge of about 70 m^3/s at atmospheric pressure. The required air discharge of a pneumatic barrier in the forebay may be a factor 2 smaller, since the density difference $\Delta\rho$ is smaller.
The air discharge of 70 m^3/s means the following. When we roughly assume that the air bubbles rise with a velocity of 1 m/s and spread over a width of 10 m near the water surface, the quantity of air in the air-water mixture is about 0.13 m^3 per m^3 of mixture. As a result the density of the mixture drops locally from a value of about 1020 kg/m^3 to a value of 890 kg/m^3. Post-Panamax vessels will not experience much hindrance when they pass the pneumatic barrier, but small yachts sink deeper in the water and may become uncontrolable. Air may also enter the engine cooling systems and vessel toilets.

Pneumatic barriers have not yet been applied in waters with a depth of 17 - 22 m as near the Post-Panamax Locks (the maximum water depth at locations where a pneumatic barrier has been installed in the Netherlands is about 15 m). Before the pneumatic barriers are applied in deeper water a further examination is needed into the functioning of the barriers.

3.7 Desalination of intruded salt water

3.7.1 Desalination practice

Desalination is practiced in arid areas where a shortage of fresh water occurs, but where brackish water or seawater is available. The desalination plant separates the dissolved salts and other minerals from the salt feedwater and produces fresh water that is suited for consumption, agriculture and industry. The waste water, called brine, contains a high quantity of salts and may cause local environmental problems when not properly discharged into the sea. Since the desalination process consumes energy, sufficient sources of thermal, electrical or mechanical energy are required. For efficiency reasons desalination plants are sometimes combined with electrical power plants.

The total fresh water production capacity of desalination plants worldwide amounts to 26x10^6 m^3 per day (in 2000), distributed among more than 120 countries. The largest producer is Saudi Arabia with a capacity of 5.4x10^6 m^3/day; the largest plant is also located in Saudi Arabia with a capacity of 0.48x10^6 m^3/day (in American units: 128 MGD (million

gallons per day)). Second producer is the Unites States with a production capacity of 4.3×10^6 m^3/day (in 2000).
Several desalination techniques have been developed; distillation techniques (multi-stage flash, multiple effect evaporation, vapor compression techniques) and membrane techniques (reverse osmosis, electro-dialysis) are most common. For a description of desalination technologies and for background information reference is made to the next reports, all of them presenting a broad analysis of the feasibility and applicability of desalination systems in specific regions or countries. The reports can be downloaded from internet:

URS Australia (2002)
'Economic and technical assessment of desalination technologies in Australia: with particular reference to national action plan priority regions'
Detailed report, 17 July 2002

Economic and Social Commission for Western Asia (ESCWA), United Nations (2001)
'Water desalination technologies in the ESCWA member countries'
United Nations Report, 27 July 2001

California Coastal Commission (1993)
'Seawater desalination in California'
Report, October 1993

The data and facts mentioned in next section come from the above reports.

3.7.2 Desalination option for locks on the Panama Canal

When desalination of the intruded salt water of the 3-lift Post-Panamax Locks is considered as an option for the Panama Canal, the feedwater for the desalination plant can best be withdrawn from a deep pit at the upstream side of the locks. In that case the withdrawal of salt water can occur without disturbing or delaying shipping, while the salt water caught in the pit has only a low salinity (up to maximum 10 ppt). The latter may allow for a desalination process that is less extended than the desalination process for pure seawater that has a salt concentration of over 30 ppt. A desalination plant should be provided both at the Pacific and the Atlantic side of the canal.

Next figure presents a schematic design of a desalination plant that is combined with a pit with perforated floor at the upstream side of the locks (compare with mitigation system 9). Apart from the desalination plant, the main elements in the design are: the pit with perforated floor, a culvert system for the transport of salt feedwater to the desalination plant, a pump system, a return culvert with valves to discharge the brine into the sea, a return system with valves to discharge the produced fresh water into the lake, and a power line to an electrical power plant.

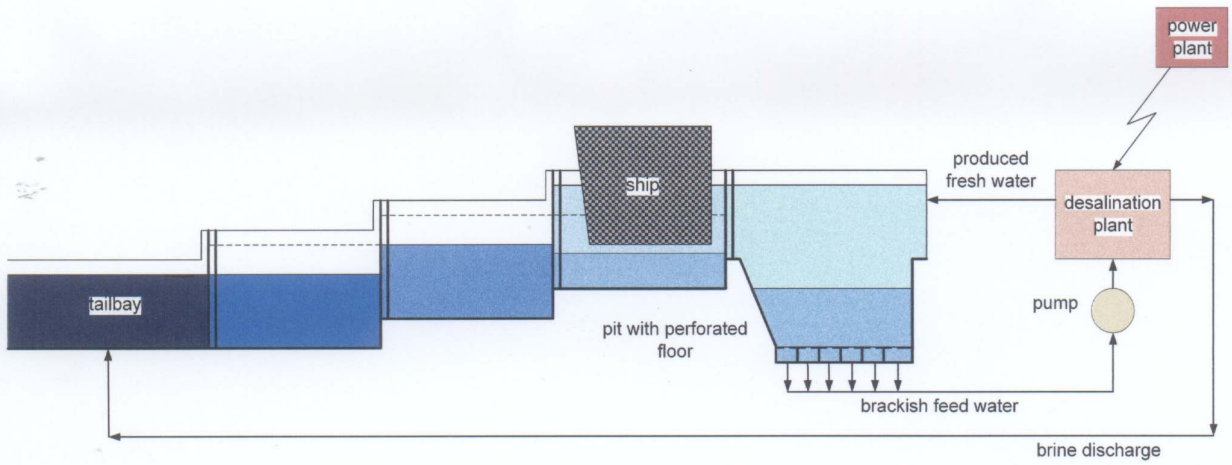


Figure 3.23 Desalination plant in combination with a pit with perforated floor

When we assume a ship traffic intensity of 15 Post-Panamax vessels a day, the total quantity of brackish water caught in the pit and transported to the desalination plant equals 15 times the quantity of water that is caught after a single ship passage. The latter quantity may roughly be estimated as 100% – 150% of the 'normal' lockage loss. The normal loss corresponds to 0.23×10^6 m^3 for the revised 3-lift locks (see introduction of Chapter 3). When we assume that water from the pit is only pumped to the desalination plant during down-lockage of ships, the raw water capacity of the desalination plant at either side of the canal should be 2×10^6 m^3/day. This is much greater than the capacity of the largest plant in Saudi Arabia.

A great number of variables influence the choice of technology of the desalination plant, for example:

- The type and source of energy
- The quantity and quality of the feedwater
- The method of disposing the saline waste water

The implications of these design variables should be considered in an early stage of plant design.

The effectiveness of desalination plants is high: the salt concentration of the product water is generally less than 0.1 ppt when brackish water is used as feed water (fresh water limit: 0.4 – 0.5 ppt). The effectiveness of a mitigation system consisting of a salt collection pit and a desalination plant is thus mainly depending on the effectiveness of the pit. Since fresh product water is returned in the lake the overall effectiveness of the desalination option will be better than the effectiveness of mitigation system 9 (see Figure 3.20).

Depending on the desalination technology used the quantity of product water of seawater plants is only 15% - 50% of the feedwater quantity; when brackish water is used as feed water the produce is higher, 50% to 90%. For the Panama Canal the latter number may implicate that the extra water loss caused by desalination of the intruded salt water is between 10% - 75% (40% on average) of the 'normal' water loss for each downlocking ship (assuming that the desalination plant in only active in the downlockage phase). The total

loss (lockage loss and loss caused by mitigation system) is thus 140 % at downlockage and 100% at uplockage (120% on average).

The energy use of desalination plants is high. The energy consumption depends on technology used, the temperature and salinity of the feed water, and the quality of the product water. Energy consumption ranges between 2 – 12 kWh per m^3 of product water.

The cost of installing $1m^3$/day of desalination capacity lies roughly between US$ 500.- and US$ 2500.-, depending on plant size, feed water quality and existing infrastructure. The construction costs of plants which treat brackish water are generally lower than the seawater plants. Taking US$ 1000.- per m^3/day as average low unit cost, the capital investment for realization of a single desalination plant with related infrastructure at one side of the Panama Canal would be US$ 2 $x10^9$.
Operating cost range between 0.5 and 2 US$ per m^3 of product water; the cost depend in particular on plant size, capital amortization and energy cost.

3.8 Comparison of mitigation systems and recommendations

3.8.1 Comparison of mitigation systems

The salt intrusion mitigation systems which have been discussed in the previous sections, will be compared on the next items:

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

The effectiveness is defined as the reduction of the salt load on Gatun Lake compared to the situation that no mitigation is applied. The effectiveness of most of the considered mitigation systems is related to the extra quantity of water that is lost by the operation of the mitigation system. Generally one can put: the higher the effectiveness the greater the extra water loss. In this analysis we mutually compare the high effectiveness values and consequently also the high water loss values.

Water losses are presented as the total water loss per lockage operation (sum of lockage loss and extra loss caused by the mitigation system). Since operation of the mitigation system during uplockage of ships contributes only little to the overall effectiveness, a considerable quantity of water can be saved when the mitigation system is only used during downlockage of ships. We therefore present the overall effectiveness and the total water loss for the situation that the mitigation system is merely active during downlockage of ships. The presented total water loss per lockage is the average value for an uplockage and a downlockage operation, and does not include the effect of wsb's. The total loss is expressed as a percentage of the 'normal' water loss. The 'normal' water loss is defined as the product of Δh, see Figure 3.2, and the area of the lock chamber (including two gate recesses). The quantity

Δh is about 1/3 of the water level difference between Gatun Lake and the oceans, the latter being 25.7 m on average.

The effectiveness of the mitigation systems is defined for the case that no water saving basins are applied. We expect however, that the use of wsb's does not have an important effect on the effectiveness of the considered mitigation systems. It should be noted that the salt load is higher when wsb's are applied; consequently the salt load is also higher when both the wsb's and the mitigation system are in operation.

The cost of the mitigation systems are expressed in the form of an amplifier, that has to be applied to the construction cost of the locks. It is emphasized that the presented costs have to be considered as a rough cost estimate.
We have used data provided by the Ministry of Transport and Public Works of the Netherlands to estimate the cost for mitigation systems 6 (similarity with Krammer locks, Bergsediep lock), 9 (similarity with Terneuzen locks) and 10 (similarity with pneumatic barriers of Terneuzen locks, IJmuiden locks). Next amplification factors (ratio of cost of lock with mitigation system and cost of lock without mitigation system) have been provided by the Ministry of Public Works:

Name of lock / similarity with system	*Amplification factor*
Krammer locks for cargo boats / system 6	2.5
Bergsediep lock / system 6	1.3
Terneuzen western lock / system 9	1.3
Terneuzen western lock / IJmuiden lock / system 10	1.02

Table 3.1 Cost amplification factor of mitigation systems in Netherlands

Mitigation 6 is applied in the lower lock of the revised 3-lift Post-Panamax Locks, and requires the construction of gated culverts from the forebay to the lower lock. The amplification factor of Krammer locks is valid for a system with perforated floor, water reservoirs and pump house. These elements are not needed in mitigation system 6. Considering also the lower cost of the simpler mitigation system of the Bergsediep lock a smaller amplification factor of 2.2 is selected for mitigation 6. As base cost we take 40% (one lock) of the total cost of the 3-lift locks. This results for the revised 3-lift locks with mitigation system 6 in a total cost of 2.2 x 40% + 60% = 148% (amplifier 1.48).

Mitigation system 9 comprises the construction of a deep pit with perforated floor, a drainage system and gated culverts to the tailbay. Especially the cost of rock excavation may be high. The pit of the Terneuzen lock is shallower and could simply be excavated and constructed in a dry building pit. The culvert system of Terneuzen may be comparable with the culverts of mitigation system 9. In view of the high excavation cost we select an amplification factor 2.0 for mitigation system 9. As base cost we take 40% (one lock) of the total cost of the 3-lift locks. Application of the amplification factor results in a total cost of 2.0 x 40% + 60% = 140% (amplifier 1.40).

The cost of the pneumatic barrier, mitigation system 10, is relatively small. As amplifier we select a value of 1.02, similar as the amplification factor of the Terneuzen western lock / IJmuiden lock.

Mitigation system 1 (dummy lockages) can be realized without extra cost (amplifier 1.0). Mitigation system 2 requires the construction of gated culverts between the middle lock and the tailbay. Since the culverts have to be excavated from rock the cost may be relatively high. As amplifier we therefore select a value of 1.05.
Mitigation system 4 requires the construction of gated culverts between upper lock and lower lock and gated culverts between upper lock and tailbay. We select a cost amplifier of 1.10 for this system.
The construction cost of a desalination plant is extremely high compared to the cost of the afore discussed alternative mitigation systems. ACP may determine the cost amplifier comparing the cost presented in Section 3.7.2 and the construction cost of the revised 3-lift locks.

3.8.2 Comparison of systems

The characteristic features of the considered mitigation systems are shown in Table 3.2. The values presented in this table are valid for the case that the mitigation system is put in operation after downlockage of each ship, but is switched off at uplockage of ships. The expected upper effectiveness limits are shown and the corresponding water losses.
The comparison of systems reveals the following (see also Table 3.2):

System 1, *stepwise flushing of all lock chambers (dummy lockage)*, is the cheapest system (no extra cost), has a good effectiveness that corresponds to a moderate extra water loss. A delay for shipping is expected in the case of a relay mode of operation.
System 2, *flushing of middle lock and upper lock*, has a higher effectiveness at a similar water loss. A delay for shipping is expected in the case of a relay mode of operation. Attention is required for the closure of valves in culverts with flowing water. Some extra construction costs have to be made.
System 4, *enhanced flushing of upper and lower lock chamber*, is the most effective system, but the extra water loss is highest. A delay for shipping is expected in the case of a relay mode of operation. In view of the negative head across gates, rolling gates are required that close off at two sides. Attention is also required for the closure of valves in culverts with flowing water. Extra construction costs are to be made.
System 6, *exchange of salt water with fresh water in lower lock chamber*, is a very complex system that has carefully to be operated (delay for shipping is unavoidable). The effectiveness is high but this is achieved at the cost of a relatively high extra water loss. This water loss can be prevented when water storage basins are applied, though this will reduce the effectiveness to some extent. Transverse forces may occur on the ship in the lower lock chamber. It is the most expensive system.
System 9, *catch salt water in a deep pit and drain the salt water away to the tailbay*, has a high effectiveness at a moderate extra water loss. The drainage of salt water does not cause delays for shipping nor hindrance. Since the salt water in the pit is not immediately at rest after inflow, a salt concentration monitoring system may be needed to optimize the drainage programme. A regular monitoring may also be required in view of siltation of the pit. The construction of the deep pit with drainage system is expensive.
System 10, *pneumatic barrier*, has a low effectiveness, but causes no extra water losses. It can only successfully be applied when the lock gates to tailbay and forebay are shortly opened. The system is cheap, but the cost of operation (power for operation of air compressors) may be high.

The option of *desalination of intruded salt water* has a high effectiveness at a relatively small extra water loss. The construction cost and the cost of operation are extremely high, when compared to the other systems.

Aspect	*System 1*	*System 2*	*System 4*	*System 6*	*System 9*	*System 10*	*Desali-nation*
upper limit of effectiveness (% reduction of salt load)	72	86	94	85	85	20	90
corresponding total water loss, wsb's not in operation (as % of normal water loss)	150	150	200	180	162	100	120
delay for shipping	yes, in case of relay mode	yes, in case of relay mode	yes, in case of relay mode	yes	no	no	no
hindrance for shipping	little	little	little	possibly transverse forces on ship	no	little for small yachts	no
complexity of system / ease of operation / points of attention	simple	not complex; closure of valves in flowing water	not complex; neg. head of gates; closure of valves	complex system; careful operation	not complex; possibly siltation of pit	simple	not complex
cost amplifier	1.00	1.05	1.10	1.48	1.40	1.02 cost of operation!	> 10 ?? also high energy cost!

Note: mitigation system is operated after each downlockage of a ship

Table 3.2 Comparison of mitigation systems

Because of the high cost the option of desalination of salt water seems not a feasible option for the Panama Canal. System 6 is not recommended because of the complexity of the system and the high construction cost. Despite of the high effectiveness of system 4, this system is not attractive because of the high loss of water. The effectiveness of system 10 is possibly too small, but may be applied to sustain the effectiveness of other systems (the system is relatively cheap and causes no extra water loss).

After a careful consideration at the meeting with ACP of 12 October 2004, mitigation systems 1, 2, 9 and 10 have been selected for a further modeling and analysis using the simulation model SWINLOCKS.

4 Extension of simulation model SWINLOCKS

4.1 Existing simulation model SWINLOCKS

The numerical salt water intrusion simulation model SWINLOCKS (developed by WL | Delft Hydraulics under ACP-contracts No SAA-74337 and No SAA-110830) will be used to study the effectiveness of the four mitigation systems, which have been selected at the meeting of 12 October 2004 (see previous Chapter 3). For a full description of the existing model reference is made to Reports A – D.

In short, the simulation model consists of a number of separate basins, which represent the various lock chambers, forebays and tailbays, and lakes of the Panama Canal system, each basin having a certain water level, water volume and salt concentration, and being mutually connected (see scheme, Figure 4.1, for the future situation with three-lift Post-Panamax Locks). When a ship sails from ocean to ocean it passes the various basins, causing a net transport of water from lakes to oceans and a migration of salt water from basin to basin.

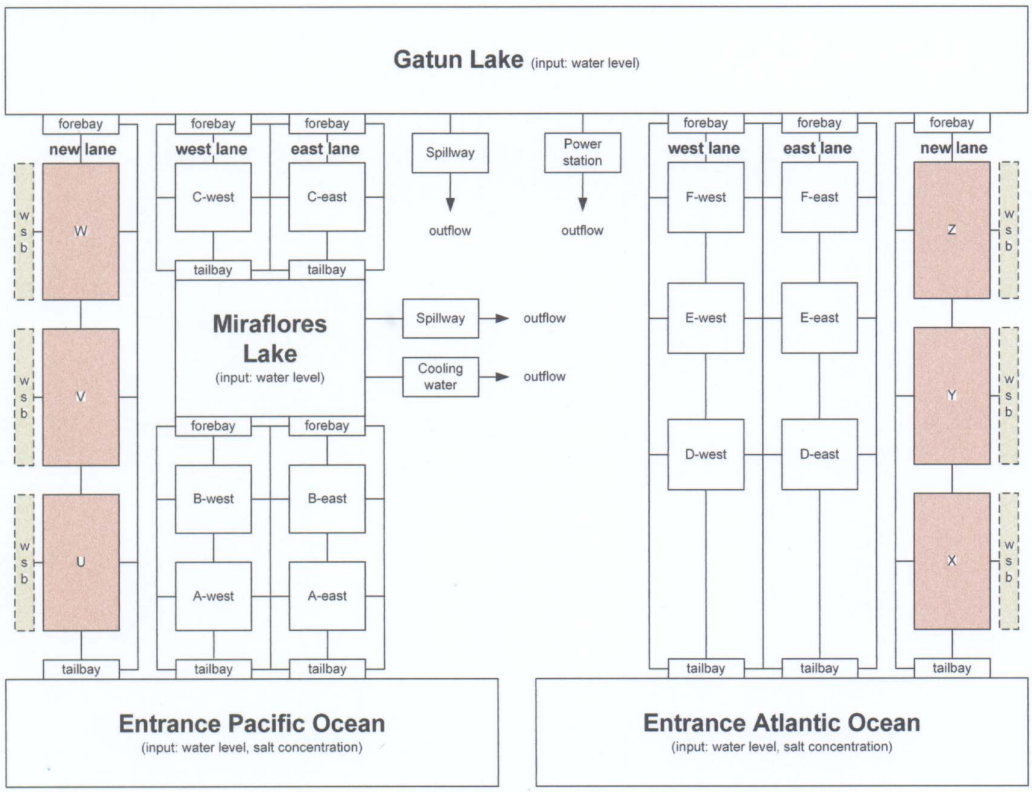


Figure 4.1 SWINLOCKS: configuration with revised 3-lift Post-Panamax Locks and wsb's

Water from Gatun Lake and Miraflores Lake goes stepwise down during uplockage and downlockage of ships, mixing up with the water in the lower locks during filling. When

water saving basins are in use water from the lock chamber is temporarily stored during leveling down, together with a part of the salt content of the lock chamber, and returned into the lock chamber during leveling up. When lock gates are open and a ship moves in or out, the ship's volume is exchanged and density flows occur between basins with different densities. The simulation model SWINLOCKS computes the transport of water and the migration of salt between the various basins in a schematized way, using the water volume and the volume-averaged salt concentration of the basins as base variables. In a water balance and salt balance analysis changes are evaluated after each step of an uplockage or downlockage process.

A forebay functions as a temporarily buffer for salt water between locks and lakes in the simulation model SWINLOCKS. Without a forebay the salt water from the locks would in the simulation model instantaneously be distributed over the full lake volume, since volume-averaged salt concentrations are computed. A time-dependent function regulates the inflow / outflow of salt water from forebay into / from the lake. In this way the intruded salt water remains for some time in the neighbourhood of the locks and enables the flow back of salt water in the phase that water is withdrawn from the forebay to level up the adjacent lock chamber or in the phase that the ship enters of leaves the lock chamber.

A forebay is in open connection with the lake; consequently, the water volume of the forebay varies with the water level of the lake. Because of the open connection the water volume of the forebay is not affected in the simulation model by the passage of a ship or the withdrawal of water in the water-leveling step (contrary to the water volume of a lock chamber). Water that is withdrawn from the forebay is immediately replenished with water from the lake.
When a ship moves from lock to lake it causes a flow from forebay to lock and subsequently from lake to forebay. The salt concentration is effected by these water movements and is computed in the salt balance. The same holds when the ship moves from lake to lock.

The tailbays of Pedro Miguel locks in Miraflores Lake are similarly treated in SWINLOCKS as forebays.

Water levels of Gatun Lake and Miraflores Lake, which vary throughout the year, and fluctuating water levels (tidal movements) and salt concentrations of the seaside tailbays form input for the simulation model, and are prescribed as a function of time. The water level variation of the lakes is the net result of flow into and out of the lakes.

Salt water intrusion into the lakes is caused by the locking operations in existing and future locks. All other water sources (Alhajuela Lake - Chagres River, creeks and rivers, precipitation, ground water) supply fresh water to the lakes. The outflow of saline water occurs through the spillways of Gatun Lake (spillage of surplus water, water for power generation) and Miraflores Lake (spillage of surplus water, cooling water). We assume that the outflow of saline water through other offtakes (drinking water, industrial water, ground water flow, evaporation) is nil or can be neglected in the analysis. That is also the reason why these offtakes are not separately modeled. The net effect of inflow and outflow of water on the water volume of the lakes is included in the water levels of the lakes, which are prescribed as a function of time; the effect of a change of the water volume of the lakes on salt concentration is accounted for in the salt balance analysis.

Ship movements, turn arounds, and water releases are prescribed through scenarios. Salt exchange coefficients are used in the formulas that describe the salt transfer between the various basins. The selection of exchange coefficients for the locking operations in the existing and future situation is based on former salinity measurements in the locks and canal area in wet and dry season and on computations with our numerical flow program Delft3D. When a scenario is executed the water levels, water volumes and salt concentrations change in the various basins (called nodes) of the simulation model.

Scenarios are combined in a day pattern. The start time of each scenario is prescribed in the day pattern. A normal day pattern consists of a number of ship-movement scenarios, turn-around scenarios and water-release scenarios. Different day patterns can be built up; the period of the year that the day pattern is active (for example: days 31 through 211) is prescribed in the day pattern.

Subsequently, day patterns are loaded in a case (Figure 4.2-a). A case contains information on start date and stop date of the simulation. Days are handled one by one; the simulation model runs the day pattern that is prescribed for the day that is in execution. After the last day of a year has been handled the simulation model starts with the first day of the next year; this process continues until the end of the simulation.

The salt exchange coefficients, which are used in the computation of the salt transfer from basin to basin, are prescribed by the user through a coefficient set. The user prescribes also the initial values of variables (water levels, water volumes and salt concentrations) and the dimensions of locks etc. through a separate input table. The set of exchange coefficients and the initial values form an inextricable part of the case.

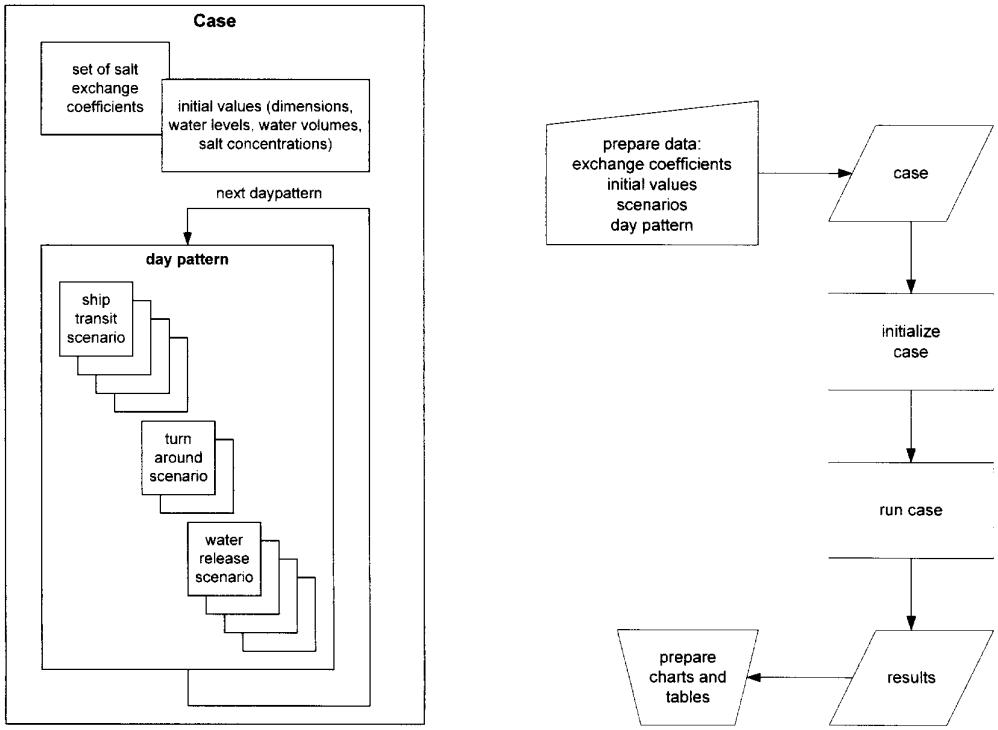


Figure 4.2 SWINLOCKS: (left) composition of a case, (right) flow chart

Computed values of nodal variables are written to a file at the end of each scenario (or as desired: day, week, month, and year). When a case is the continuation of a previous case, end values of salt concentrations in nodes (except Pacific and Atlantic Entrance) can be used as initial values in the new case. After the case has been run the value of nodal variables can be presented in tables or graphs as a function of time. The concept of the numerical model is reflected in Figure 4.2-b.

4.2 Computation of nodal variables

Ship movement scenarios, turn around scenarios and water release scenarios are simulated as a series of subsequent steps in the numerical model. The value of the nodal variables (water level, water depth, water volume, salt concentration) is computed after each step of the scenario. End values of a step are taken as start values for a next step in the current or in the next scenario. Both the water balance and the salt balance of two adjacent, mutually connected basins are drawn up in a step. Exchange coefficients e_x are applied in the salt balance; the values of these exchange coefficients are prescribed through the input table 'Coefficient Set'. Notice that the term 'basin' is used for all water-containing elements of the simulation model (tailbays, lock chambers, water saving basins, forebays, and lakes). The abbreviation wsb is used for the water saving basins.

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Salt concentrations of basins are volume-averaged values. A salt concentration multiplied by a water volume represents a quantity of salt. In salt balance equations use is made of a reference exchange volume V_{ref} in combination with the exchange coefficient e_x; the latter may be different in each step. The water quantity that is temporarily stored in the water saving basins of a lock is referred to as V_{save}.

Two basic steps can be distinguished in the uplockage or downlockage process:

I the water level in the low basin is equalized with the water level in the high basin; if relevant: the wsb's of the lower lock are emptied, the wsb's of the higher lock are filled; water is transferred from high basin to low basin

II lock gates are opened and the ship moves from the one basin to the other basin; a net water quantity equal to the ship volume S is displaced in opposite direction and density flows develop

These two basic steps are repeated for each set of adjacent basins in ship movement scenarios. In turn around scenarios basic step II is not relevant. The time-dependent exchange of salt water between forebays and lakes is handled in a 'special step' within a scenario (note that tailbays of Pedro Miguel locks are similarly treated as forebays).

Step I

The next starting points apply in the set up of the water balance and salt balance in **step I**:

- the water volume V_{save} that is transferred to or supplied from the wsb's of locks is equal to maximum (100*n)/(n+2) % of the water volume V_{ref} that would be exchanged between these locks when no wsb's were present (n = number of wsb's per lift)

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- consequently, the quantity of water that is exchanged between two adjacent basins amounts to: $V_{ref} - V_{save}$
- when wsb's get full or have insufficient water (this is checked in the simulation) a lesser quantity of water is transferred to or supplied from the wsb's

Step II

The exchange coefficient e_x used in salt balance formulas of **step II** is dependent on the ship volume S. The value of e_x prescribed through the Coefficient Set is valid for S = 0. In the general case with $S \neq 0$, next value of e_x is applied in the simulation:

$$e_x = \left(1 - \frac{S}{V_{ref}}\right) \cdot e_{x0}$$, where: e_{x0} = value of e_x for S = 0.

Sign of exchange coefficient e_x in step I and step II

The salt exchange coefficient e_x is positive ($e_x \geq 0$); the salt exchange formulas are defined in such a way that:

- a positive value of e_x in the formulas of **step I** (leveling of water) results in a salt transfer from high basin to low basin, salt feeding to the wsb that is filled, and salt withdrawal from the wsb that is emptied
- a positive value of e_x in the formulas of **step II** (movement of ship) results in a salt transfer from low basin to high basin, provided that the average salt concentration of the water in the high basin is smaller than the average concentration of the water in the low basin; otherwise the salt transfer is in the opposite direction

Special step: time dependent exchange of 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, which 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 step of the lockage operation the water level of the lock chamber is equalized with the water level of the forebay, 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, the exchange flows and density flows may be affected 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 linear 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 (all concentrations are volume-averaged quantities). 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 quantity of salt water that is exchanged between forebay and lake is dependent on the actual density difference and is also a function of time. Next salt balance formulas are used in the simulation model SWINLOCKS to describe the time dependent exchange of salt water (note: c = salt concentration, V = volume, subscript 1 refers to the beginning of the step, subscript 2 to the end of the step; known values at the beginning of step: c_{lake1}, $c_{forebay1}$):

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

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

The exchange coefficient e_x is defined as a function of the time difference between two subsequent actions in the forebay, for example two ship passages or a ship passage and a turn around. The time difference is derived from the start times of ship movement and turn around scenarios.

The value of the exchange coefficient e_x is in the range: $0 \geq e_x \geq 1$; $e_x = 0$ means no salt exchange, $e_x = 1$ means full salt exchange (the salt concentration in the forebay becomes equal to the salt concentration in the lake). Assuming that the salt exchange process is a linear function of time the following relationship is applied in SWINLOCKS:

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

where:

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 starting from the assumption that the propagation velocity of a salt tongue is in the order of 0.1 – 0.2 m/s. For the forebays in Miraflores Lake a shorter period T = 1800 s is selected because of the generally higher density differences (note that tailbays of Pedro Miguel locks are similarly treated as forebays).

Water releases

Water releases from the lakes (Gatun Dam: electrical power generation, spillage of surplus water; Miraflores Dam: cooling water, spillage of surplus water) are effectuated by special scenarios. The effect of these releases on salt concentration of the lakes is computed with the next formula (note: c = salt concentration, V_{lake} = lake volume, V_{spill} = released water quantity, subscript 1 refers to the beginning of the step, subscript 2 to the end of the step; known value at the beginning of step: c_{lake1}):

$$c_{lake2} = c_{lake1} - e_x \cdot \frac{V_{spill}}{V_{lake}} . c_{lake1}$$

Water level variation of lakes

The water levels of the lakes and the corresponding water volumes form input for the simulation model. The effect of a water level change (and thus volume change) on the salt concentration of the lake is computed with next formula (note: c = salt concentration, V_{lake} = lake volume, subscript 1 refers to the beginning of the step, subscript 2 to the end of the step):

$$c_{lake2} = \frac{V_{lake1}}{V_{lake2}} . c_{lake1}$$

At the start of each new day the effect of a water level change on salt concentration of the lake is computed in a SWINLOCKS run.

4.3 Extension of simulation model SWINLOCKS

The salt intrusion simulation model comprises both the existing locks and different configurations of Post-Panamax Locks. Next configurations of Post-Panamax Locks were already available in the simulation model at the start of the present contract (note: nominal length is gross length of lock chamber from gate axis to gate axis or from step in bottom to step in bottom):

- **Configuration B**: 3-lift locks with 3 wsb's per lift (wsb's can be switched off); nominal length 472 m, width 61,0 m, depth over sill 18.3 m (1550 ft x 200 ft x 60 ft)
- **Configuration C**: 2-lift locks 2 wsb's per lift (wsb's can be switched off); nominal length 515 m, width 61,0 m, depth over sill 18.3 m (1690 ft x 200 ft x 60 ft)
- **Configuration D**: 1-lift locks with 6 wsb's (wsb's can be switched off); nominal length 480 m, width 61,0 m, depth over sill 18.3 m (1575 ft x 200 ft x 60 ft)

ACP has reconsidered the nominal dimensions of Post-Panamax vessels (a smaller beam has been selected), and in coherence with it also the dimensions of the locks, which have been reduced. It was therefore required to extend the simulation model with a revised 3-lift lock system, with lock chamber dimensions, which are smaller than the sizes of the lock chambers used in previous simulations. Two options for water saving basins have been modeled:

- **Configuration E**: revised 3-lift locks with 2 wsb's per lift (wsb's can be switched off); nominal length 457.2 m, width 54.86 m, depth over sill 16.76 m (1500 ft x 180 ft x 55 ft)
- **Configuration F**: revised 3-lift locks with 3 wsb's per lift (wsb's can be switched off); nominal length 457.2 m, width 54.86 m, depth over sill 16.76 m (1500 ft x 180 ft x 55 ft)

The existing locks are referred to as **configuration A**.
The extension with revised 3-lift locks is shown in Figure 4.3.

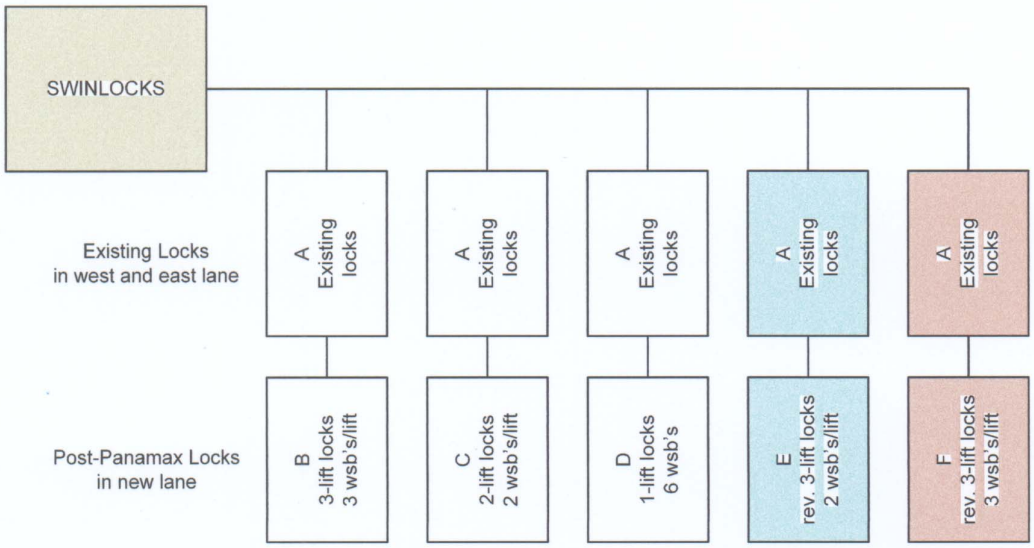


Figure 4.3 SWINLOCKS: extension of available lock configurations with revised 3-lift locks

To the purpose of simulating the effects of salt water intrusion mitigation systems, special ship movement scenarios and turn around scenarios have been developed in SWINLOCKS, and adequate salt exchange coefficients selected. The latter have been derived from Delft3D flow computations and former scale model experiments for similar mitigation systems.

To provide a better insight into the quantities of salt that enter Gatun Lake and Miraflores Lake through the forebays of the locks and leave through the spillways etc, the SWINLOCKS model has such been adapted that the salt load on Gatun Lake and Miraflores Lake and the salt drain from the lakes (in kg per unit of time) can be displayed in a graph. These salt quantities can be used as input in future water quality computations.

The Post-Panamax Locks will not solely be used to lock through Post-Panamax vessels; also Panamax vessels and regular vessels, handled in tandem lockages, will make use of the Post-Panamax Locks.
Next table of ACP presents a preliminary assessment of the traffic intensity (number of ship transfers a day) in years 2015, 2020, and 2025 in existing locks and Post-Panamax Locks:

Year	*Post-Panamax Locks*	*Panamax Locks*	
	new lane	*west lane*	*east lane*
2015	16.8	17.3	17.3
2020	19.8	18.4	18.4
2025	20.4	21.4	21.4

Table 4.1 Expected traffic intensity

At present a lesser traffic intensity in the new lane is expected that is based on revised shipping projections.

In previous studies the nominal dimensions of a Post-Panamax vessel were selected by ACP as: beam 54.86 m (180 ft), draft 15.24 m (50 ft, in tropical fresh water) and length 385.7 m (1265 ft). For the present study the nominal beam of a Post-Panamax vessel is reduced to 45.72 m (150 ft).
During the first phase (first four year after opening of the new lane) the maximum draft is limited to 13.11 m (43 ft); this is due to the restricted depth of the shipping channel.

The available list of ship types in SWINLOCKS has been extended in view of the new selected nominal dimensions of the Post-Panamax vessel and to cover various mixtures of ship types, which may be handled in tandem in the Post-Panamax Locks.

The adaptations and extension of the SWINLOCKS model are discussed in next sections.

4.3.1 Revised 3-lift lock configurations in SWINLOCKS

The design of the revised 3-lift lock configuration is not yet available, but for simulation purposes the previous design of CPP for the 3-lift locks can be chosen as a starting point (see description in Report C). The sill levels of the lock chambers and forebays have been derived by ACP taking into account a smaller keel clearance under the ship in the lock

chambers (1.52 m (5.0 ft) instead of 3.05 m (10.0 ft) as in the previous design of CPP) and a minimum operating water level of PLD +25.0 m (+82.0 ft) in Gatun Lake in phase II instead of PLD +23.93 m (+78.5 ft)). Next Figures 4.4 and 4.5 present a schematic picture of the revised 3-lift Post-Panamax Locks at the Pacific side and the Atlantic side of the canal respectively.

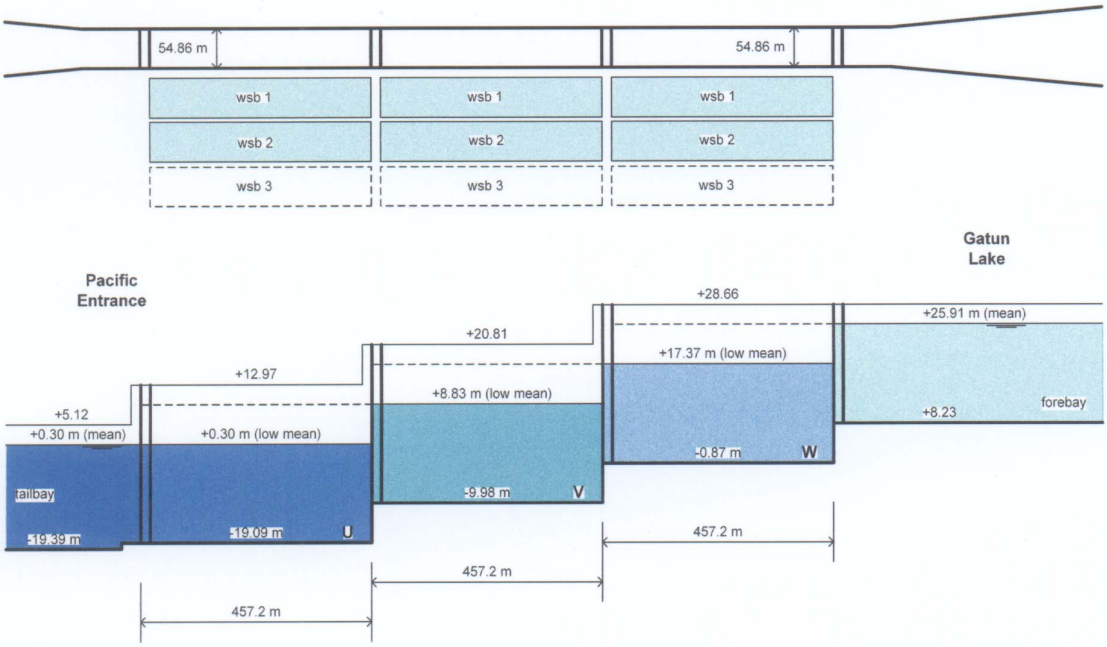


Figure 4.4 SWINLOCKS: revised 3-lift Post-Panamax Locks at Pacific side (configuration E: 2 wsb's per lift, configuration F: 3 wsb's per lift)

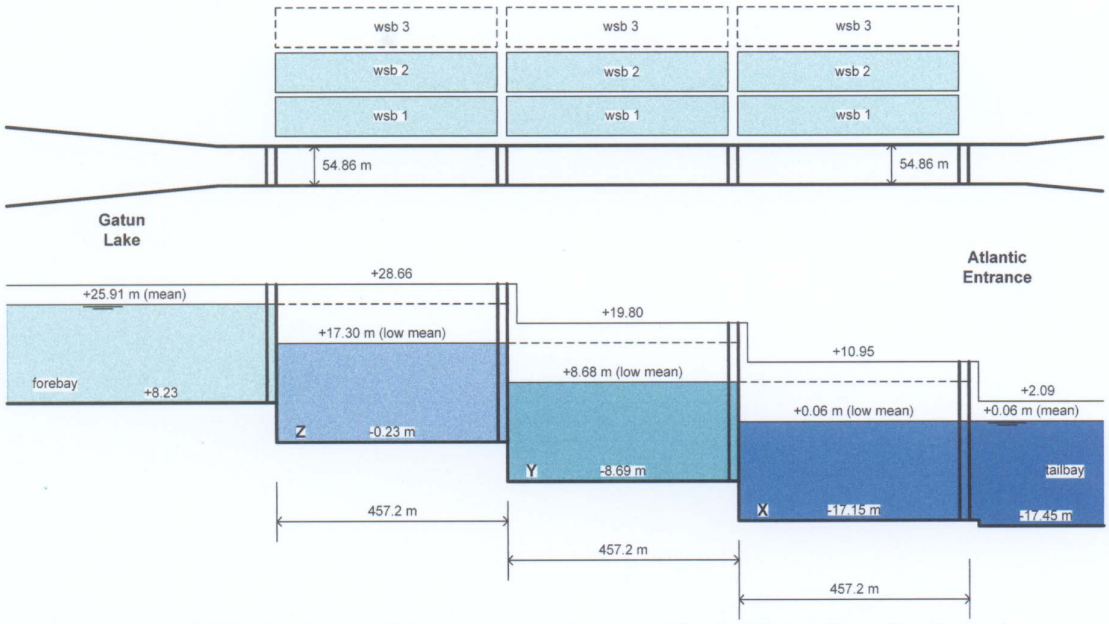


Figure 4.5 SWINLOCKS: revised 3-lift Post-Panamax Locks at Atlantic side (configuration E: 2 wsb's per lift, configuration F: 3 wsb's per lift)

As is shown a double set of rolling gates is present at both ends of a lock chamber. The nominal length of the lock chamber between the center line of the upper gates and the center line of the lower gates is 457.2 m; the lock chamber width is 54.86 m. The locks are named lock U, lock V and lock W at the Pacific side and lock X, lock Y and lock Z at the Atlantic side. Three options are considered by ACP: locks without water saving basins (wsb's), locks with 2 wsb's per lift and locks with 3 wsb's per lift. Water saving basins are arranged side by side along each of the locks. Locks with 2 wsb's per lift are called in this report lock U2 etc., locks with 3 wsb's per lift are called lock U3 etc.
The lock configuration with 2 wsb's per lift is referred to as configuration E throughout this report and the lock configuration with 3 wsb's per lift is referred to as configuration F. In SWINLOCKS the wsb's can be switched off; doing so configuration E becomes equal to configuration F.

Similar as in the earlier CPP design a multiport filling and emptying system is assumed with openings in both lock chamber walls just above the bottom along the full lock chamber length. The bottom of the lock chambers is flat without sills.

The quantity of water that is transferred in downstream direction during uplockage or downlockage of a ship is equal to the product of nominal lock chamber length, chamber width and water-level difference between adjacent locks. Also the recesses of the rolling gates contribute to the quantity of lockage water. The latter is accounted for in the simulation model SWINLOCKS by increasing the area of the lock chamber with the area of two gate recesses; this results in an effective lock chamber length of 457.2 m + about 2 x 16.5 m = 490 m in the numerical simulations. The characteristic dimensions of the revised 3-lift locks with wsb's and forebays, as built in SWINLOCKS, are shown in next tables:

basin	*effective length (m)*	*width (m)*	*nominal, mean water level (m to PLD)*		*floor level / sill level (m to PLD)*	*step in bottom (m)*	*coping level (m to PLD)*
			high	*low*			
Pacific side							
wsb's lock U2	490	54.86		+0.70	+0.20		
Lock U2	490	54.86	+8.83	+0.30	-19.09	9.11	+12.97
wsb's lock V2	490	54.86		+9.40	+8.90		
Lock V2	490	54.86	+17.37	+8.83	-9.98	9.11	+20.81
wsb's lock W2	490	54.86		+18.10	+17.60		
Lock W2	490	54.86	+25.91	+17.37	-0.87	9.11	+28.66
Gatun W2 forebay			+25.91		+8.23		+28.66
Atlantic side							
Gatun Z2 forebay			+25.91		+8.23		+28.66
wsb's lock Z2	490	54.86		+18.60	+18.10		
Lock Z2	490	54.86	+25.91	+17.30	-0.23	8.46	+28.66
wsb's lock Y2	490	54.86		+10.40	+9.90		
Lock Y2	490	54.86	+17.30	+8.68	-8.69	8.46	+19.80
wsb's lock X2	490	54.86		+2.20	+1.70		
Lock X2	490	54.86	+8.68	+0.06	-17.15	8.46	+10.95

Table 4.2 SWINLOCKS: dimensions of 3-lift Post-Panamax Locks, 2 wsb's per lift, revised design (configuration E)

basin	*effective length (m)*	*width (m)*	*nominal, mean water level (m to PLD)*		*floor level / sill level (m to PLD)*	*step in bottom (m)*	*coping level (m to PLD)*
			high	*low*			
Pacific side							
wsb's lock U3	490	54.86		+0.20	-0.30		
Lock U3	490	54.86	+8.83	+0.30	-19.09	9.11	+12.97
wsb's lock V3	490	54.86		+9.10	+8.60		
Lock V3	490	54.86	+17.37	+8.83	-9.98	9.11	+20.81
wsb's lock W3	490	54.86		+17.60	+17.10		
Lock W3	490	54.86	+25.91	+17.37	-0.87	9.11	+28.66
Gatun W3 forebay			+25.91		+8.23		+28.66
Atlantic side							
Gatun Z3 forebay			+25.91		+8.23		+28.66
wsb's lock Z3	490	54.86		+18.10	+17.60		
Lock Z3	490	54.86	+25.91	+17.30	-0.23	8.46	+28.66
wsb's lock Y3	490	54.86		+10.10	+9.60		
Lock Y3	490	54.86	+17.30	+8.68	-8.69	8.46	+19.80
wsb's lock X3	490	54.86		+1.70	+1.20		
Lock X3	490	54.86	+8.68	+0.06	-17.15	8.46	+10.95

Table 4.3 SWINLOCKS: dimensions of 3-lift Post-Panamax Locks, 3 wsb's per lift, revised design (configuration F)

Nominal water levels

Nominal mean high and low water levels in above tables are based on the mean water level of Gatun Lake of about PLD + 25.9 m during the last decades, mean tide level of PLD +0.30 m at the Pacific side and mean tide level of PLD +0.06 m at the Atlantic side.
High water levels in Gatun Lake and Miraflores Lake are controled by Gatun Spillway and Miraflores Spillway. Low water levels, which occur in the dry season, can not fully be controled (but water releases and water withdrawal can be stopped, and the number of lockages reduced); to maintain a minimum water level in the dry season the supply of additional water from other resources may therefore be required.

For the present study ACP has selected a minimum operating level of Gatun Lake of PLD +25.0 m (PLD + 82.0 ft) and a maximum operating level of PLD +27.13 m (PLD + 89.0 ft). The water level of Miraflores Lake is maintained at PLD +16.6 m (PLD +54.4 ft). For further considerations about the control of the water level reference is made to Section 5.1.

Water saving basins

The set of two or three wsb's per lock is replaced by a single wsb in the simulation model. The storage capacity of this single wsb is equal to the storage capacity of the two (three) wsb's together, as well as the total fill and emptying time. The salt exchange coefficient in the formulas that describe the exchange of salt water between single wsb and lock chamber, is such selected that it is representative for the exchange of salt water between the set of two (three) individual wsb's and the lock chamber.

4.3.2 Additional ship types in SWINLOCKS

The following three vessel classes have been defined in Report A for ship movements in the existing two lanes:

vessel class	*water displacement S*	*beam*	*length*	*draught*	*percentage of number of transits*
I	15,000 m^3	21.3 m (70 ft)	150 m (≈ 500 ft)	4.7 m (15.4 ft)	45%
II	45,000 m^3	27.4 m (90 ft)	215 m (≈ 700 ft)	7.6 m (24.9 ft)	20%
III	90,000 m^3	32.0 m (105 ft)	275 m (≈ 900 ft)	10.2 m (33.5 ft)	35%

Table 4.4 SWINLOCKS: regular vessels (existing shipping lanes)

These vessel classes may represent the different ship types that pass the canal in the present situation. A special vessel class '0' (ship with zero water displacement) is available for lock operations without a ship.

Additional vessel classes were defined in previous studies (see Table 4.5). Vessel class IV was used for representation of Panamax-Plus vessels, vessel class VII for Post-Panamax vessels with limited draught (in view of constricted depth of shipping channel in phase I after opening of the new lane), and vessel class VIII for Post-Panamax vessels.

vessel class	*water displacement S*	*beam*	*length*	*draught*
IV	120,000 m^3	32.3 m (106 ft)	294 m (965 ft)	14.0 m (45.9 ft)
V	145,000 m^3	32.3 m (106 ft)	326 m (1069 ft)	15.2 m (49.9 ft)
VI	200,000 m^3	54.0 m (177 ft)	386 m (1266 ft)	10.7 m (35.1 ft)
VII	260,000 m^3	54.0 m (177 ft)	386 m (1266 ft)	14.0 m (45.9 ft)
VIII	285,000 m^3	54.0 m (177 ft)	386 m (1266 ft)	15.2 m (49.9 ft)

Table 4.5 SWINLOCKS: additional vessels (new shipping lane); previous study

In the present study next two ship classes have been added, which allow for a simulation of ships with a different water displacement. With these additional ship types also Post-Panamax vessels with a nominal beam of 45.73 m (150 ft) are covered.

vessel class	*water displacement S*	*beam*	*length*	*draught*
IX	170,000 m^3	45.7 m (150 ft)	315.3 m (1035 ft)	13.11 m (43 ft)
X	235,000 m^3	45.7 m (150 ft)	385.7 m (1265 ft)	15.24 m (50 ft)

Table 4.6 SWINLOCKS: additional vessels (new lane); present study

It should be noted that only the water displacement S of ships is used in numerical simulations.

4.3.3 Selected mitigation systems

At the meeting of 12 October 2004 four mitigation systems have been selected by ACP for a further modeling and analysis, using the simulation model SWINLOCKS (see Section 3.8.2). These systems are:

Mitigation system	*Description*	*Figures in Section 2.5*	*Name of mitigation system in SWINLOCKS*
System 1	Stepwise flushing of all lock chambers (dummy lockage)	Figures 2.4a/b	Mitigation System I
System 2	Flushing of middle and upper lock chamber	Figures 2.5a/b	Mitigation System II
System 9	Flushing of salt water from pit with perforated floor	Figure 2.12	Mitigation System III
System 10	Pneumatic barrier (air bubble screen)	Figure 2.13	Mitigation System IV

Table 4.7 SWINLOCKS: mitigation systems

Modeling of these mitigation systems required an adaptation and extension of the simulation model SWINLOCKS. Extra mitigation scenarios have been developed, which are discussed in Section 4.4, together with the set up of water balance and salt balance in subsequent steps of the mitigation scenarios. The equations which are used in the computation of nodal variables are presented in a general form. Subscript 'high' refers to the higher basin of two adjacent basins, subscript 'low' to the lower basin; subscript 1 refers to the beginning of the step, subscript 2 to the end of the step.

4.4 Modeling of selected mitigation systems

4.4.1 Mitigation system I

Mitigation scenarios

Mitigation system I (stepwise flushing of all lock chambers, see Figures 2.4a/b) is in operation after uplockage or downlockage of a ship, but not necessarily after each ship lockage. The mitigation action is executed in SWINLOCKS through a separate mitigation scenario. Water saving basins are not active during execution of the scenario. Four different mitigation scenarios have been modeled, both for the 3-lift lock configuration with 2 wsb's per lift and the 3-lift lock configuration with 3 wsb's per lift:

no	*scenario*	*up- or downlockage*	*remarks*
1	Mitigation I, Pacific Ocean → Gatun Lake	uplockage	rev.3-lift locks 2wsb
2	Mitigation I, Gatun Lake → Pacific Ocean	downlockage	rev.3-lift locks 2wsb
3	Mitigation I, Atlantic Ocean → Gatun Lake	uplockage	rev.3-lift locks 2wsb
4	Mitigation I, Gatun Lake → Atlantic Ocean	downlockage	rev.3-lift locks 2wsb

no	*scenario*	*up- or downlockage*	*remarks*
5	Mitigation I, Pacific Ocean → Gatun Lake	uplockage	rev.3-lift locks 3wsb
6	Mitigation I, Gatun Lake → Pacific Ocean	downlockage	rev.3-lift locks 3wsb
7	Mitigation I, Atlantic Ocean → Gatun Lake	uplockage	rev.3-lift locks 3wsb
8	Mitigation I, Gatun Lake → Atlantic Ocean	downlockage	rev.3-lift locks 3wsb

Table 4.8 SWINLOCKS: additional scenarios for mitigation system I, revised 3-lift locks

Next steps can be distinguished in scenario Mitigation I, Pacific Ocean → Gatun Lake:

Low basin	*High basin*	*Operation (Remarks)*
Pacific Ocean	Lock U	Equalize water levels
Lock U	Lock V	Equalize water levels
Lock V	Lock W	Equalize water levels
Lock W	Gatun W forebay	Equalize water levels
Gatun W forebay	Gatun Lake	(Density flows)

Table 4.9 Steps in scenario Mitigation I, Pacific Ocean → Gatun Lake (uplockage)

Remark: read Lock U**2** etc. for revised 3-lift locks with **2** wsb's per lift, Lock U**3** etc. for revised 3-lift locks with **3** wsb's per lift.

The steps in scenario Mitigation I, Gatun Lake → Pacific Ocean are:

High basin	*Low basin*	*Operation (Remarks)*
Gatun Lake	Gatun W forebay	(Density flows)
Gatun W forebay	Lock W	Equalize water levels
Lock W	Lock V	Equalize water levels
Lock V	Lock U	Equalize water levels
Lock U	Pacific Ocean	Equalize water levels

Table 4.10 Steps in scenario Mitigation I, Gatun Lake → Pacific Ocean (downlockage)

The steps in scenarios Mitigation I, Atlantic Ocean → Gatun Lake and Mitigation I, Gatun Lake → Atlantic Ocean are similar.

Water balance and salt balance

First the reference water quantity V_{refmit} (equivalent to the 'normal' water loss) is computed:

$$V_{refmit} = \frac{(h_{lake} - h_{sea})}{3} \cdot A_{lock}$$

where: A_{lock} = area of lock chambers
h_{lake} = water level Gatun Lake
h_{sea} = water level sea entrance (Pacific of Atlantic)

V_{refmit} is the quantity of water that is used to flush the lock chambers in the mitigation action (see Figures 2.4a/b). In order to facilitate the application of a smaller quantity of flushing water in simulations, the quantity V_{refmit} is multiplied with a reduction factor λ ($\lambda = 1$ means no reduction). The reduction factor is prescribed by the user in the "Coefficient Set'; different values of λ can be selected for uplockage and downlockage.

The water balance and the salt balance are drawn up in each step of the mitigation scenario. Next formulas apply for different combinations of basins (valid both for uplockage and downlockage):

Low basin = tailbay, high basin = lower lock

Water balance:

$$V_{high2} = V_{high1} - \lambda . V_{refmit}$$

Salt balance:

$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_x \cdot \lambda . V_{refmit} \cdot c_{high1})}{V_{high2}}$$

Low basin = lower lock, high basin = middle lock
Low basin = middle lock, high basin = upper lock

Water balance:

$$V_{low2} = V_{low1} + \lambda . V_{refmit}$$
$$V_{high2} = V_{high1} - \lambda . V_{refmit}$$

Salt balance:

$$c_{low2} = \frac{(V_{low1} \cdot c_{low1}) + (e_x \cdot \lambda . V_{refmit} \cdot c_{high1})}{V_{low2}}$$
$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_x \cdot \lambda . V_{refmit} \cdot c_{high1})}{V_{high2}}$$

Low basin = upper lock, high basin = forebay

Water balance:

$$V_{low2} = V_{low1} + \lambda . V_{refmit}$$
$$V_{high2} = V_{high1} = V_{forebay}$$

Salt balance:

$$c_{low2} = \frac{(V_{low1} \cdot c_{low1}) + (e_x \cdot \lambda . V_{refmit} \cdot c_{high1})}{V_{low2}}$$
$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_x \cdot \lambda . V_{refmit} \cdot c_{high1}) + (\lambda . V_{refmit} \cdot c_{lake1})}{V_{high2}} = c_{forebay2}$$
$$c_{lake2} = c_{lake1} - \frac{\lambda . V_{refmit}}{V_{lake}} . c_{lake1}$$

4.4.2 Mitigation system II

Mitigation scenarios

Mitigation system II (flushing of middle and upper lock chamber, see Figures 2.5a/b) is in operation after uplockage or downlockage of a ship, but not necessarily after each ship lockage. The mitigation action is executed in SWINLOCKS through a separate mitigation scenario. Water saving basins are not active during execution of the scenario. Four different mitigation scenarios have been modeled, both for the 3-lift lock configuration with 2 wsb's per lift and the 3-lift lock configuration with 3 wsb's per lift:

no	*scenario*	*up- or downlockage*	*remarks*
1	Mitigation II, Pacific Ocean → Gatun Lake	uplockage	rev.3-lift locks 2wsb
2	Mitigation II, Gatun Lake → Pacific Ocean	downlockage	rev.3-lift locks 2wsb
3	Mitigation II, Atlantic Ocean → Gatun Lake	uplockage	rev.3-lift locks 2wsb
4	Mitigation II, Gatun Lake → Atlantic Ocean	downlockage	rev.3-lift locks 2wsb

no	*scenario*	*up- or downlockage*	*remarks*
5	Mitigation II, Pacific Ocean → Gatun Lake	uplockage	rev.3-lift locks 3wsb
6	Mitigation II, Gatun Lake → Pacific Ocean	downlockage	rev.3-lift locks 3wsb
7	Mitigation II, Atlantic Ocean → Gatun Lake	uplockage	rev.3-lift locks 3wsb
8	Mitigation II, Gatun Lake → Atlantic Ocean	downlockage	rev.3-lift locks 3wsb

Table 4.11 SWINLOCKS: additional scenarios for mitigation system II, revised 3-lift locks

Next steps can be distinguished in scenario Mitigation II, Pacific Ocean → Gatun Lake:

Low basin	*High basin*	*Operation (Remarks)*
Pacific Ocean	Lock V	Equalize with Lock U
Lock V	Lock W	Equalize water levels
Lock W	Gatun W forebay	Equalize water levels
Gatun W forebay	Gatun Lake	(Density flows)

Table 4.12 Steps in scenario Mitigation II, Pacific Ocean → Gatun Lake (uplockage)

Remark: read Lock U**2** etc. for revised 3-lift locks with **2** wsb's per lift, Lock U**3** etc. for revised 3-lift locks with **3** wsb's per lift.

Steps in scenario Mitigation II, Gatun Lake → Pacific Ocean are:

High basin	*Low basin*	*Operation (Remarks)*
Lock V	Pacific Ocean	Equalize with tailbay
Lock W	Lock V	Equalize water levels
Gatun W forebay	Lock W	Equalize with mean of lock V and forebay
Gatun Lake	Gatun W forebay	(Density flows)

Table 4.13 Steps in scenario Mitigation II, Gatun Lake → Pacific Ocean (downlockage)

The steps in scenarios Mitigation II, Atlantic Ocean → Gatun Lake and Mitigation II, Gatun Lake → Atlantic Ocean are similar.

Water balance and salt balance

First the reference water quantity V_{refmit} (equivalent to the 'normal' water loss) is computed:

$$V_{refmit} = \frac{(h_{lake} - h_{sea})}{3} \cdot A_{lock}$$

where: A_{lock} = area of lock chambers
h_{lake} = water level Gatun Lake
h_{sea} = water level sea entrance (Pacific of Atlantic)

V_{refmit} is the quantity of water that is used to flush the middle and upper lock chamber in the mitigation action (see Figures 2.5a/b). Similar as in Mitigation system I a smaller quantity of flushing water can be used in simulations: to that purpose the quantity V_{refmit} is multiplied with a reduction factor λ ($\lambda = 1$ means no reduction). The reduction factor is prescribed by the user in the "Coefficient Set'; different values of λ can be selected for uplockage and downlockage.

The water balance and the salt balance are drawn up in each step of the mitigation scenario. Next formulas apply for different combinations of basins (valid both for uplockage and downlockage):

Low basin = tailbay, high basin =* MIDDLE *lock

Water balance

$$V_{high2} = V_{high1} - \lambda . V_{refmit}$$

Salt balance

$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_x \cdot \lambda . V_{refmit} \cdot c_{high1})}{V_{high2}}$$

Low basin =middle lock, high basin = upper lock

Water balance

$$V_{low2} = V_{low1} + \lambda . V_{refmit}$$
$$V_{high2} = V_{high1} - \lambda . V_{refmit}$$

Salt balance

$$c_{low2} = \frac{(V_{low1} \cdot c_{low1}) + (e_x \cdot \lambda . V_{refmit} \cdot c_{high1})}{V_{low2}}$$

$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_x \cdot \lambda . V_{refmit} \cdot c_{high1})}{V_{high2}}$$

Low basin = upper lock, high basin = forebay

Water balance

$$V_{low2} = V_{low1} + \lambda . V_{refmit}$$
$$V_{high2} = V_{high1} = V_{forebay}$$

Salt balance

$$c_{low2} = \frac{(V_{low1} \cdot c_{low1}) + (e_x \cdot \lambda . V_{refmit} \cdot c_{high1})}{V_{low2}}$$

$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_x \cdot \lambda . V_{refmit} \cdot c_{high1}) + (\lambda . V_{refmit} \cdot c_{lake1})}{V_{high2}} = c_{forebay2}$$

$$c_{lake2} = c_{lake1} - \frac{\lambda . V_{refmit}}{V_{lake}} . c_{lake1}$$

4.4.3 Mitigation system III

Mitigation scenarios

Mitigation system III (flushing of salt water from a salt collecting pit, see Figure 2.12) is in operation after uplockage or downlockage of a ship. Since the salt collecting pit has limited dimensions, the pit should at least be flushed after each downlockage operation. At uplockage flushing is less critical, because a lesser quantity of salt water enters the salt pit. The quantity of water that is used in the flushing operation may be varied.

The mitigation action is executed in SWINLOCKS within special ship movement scenarios. Water saving basins can be applied in the normal way in these scenarios. Four special scenarios including the mitigation step have been modeled, both for the 3-lift lock configuration with 2 wsb's per lift and the 3-lift lock configuration with 3 wsb's per lift:

no	*scenario*	*up- or downlockage*	*remarks*
1	Mitigation III, Pacific Ocean → Gatun Lake	uplockage	rev.3-lift locks 2wsb
2	Mitigation III, Gatun Lake → Pacific Ocean	downlockage	rev.3-lift locks 2wsb
3	Mitigation III, Atlantic Ocean → Gatun Lake	uplockage	rev.3-lift locks 2wsb
4	Mitigation III, Gatun Lake → Atlantic Ocean	downlockage	rev.3-lift locks 2wsb

no	*scenario*	*up- or downlockage*	*remarks*
5	Mitigation III, Pacific Ocean → Gatun Lake	uplockage	rev.3-lift locks 3wsb
6	Mitigation III, Gatun Lake → Pacific Ocean	downlockage	rev.3-lift locks 3wsb
7	Mitigation III, Atlantic Ocean → Gatun Lake	uplockage	rev.3-lift locks 3wsb
8	Mitigation III, Gatun Lake → Atlantic Ocean	downlockage	rev.3-lift locks 3wsb

Table 4.14 Additional scenarios for mitigation system III; revised three-lift locks

The various subsequent steps that can be distinguished in the special ship movement scenario Mitigation III, Pacific Ocean → Gatun Lake, are shown in Table 4.15. An additional step 'flush salt pit' (in bold) has been added to this scenario.

The subsequent steps in the special ship movement scenario Mitigation III, Gatun Lake → Pacific Ocean, with extra step 'flush salt pit' in bold, are shown in Table 4.16.

Note that the steps in scenarios Mitigation III, Atlantic Ocean → Gatun Lake and Mitigation III, Gatun Lake → Atlantic Ocean are similar.

Low basin	*High basin*	*Operation (Remarks)*
Pacific Ocean	Lock U	Fill wsb's of lock U
Pacific Ocean	Lock U	Equalize water levels
Pacific Ocean	Lock U	Move ship
Lock U	Lock V	Empty wsb's of lock U
Lock U	Lock V	Fill wsb's of lock V
Lock U	Lock V	Equalize water levels
Lock U	Lock V	Move ship
Lock V	Lock W	Empty wsb's of lock V
Lock V	Lock W	Fill wsb's of lock W
Lock V	Lock W	Equalize water levels
Lock V	Lock W	Move ship
Lock W	Gatun W Forebay	Empty wsb's of lock W
Lock W	Gatun W Forebay	Equalize water levels
Lock W	Gatun W Forebay	Move ship
Pacific Ocean	**Salt pit**	**Flush salt pit**
Gatun W Forebay	Gatun Lake	(Density flows)

Table 4.15 Steps in scenario Mitigation III, Pacific Ocean → Gatun Lake (uplockage)

High basin	*Low basin*	*Operation (Remarks)*
Gatun Lake	Gatun W Forebay	(Density flows)
Gatun W Forebay	Lock W	Empty wsb's of lock W
Gatun W Forebay	Lock W	Equalize water levels
Gatun W Forebay	Lock W	Move ship
Salt pit	**Pacific Ocean**	**Flush salt pit**
Lock W	Lock V	Fill wsb's of lock W
Lock W	Lock V	Empty wsb's of lock V
Lock W	Lock V	Equalize water levels
Lock W	Lock V	Move ship
Lock V	Lock U	Fill wsb's of lock V
Lock V	Lock U	Empty wsb's of lock U
Lock V	Lock U	Equalize water levels
Lock V	Lock U	Move ship
Lock U	Pacific Ocean	Fill wsb's of lock U
Lock U	Pacific Ocean	Equalize water levels
Lock U	Pacific Ocean	Move ship

Table 4.16 Steps in scenario Mitigation III, Gatun Lake → Pacific Ocean (downlockage)

Remark: read Lock U**2** etc. for revised 3-lift locks with **2** wsb's per lift, Lock U**3** etc. for revised 3-lift locks with **3** wsb's per lift.

Water balance and salt balance

First the reference water quantity V_{refmit} (equivalent to the 'normal' water loss) is computed:

$$V_{refmit} = \frac{(h_{lake} - h_{sea})}{3} \cdot A_{lock}$$

where: A_{lock} = area of lock chambers
h_{lake} = water level Gatun Lake
h_{sea} = water level sea entrance (Pacific of Atlantic)

V_{refmit} is the quantity of water that is used to flush the salt collecting pit (see Figures 2.5a/b), but also a smaller or larger quantity of flushing water may be used. To that purpose the quantity V_{refmit} is multiplied in SWINLOCKS with an amplification factor λ ($\lambda = 1$ means no amplification). The amplification factor is prescribed by the user in the "Coefficient Set'; different values of λ can be selected for uplockage and downlockage.

The salt collecting pit forms an integral part of the forebay in SWINLOCKS. When the pit is flushed, water is withdrawn from the forebay and simultaneously this loss of water is replenished with water from the lake. The effectiveness of the flushing process is modeled through the exchange coefficient e_x in the salt balance formulas; this exchange coefficient can be different for uplockage and downlockage, and is prescribed by the user in the "Coefficient Set'.

Next formulas apply in the mitigation step (valid both for uplockage and downlockage):

Water balance

$$V_{forebay1} = V_{forebay2} = V_{forebay}$$

Salt balance

$$c_{forebay2} = \frac{(V_{forebay}.c_{forebay1}) - (e_x.\lambda.V_{refmit}.c_{forebay1}) + (\lambda.V_{refmit}.c_{lake1})}{V_{forebay}}$$

$$c_{lake2} = c_{lake1} - \frac{\lambda.V_{refmit}}{V_{lake}}.c_{lake1}$$

4.4.4 Mitigation system IV

Mitigation scenarios

Mitigation system IV (air bubble screen at the entrance to the lower lock and, alternatively, also at the entrance to the upper lock, see Figure 2.13) is in operation during uplockage or downlockage of a ship. The pneumatic barrier is put in operation when the gates of the lock are opened and is switched off again as soon as the lock gates have been closed.

The mitigation action is executed in SWINLOCKS within special ship movement scenarios. Water saving basins can be applied in the normal way in these scenarios. Four special scenarios including the mitigation step have been modeled, both for the 3-lift lock configuration with 2 wsb's per lift and the 3-lift lock configuration with 3 wsb's per lift:

no	*scenario*	*up- or downlockage*	*remarks*
1	Mitigation IV, Pacific Ocean → Gatun Lake	uplockage	rev.3-lift locks 2wsb
2	Mitigation IV, Gatun Lake → Pacific Ocean	downlockage	rev.3-lift locks 2wsb
3	Mitigation IV, Atlantic Ocean → Gatun Lake	uplockage	rev.3-lift locks 2wsb
4	Mitigation IV, Gatun Lake → Atlantic Ocean	downlockage	rev.3-lift locks 2wsb

no	*scenario*	*up- or downlockage*	*remarks*
5	Mitigation IV, Pacific Ocean → Gatun Lake	uplockage	rev.3-lift locks 3wsb
6	Mitigation IV, Gatun Lake → Pacific Ocean	downlockage	rev.3-lift locks 3wsb
7	Mitigation IV, Atlantic Ocean → Gatun Lake	uplockage	rev.3-lift locks 3wsb
8	Mitigation IV, Gatun Lake → Atlantic Ocean	downlockage	rev.3-lift locks 3wsb

Table 4.17 Additional scenarios for mitigation system IV; revised three-lift locks

The various subsequent steps that can be distinguished in the special ship movement scenario Mitigation IV, Pacific Ocean → Gatun Lake, are shown in Table 4.18. The mitigation action takes place in the first and last 'move ship' step (indicated in bold). The effect of the pneumatic barrier is realised by a multiplication of the exchange coefficient e_x, used in the move ship step, with a reduction factor ξ. The reduction factor is prescribed by the user in the "Coefficient Set'; different values of ξ can be selected for uplockage and downlockage, and for the barrier at the lower lock and the upper lock. The pneumatic barrier can be put out of action by selecting $\xi = 1$.

The subsequent steps in the special ship movement scenario Mitigation IV, Gatun Lake → Pacific Ocean are shown in Table 4.19.

Note that the steps in scenarios Mitigation IV, Atlantic Ocean → Gatun Lake and Mitigation IV, Gatun Lake → Atlantic Ocean are similar.

Low basin	*High basin*	*Operation (Remarks)*
Tailbay Lock U	Lock U	Fill wsb's of lock U
Tailbay Lock U	Lock U	Equalize water levels
Tailbay Lock U	Lock U	**Move ship**
Lock U	Lock V	Empty wsb's of lock U
Lock U	Lock V	Fill wsb's of lock V
Lock U	Lock V	Equalize water levels
Lock U	Lock V	Move ship
Lock V	Lock W	Empty wsb's of lock V
Lock V	Lock W	Fill wsb's of lock W
Lock V	Lock W	Equalize water levels
Lock V	Lock W	Move ship
Lock W	Forebay Lock W	Empty wsb's of lock W
Lock W	Forebay Lock W	Equalize water levels
Lock W	Forebay Lock W	**Move ship**
Forebay Lock W	Gatun Lake	(Density flows)

Table 4.18 Steps in scenario Mitigation IV, Pacific Ocean → Gatun Lake (uplockage)

High basin	*Low basin*	*Operation (Remarks)*
Gatun Lake	Forebay Lock W	(Density flows)
Forebay Lock W	Lock W	Empty wsb's of lock W
Forebay Lock W	Lock W	Equalize water levels
Forebay Lock W	Lock W	**Move ship**
Lock W	Lock V	Fill wsb's of lock W
Lock W	Lock V	Empty wsb's of lock V
Lock W	Lock V	Equalize water levels
Lock W	Lock V	Move ship
Lock V	Lock U	Fill wsb's of lock V
Lock V	Lock U	Empty wsb's of lock U
Lock V	Lock U	Equalize water levels
Lock V	Lock U	Move ship
Lock U	Tailbay Lock U	Fill wsb's of lock U
Lock U	Tailbay Lock U	Equalize water levels
Lock U	Tailbay Lock U	**Move ship**

Table 4.19 Steps in scenario Mitigation IV, Gatun Lake → Pacific Ocean (downlockage)

Remark: read Lock U**2** etc. for revised 3-lift locks with **2** wsb's per lift, Lock U**3** etc. for revised 3-lift locks with **3** wsb's per lift.

Water balance and salt balance

Next formulas apply in the mitigation step for different combinations of basins:

Uplockage

Water balance

The formulas are similar as in normal uplockage ship movement scenarios (reference is made to Report C for a description).

Salt balance

Low basin = tailbay, high basin = lower lock

$$c_{high2} = \frac{(V_{high1}.c_{high1}) + (\xi.e_x.V_{ref}.(c_{low1} - c_{high1})) - (S.c_{high1})}{V_{high2}}$$

Low basin = upper lock, high basin = forebay

$$c_{low2} = \frac{(V_{low1}.c_{low1}) - (\xi .e_x.V_{ref}.(c_{low1} - c_{high1})) + (S.c_{high1})}{V_{low2}}$$

$$c_{high2} = \frac{(V_{high1}.c_{high1}) + (\xi .e_x.V_{ref}.(c_{low1} - c_{high1})) - (S.c_{high1}) + (S.c_{lake1})}{V_{high2}} = c_{forebay2}$$

$$c_{lake2} = c_{lake1} - \frac{S}{V_{lake}}.c_{lake1}$$

Downlockage

Water balance

The formulas are similar as in normal downlockage ship movement scenarios (reference is made to Report C for a description).

Salt balance

High basin = forebay, low basin = upper lock

$$c_{high2} = \frac{(V_{high1}.c_{high1}) + (\xi .e_x.V_{ref}.(c_{low1} - c_{high1})) + (S.c_{low1}) - (S.c_{high1})}{V_{high2}} = c_{forebay2}$$

$$c_{low2} = \frac{(V_{low1}.c_{low1}) - (\xi .e_x.V_{ref}.(c_{low1} - c_{high1})) - (S.c_{low1})}{V_{low2}}$$

$$c_{lake2} = c_{lake1} + \frac{S}{V_{lake}}.c_{forebay1}$$

High basin = lower lock, low basin = tailbay

$$c_{high2} = \frac{(V_{high1}.c_{high1}) + (\xi .e_x.V_{ref}.(c_{low1} - c_{high1})) + (S.c_{low1})}{V_{high2}}$$

4.5 Exchange coefficients

4.5.1 Exchange coefficients when mitigation systems are not in operation

Salt exchange coefficients are used in the formulas that describe the salt transfer between the various basins in the SWINLOCKS model. The values of these exchange coefficients are based on salinity measurements in the existing locks in wet and dry season (see Report A for a description) and on computations with our numerical program Delft3D (see Report C for an explanation on the derivation of exchange coefficients for the earlier 3-lift lock design of CPP). Though the revised 3-lift locks have smaller dimensions (smaller width and smaller depth) than the 3-lift locks designed by CPP, the hydraulic processes and density flow phenomena are very similar. For that reason equal exchange coefficients can be selected.

Next Tables 4.20 and 4.21 present an overview of exchange coefficients, which are used in uplockage and downlockage ship movement scenarios, Pacific side. The exchange coefficients are equally valid for revised 3-lift locks with 3 wsb's per lift and revised 3-lift locks with 2 wsb's per lift. The reason is that 3 wsb's per lift or 2 wsb's per lift are modeled in SWINLOCKS as a single wsb; though the quantity of water that is saved in the single wsb is different (60% versus 50%), the process of withdrawal of water from the lock chamber or filling from the wsb is similar. The overall qualitative effect on mixing and density flow phenomena is very similar (as appears from earlier Delft3D simulations); the quantitative effect is accounted for by the quantity of water that is saved in the wsb.

Low basin	*High basin*	*Operation (Remarks)*	*Exchange coefficient*
Tailbay Lock U	Lock U	Fill wsb's of lock U	1.35
Tailbay Lock U	Lock U	Equalize water levels	1.25
Tailbay Lock U	Lock U	Move ship	0.7*
Lock U	Lock V	Empty wsb's of lock U	1.0
Lock U	Lock V	Fill wsb's of lock V	1.35
Lock U	Lock V	Equalize water levels	1.25
Lock U	Lock V	Move ship	0.05*
Lock V	Lock W	Empty wsb's of lock V	1.0
Lock V	Lock W	Fill wsb's of lock W	1.35
Lock V	Lock W	Equalize water levels	1.25
Lock V	Lock W	Move ship	0.0*
Lock W	Forebay Lock W	Empty wsb's of lock W	1.0
Lock W	Forebay Lock W	Equalize water levels	0.95
Lock W	Forebay Lock W	Move ship	0.0*
Forebay Lock W	Gatun Lake	(Density flows)	1.0**

*) exchange coefficient is a function of S/V_{ref}; value is valid for $S/V_{ref} = 0$
**) exchange coefficient is time dependent; final value (full exchange) is shown

Table 4.20 Exchange coefficients uplockage. Pacific Ocean → Gatun Lake. Revised 3-lift locks with 2 or 3 wsb's per lift.

High basin	*Low basin*	*Operation (Remarks)*	*Exchange coefficient*
Gatun Lake	Forebay Lock W	(Density flows)	1.0**
Forebay Lock W	Lock W	Empty wsb's of lock W	1.0
Forebay Lock W	Lock W	Equalize water levels	0.85
Forebay Lock W	Lock W	Move ship	0.05*
Lock W	Lock V	Fill wsb's of lock W	1.2
Lock W	Lock V	Empty wsb's of lock V	1.0
Lock W	Lock V	Equalize water levels	1.2
Lock W	Lock V	Move ship	0.1*
Lock V	Lock U	Fill wsb's of lock V	1.2
Lock V	Lock U	Empty wsb's of lock U	1.0
Lock V	Lock U	Equalize water levels	1.2
Lock V	Lock U	Move ship	0.15*
Lock U	Tailbay Lock U	Fill wsb's of lock U	1.2
Lock U	Tailbay Lock U	Equalize water levels	1.2
Lock U	Tailbay Lock U	Move ship	0.4*

*) exchange coefficient is a function of S/V_{ref}; value is valid for $S/V_{ref} = 0$
**) exchange coefficient is time dependent; final value (full exchange) is shown

Table 4.21 Exchange coefficients downlockage. Gatun Lake → Pacific Ocean. Revised 3-lift locks with 2 or 3 wsb's per lift.

Equal exchange coefficients are selected in scenarios for ship movements at the Atlantic side.

When the wsb's of the revised 3-lift locks are switched off in salt water intrusion simulations next exchange coefficients are used:

Low basin	*High basin*	*Operation (Remarks)*	*Exchange coefficient*
Tailbay Lock U	Lock U	Equalize water levels	1.3
Tailbay Lock U	Lock U	Move ship	0.7*
Lock U	Lock V	Equalize water levels	1.3
Lock U	Lock V	Move ship	0.05*
Lock V	Lock W	Equalize water levels	1.3
Lock V	Lock W	Move ship	0.0*
Lock W	Forebay Lock W	Equalize water levels	0.95
Lock W	Forebay Lock W	Move ship	0.0*
Forebay Lock W	Gatun Lake	(Density flows)	1.0**

*) exchange coefficient is a function of S/V_{ref}; value is valid for $S/V_{ref} = 0$
**) exchange coefficient is time dependent; final value (full exchange) is shown

Table 4.22 Exchange coefficients uplockage. Pacific Ocean → Gatun Lake. Revised 3-lift locks, wsb's switched off.

High basin	*Low basin*	*Operation (Remarks)*	*Exchange coefficient*
Gatun Lake	Forebay Lock W	(Density flows)	1.0**
Forebay Lock W	Lock W	Equalize water levels	0.85
Forebay Lock W	Lock W	Move ship	0.05*
Lock W	Lock V	Equalize water levels	1.2
Lock W	Lock V	Move ship	0.1*
Lock V	Lock U	Equalize water levels	1.2
Lock V	Lock U	Move ship	0.15*
Lock U	Tailbay Lock U	Equalize water levels	1.2
Lock U	Tailbay Lock U	Move ship	0.4*

*) exchange coefficient is a function of S/V_{ref}; value is valid for $S/V_{ref} = 0$
**) exchange coefficient is time dependent; final value (full exchange) is shown

Table 4.23 Exchange coefficients downlockage. Gatun Lake → Pacific Ocean. Revised 3-lift locks, wsb's switched off.

Equal exchange coefficients are selected in scenarios for ship movements at the Atlantic side.

In turn around scenarios the same exchange coefficients are used as in ship movement scenarios, but the 'move ship' step is not executed in these scenarios.

4.5.2 Exchange coefficients when mitigation systems are in operation

The exchange coefficients used in simulations in which salt water intrusion mitigation systems are in operation, are discussed for each system separately:

Mitigation system I

The mitigation action (stepwise flushing of all lock chambers, see Figures 2.4a/b) takes place after uplockage or downlockage of a ship. Afterwards, a next ship is locked up or locked down.
The mitigation action consists of a stepwise transfer of water from the forebay to upper lock, middle lock, lower lock and finally the tailbay. The water is transferred through the filling and emptying system. Lock gates are not opened and there is no ship movement with corresponding exchange flows between adjacent lock chambers. This means that the density flow phenomena deviate from the phenomena that occur during a normal lockage. Consequently, the 'normal' exchange coefficients (shown in Tables 4.22 and 4.23) can not be used in the mitigation action.

At the end of downlockage, when a ship has left the lower lock, water levels in all lock chambers are low (Figure 2.4a). A supply of water to a lock chamber through the lock filling system (with openings in the bottom or in the walls near the bottom) causes a mixing up of the water in that lock chamber. This is also true when a smaller quantity of water than V_{refmit} (see Section 4.4.1) is used to flush the lock chamber (but this reduces the effectiveness of the system). As a consequence, when - after filling - water is transferred to the next lower

lock, water is withdrawn from a lock chamber with almost uniform density and salt concentration. This means that, generally, a value e_x = 1.0 is the best choice for the exchange coefficient.

At the end of uplockage, when a ship has left the upper lock, water levels in all lock chambers are high (see Figure 2.4b). The salt concentration is highest near the bottom of the lock chambers. When in the mitigation action water is withdrawn through the emptying system of the lock chamber (with openings in the bottom or in the walls near the bottom), the water with highest salt concentration is evacuated from the chamber. This is similar as during a regular uplockage, which implies that the 'normal' exchange coefficient can be applied, that takes into account the effect of a higher salt concentration near the bottom. In the next step, water from the adjacent higher lock is supplied to the same lock chamber and the water is mixed up, resulting in a rather uniform salt concentration. When this lock chamber is emptied for the second time in the next uplockage ship movement scenario, a value e_x = 1.0 should therefore be selected, instead of the 'normal' exchange coefficient. This is difficult to model in the simulation model, since not all ship movement scenarios are necessarily combined with a mitigation scenario. In addition, there are also other mitigation options that can be chosen in a simulation run. It is therefore that e_x = 1.0 is used in the mitigation scenario when the lock chamber is emptied for the first time. In the next ship movement scenario, when the lock chamber is emptied for the second time, the 'normal' exchange coefficient is used. The overall effect of this interchange of exchange coefficients is almost neutral.

Mitigation system II

The mitigation action (flushing of middle and upper lock chamber, see Figures 2.5a/b) is executed after uplockage or downlockage of a ship; subsequently the next ship can be handled. Both at uplockage and downlockage first the middle lock chamber is leveled down, than the upper lock chamber. This sequence has the advantage that water with highest salt concentration is evacuated from middle and upper lock.

At downlockage (Figure 2.5a) the 'normal' exchange coefficients can be applied in the mitigation action; these coefficients take into account the effect of a higher salt concentration near the bottom of the lock chambers. In the next downlockage ship movement scenario lock chambers are first leveled up; this means that the hydraulic and density flow phenomena are similar as in a normal downlockage scenario and consequently the 'normal' exchange coefficients can be applied.
At uplockage (Figure 2.5b) the 'normal' exchange coefficients can be applied in the mitigation action, but this has as a consequence that in the next uplockage ship movement scenario a value e_x = 1.0 has to be used in the step that the lock chambers are leveled down for the second time. This is however, not required since not all ship movement scenarios are necessarily combined with a mitigation scenario in a simulation run; therefore, similar as in mitigation system I, the exchange coefficients are interchanged at uplockage, meaning that e_x = 1.0 is used in the mitigation action and the 'normal' exchange coefficient is used in the next uplockage ship movement scenario.

Similar exchange coefficients are applied when a smaller quantity of water than V_{refmit} (λ < 1.0, see Section 4.4.2) is used to flush the lock chamber (causing a lesser effectiveness!).

Mitigation system III

The mitigation action (flushing of salt water from the salt collecting pit, see Figure 2.12) is executed within an uplockage or downlockage scenario; the mitigation step is handled after the ship movement step in the upper lock. The quantity of water that is used in the flushing operation ($\lambda.V_{refmit}$) can be prescribed by means of the amplification factor λ, see Section 4.4.3. When flushing of the salt pit is not desired, a factor $\lambda = 0$ has to be selected. The salt water that enters the forebay will than escape to the lake.

The salt exchange coefficient e_x that is used in the salt balance between the salt pit and the tailbay at the seaside (see Section 4.4.3) is the decisive factor for the drainage of salt water from the pit; the salt water that is not drained away remains in the forebay and escapes finally to the lake. The salt exchange coefficient has been derived on the basis of Delft3D computations (2DV computations). Next table presents an overview of computations for different salt pit configurations (slope 1:1 and 1:10, depth of pit 26.4 m and 17.0 m) and operational modes. In all computations the salt concentration c was selected as: upper lock c = 2.0 ppt and forebay c = 0.

Comp. no	Gates of upper lock	salt pit			downlockage	uplockage
		tangent of slope at entrance of pit	depth of pit below forebay bed (m)	length of pit without slope (m)	mode of entry of ship upper lock	mode of exit of ship upper lock
1	remain open	no salt pit			-	-
2	remain open	1:1	26.4	490	-	-
3	remain open	1:10	26.4	490	-	-
4	remain open	1:1	17.0	490	-	-
5	remain open	1:10	17.0	490	-	-
6	remain open	1:10	17.0	490	direct entry	-
7	remain open	1:10	17.0	490	delayed entry	-
8	remain open	1:10	17.0	490	-	fast exit
9	remain open	1:10	17.0	490	-	slow exit
10	close at t = 0.5 h	1:10	17.0	490	-	-

Table 4.24 Delft3D computations for salt pit

Explanation:
At time t = 0 computations start, lock gates are opened and density flows develop. Computations stop at time t = 9 hours.
Reference computation no 1: no salt pit, no ship, only exchange flows.
Computations no 2 – 5: different salt pit configurations, no ship.
Computations no 6 – 9 for selected salt pit configuration: downlockage and uplockage of a ship (ship type X, see Section 4.2.2).
Computation no 10: similar as computation no 5, but at time t = 0.5 h the lock gates are closed.
Entry of ship: ship accelerates in 100 s to constant speed of 0.75 m/s and slows down in lock chamber in 200 s. Direct entry of ship: ship starts moving at time t = 0. Delayed entry of ship: ship starts moving at time t = 600 s.

Exit of ship: Ship starts moving at time t = 0. Fast exit of ship: ship accelerates in 200 s to constant speed of 1.5 m/s. Slow exit of ship: ship accelerates in 100 s to constant speed of 0.75 m/s.

The results of the computations are shown in next figures.

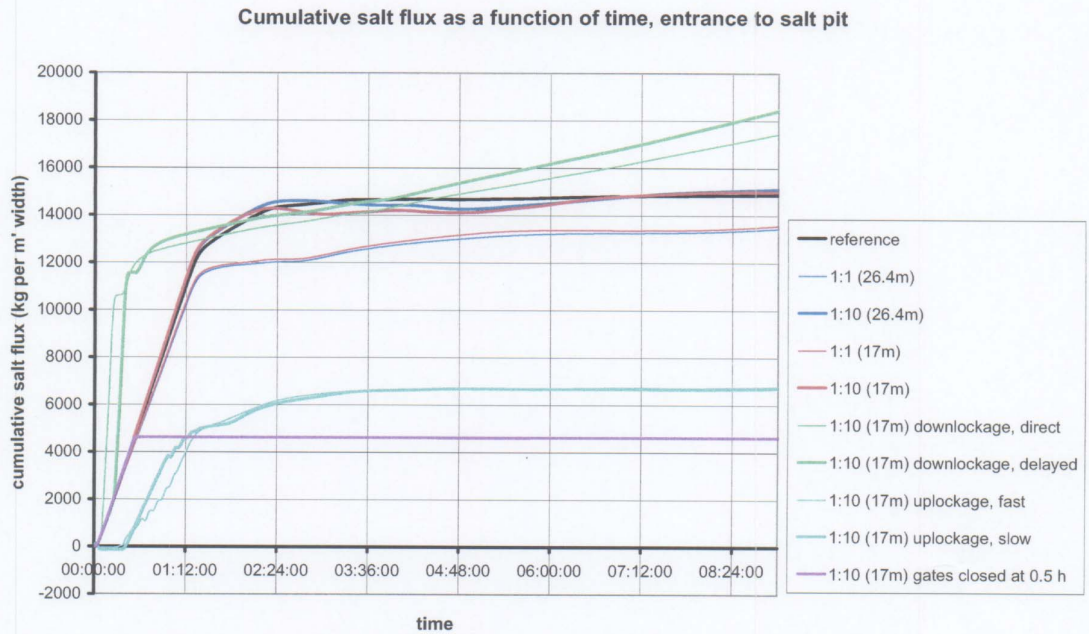


Figure 4.6 Delft3D results: cumulative salt flux. Location: entrance to salt pit

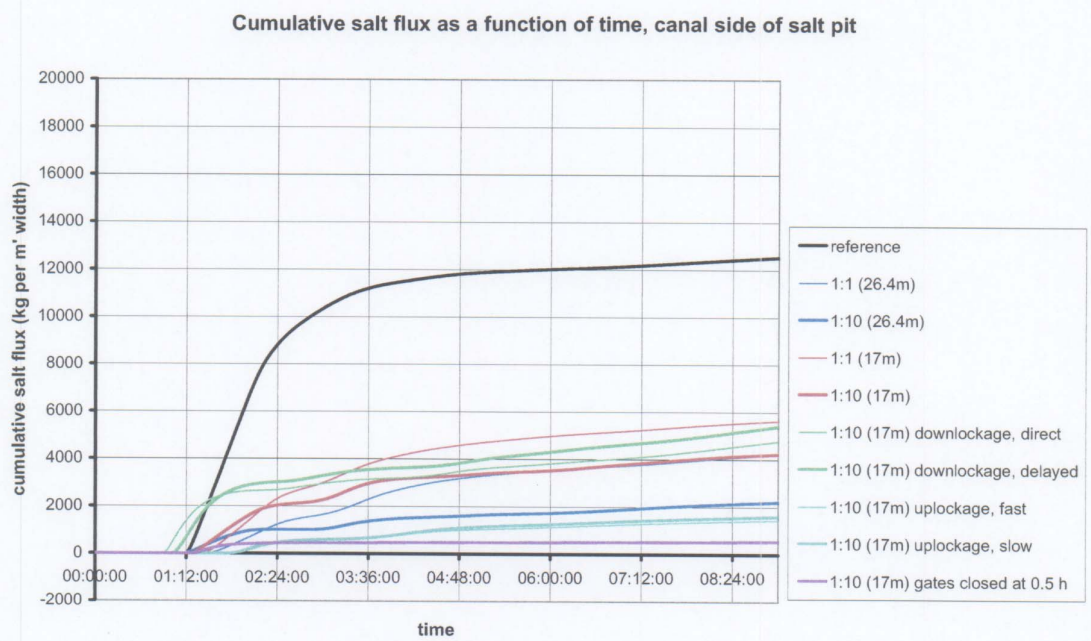


Figure 4.7 Delft3D results: cumulative salt flux. Location: canal side of salt pit

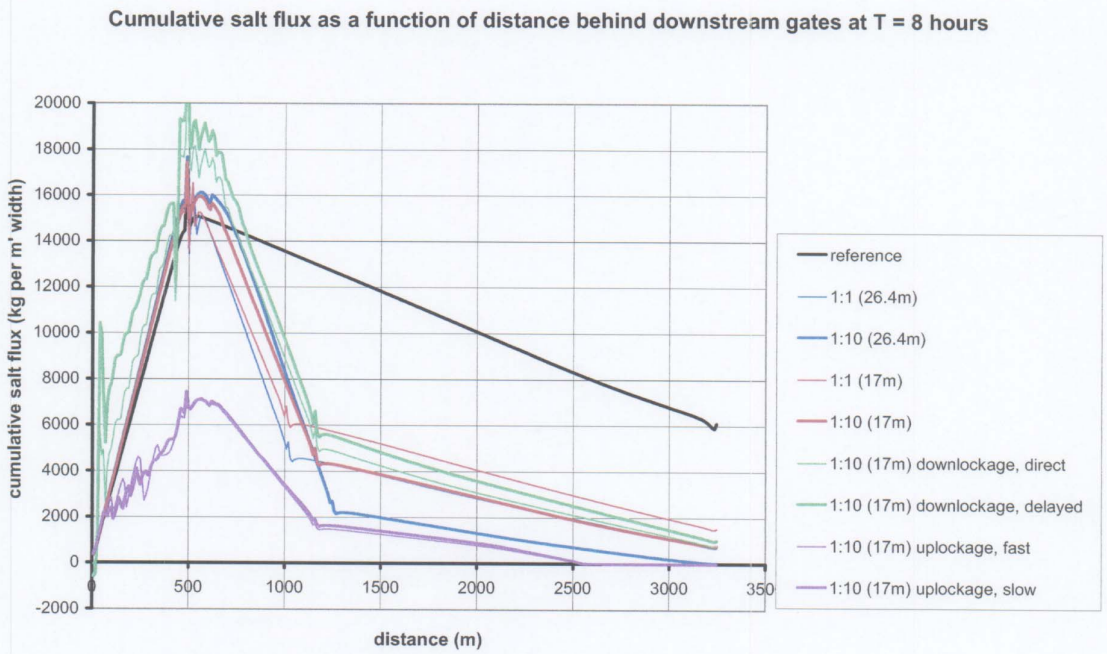


Figure 4.8 Delft3D results: cumulative salt flux after 8 hours

Figure 4.6 presents the cumulative salt flux in kg salt per unit width of the upper lock as a function of time for a location just outside of the lock, at the entrance to the salt pit. Figure 4.7 presents the salt flux at a location in the canal, just at the edge of the salt pit. Figure 4.8 presents the cumulative salt flux as a function of the distance behind the downstream gates of the upper lock for the moment of time T = 8 hours.

From Figure 4.6 we can learn that:

- Most salt water in the lock chamber above the level of the step in the floor is exchanged with fresh water from the forebay, provided that the lock gates are open during a sufficiently long period of time. In the present computations the quantity of salt above the step is about 16700 kg per m' width of the lock, when no ship is inside; the exchange rate is about 15000 / 16700 = 0.9. The exchange is not strongly affected by the layout of the salt pit.
- When a ship sails into the lock chamber (downlockage) a forced and thus faster exchange of salt water and fresh water occurs (green lines). The earlier the ship starts moving, the earlier the salt water is pushed out of the lock chamber.
- When a ship sails out of the lock chamber (uplockage) a delayed exchange occurs (light blue lines). The faster the ship sails, the stronger the delay. The quantity of salt that escapes to the forebay when the lock gates remain open is considerably smaller than at downlockage. This is caused by the fact that the quantity of salt in the lock chamber above the level of the step is smaller when a ship is inside (about 5900 kg per m' width in the present computations).
- The quantity of salt water that escapes to the forebay is smaller as the lock gates are closed sooner, but at downlockage the forced exchange of salt water is the dominant factor.

When Figure 4.7 is compared with Figure 4.6 it appears that only a part of the salt, which has escaped from the lock to the forebay, passes a cross section downstream of the salt pit. The smaller the salt quantity that passes this cross section, the more salt is caught in the salt pit. The escape of salt out of the salt pit is due to internal-wave overtopping at the downstream side of the salt pit and mixing up of salt water and fresh water. The escape of salt from the salt pit can also be read from Figure 4.8, that presents the passage of salt as a function of the distance behind the downstream gates of the upper lock for the moment of time T = 8 hours.
From Figure 4.7 we can conclude that a deeper pit (26.4 m) is more effective than a less deeper pit (17.0 m) and a gentle slope (1:10) of the pit is better than a steep slope (1:1). We can also learn that an early closure of the lock gates helps to prevent the escape of salt water from the lock chamber; it may eventually also help to reduce the escape of salt water from the salt pit (with a lesser salt water discharge into the salt pit lesser wave overtopping phenomena occur).

In general, as we have seen previously, the quantity of salt water caught by the salt pit depends on sailing direction, ship size, density difference between lock and forebay, the time that lock gates are open, and the pit layout. In the final design stage of the locks the layout of the salt pit has to be optimized (when this mitigation system is selected for application at the Panama Canal). For the moment being we assume that a salt pit design with a depth of 17 m and a slope of 1:10 is adequate (but a deeper pit would be more effective, however at a much higher construction cost). We also assume that lock gates are closed 0.5 hours after opening. From the results of the Delft3D computations we can then derive the next values for the fraction of salt that is caught by the salt pit:

downlockage: $\alpha = 0.7$
uplockage: $\alpha = 0.95$

where:
α = ratio of salt caught by the salt pit and the salt escaped from the lock chamber.

When a deeper pit (26.4 m) was selected the value of α would raise to 0.85 – 0.9 at downlockage.
Though the above figures are derived for specific conditions, we can assume that they are sufficient representative at this stage of the analysis.

When the flushing operation of the salt pit is carefully planned and executed, the flushing quantity $\lambda.V_{refmit}$, see Section 4.4.3, equals the quantity of salt water that is caught by the salt pit after downlockage or uplockage of a ship plus a minimum quantity of fresh water, which is drained away together with the salt water. The quantity of fresh water that is drained away is difficult to define beforehand, because it is strongly depending on the operation of the salt pit. The fresh water losses need to be investigated in the final design stage.
In the present study we start from the assumption that all the salt water in the salt pit is drained away when we select $\lambda = 1.25$ at downlockage (corresponding to an estimated water loss of the order of magnitude of 100% - 150 % of the 'normal' water loss V_{refmit}) and λ = 0.5 at uplockage (corresponding to an estimated water loss of the order of magnitude of 25% - 75 % of the 'normal' loss). When in simulations a lesser value for λ is applied a propor-

tionally lesser quantity of salt water is drained away. The portion remaining in the salt pit is finally lost to Gatun Lake.

By definition the exchange coefficient e_x used in salt balance formulas of Mitigation system III, see Section 4.4.3, equals:

$$e_x = \frac{V_{forebay}}{\lambda . V_{refmit}} . \alpha$$

valid for $\lambda_{down} = 1.25$ (at downlockage) and $\lambda_{up} = 0.5$ (at uplockage).
Taking average values for $V_{forebay}$ and V_{refmit} we obtain:

downlockage:	$\alpha = 0.7$	$\lambda_{down} = 1.25$	$e_x = 1.16$
uplockage:	$\alpha = 0.95$	$\lambda_{up} = 0.5$	$e_x = 3.92$

When a smaller quantity of water is applied to drain the salt from the salt pit the exchange coefficient e_x and thus the effectiveness reduces proportionally:

downlockage: $e_x = 1.16.\frac{\lambda_{down}}{1.25}$ valid for $\lambda_{down} \leq 1.25$

uplockage: $e_x = 3.92.\frac{\lambda_{up}}{0.5}$ valid for $\lambda_{up} \leq 0.5$

Combinations of λ and e_x derived from these relationships are applied in the salt water intrusion simulations for mitigation system III.

Mitigation system IV

The mitigation action (pneumatic barrier at the entrance to the lower lock and, alternatively, also at the entrance to the upper lock, see Figure 2.13) is executed within an uplockage or downlockage scenario. The pneumatic barrier is put in operation when the gates of the lock are opened and is switched off again as soon as the lock gates have been closed.

The effect of the pneumatic barrier is realised by a multiplication of the exchange coefficient e_x, used in the 'move ship' step of the scenario, with a reduction factor ξ. This factor reduces the density driven exchange flow, not the ship bound exchange flow, and is equivalent with the exchange rate as defined in Section 3.6 (see also Figure 3.21). The density driven exchange flow is dependent on the density difference between lock and tailbay / forebay and the time that the lock gates are open, and is also affected by the sailing direction of the ship. These influencing factors are already accounted for in the value of the 'normal' exchange coefficient e_x. Different values of e_x apply for uplockage and downlockage and for tailbay and forebay.

In salt water intrusion simulations we will start from the assumption that the pneumatic barrier is well designed (air supply capacity is sufficient) and is functioning well. The optimal effect of the pneumatic barrier can then be estimated as $\xi = 0.2$ (= exchange rate at

$t/T_a = 1$ in Figure 3.21, which corresponds to a reduction of 80%). This value can be applied for pneumatic barriers in tailbay and forebay, both for uplockage and downlockage.
However, the functioning of the pneumatic barrier under the conditions that prevail at the Panama Canal still has to be investigated. When the pneumatic barrier is not optimally working the value of ξ rises to maximum 1.0 (= no effect of pneumatic barrier).

4.5.3 Other exchange coefficients

Salt exchange coefficients in scenarios for ship movements in the existing locks are presented in Report A. These coefficients are also used in the present simulations.

The exchange coefficients which are used in the formulas that describe the effects of water releases at Gatun Dam and Miraflores Dam, have been selected on the basis of validation runs for the existing situation (see Report A). These exchange coefficients are also used in the present simulations:

Outlet	*Exchange coefficient*
Miraflores Spillway	1.5
Miraflores Cooling Water Offtake	1.5
Gatun Spillway	7.5
Gatun Power Station	7.5

Table 4.24 Exchange coefficients outlets

For considerations about the selection of these coefficients reference is made to Section 8.1.

4.6 Testing of simulation model

The adaptations and extensions of SWINLOCKS have extensively been tested. Firstly, the revised 3-lift lock configurations were tested using the dimensions of the former 3-lift lock configuration (CPP design). The extended model produced fully identical results.
Then the modeled mitigation systems I – IV were separately tested. Test cases were such designed that the functioning of mitigation systems could be checked. The Day Patterns and Coefficient Set used in the test runs for revised 3-lift locks with either 2 wsb's/lift or 3 wsb's/lift are shown in Tables 4.25 and 4.26. The exchange coefficients and reduction coefficients in the Coefficient Set 'mit' have all different values; these values are not realistic but were selected for the purpose of a fast check of the use of the various coefficients in the salt balance computations.

Day Pattern	*Scenarios in Day Pattern*	*Locks / mitigation*
mit I	ship movement Pac.→GL, mitigation I action, turn around N→S, ship movement GL→Pac., mitigation I action, turn around S→N; ship type X	revised 3-lift locks, mitigation action at uplockage and down-lockage, Pacific side
mit II	ship movement Pac.→GL, mitigation II action, turn around N→S, ship movement GL→Pac., mitigation II action, turn around S→N; ship type X	revised 3-lift locks, mitigation action at uplockage and down-lockage, Pacific side
mit III	ship movement Pac.→GL, mitigation III action, turn around N→S, ship movement GL→Pac., mitigation III action, turn around S→N; ship type X	revised 3-lift locks, mitigation action at uplockage and down-lockage, Pacific side
mit IV	ship movement Pac.→GL, mitigation IV action, turn around N→S, ship movement GL→Pac., mitigation IV action, turn around S→N; ship type X	revised 3-lift locks, mitigation action at uplockage and down-lockage, Pacific side
mit I-r	ship movement Atl.→GL, mitigation I action, turn around S→N, ship movement GL→Atl., mitigation I action, turn around N→S; ship type X	revised 3-lift locks, mitigation action at uplockage and down-lockage, Atlantic side
mit II-r	ship movement Atl.→GL, mitigation II action, turn around S→N, ship movement GL→Atl., mitigation II action, turn around N→S; ship type X	revised 3-lift locks, mitigation action at uplockage and down-lockage, Atlantic side
mit III-r	ship movement Atl.→GL, mitigation III action, turn around S→N, ship movement GL→Atl., mitigation III action, turn around N→S; ship type X	revised 3-lift locks, mitigation action at uplockage and down-lockage, Atlantic side
mit IV-r	ship movement Atl.→GL, mitigation IV action, turn around S→N, ship movement GL→Atl., mitigation IV action, turn around N→S; ship type X	revised 3-lift locks, mitigation action at uplockage and down-lockage, Atlantic side

Table 4.25 Overview of Day Patterns used in test cases, revised three-lift locks / mitigation systems

Basins involved in exchange	*up fill wsb*	*up empty wsb*	*down fill wsb*	*down empty wsb*
Lock U ⇔ U-wsb	0.111	0.211	0.311	0.411
Lock V ⇔ V-wsb	0.122	0.222	0.322	0.422
Lock W ⇔ W-wsb	0.133	0.233	0.333	0.433
Lock Z ⇔ Z-wsb	0.177	0.277	0.377	0.477
Lock Y ⇔ Y-wsb	0.166	0.266	0.366	0.466
Lock X ⇔ X-wsb	0.155	0.255	0.355	0.455
	up equalize	*up move ship*	*down equalize*	*down move ship*
tailbay U ⇔ Lock U	0.11	0.21	0.31	0.41
Lock U ⇔ Lock V	0.12	0.22	0.32	0.42
Lock V ⇔ Lock W	0.13	0.23	0.33	0.43
Lock W ⇔ forebay W	0.14	0.24	0.34	0.44
Lock Z ⇔ forebay Z	0.18	0.28	0.38	0.48
Lock Y ⇔ Lock Z	0.17	0.27	0.37	0.47
Lock X ⇔ Lock Y	0.16	0.26	0.36	0.46
tailbay X ⇔ Lock X	0.15	0.25	0.35	0.45
	up mitigation	*up mitigation*	*down mitigation*	*down mitigation*
Mitigation system I	$\lambda_{up} = 0.2$	--	$\lambda_{down} = 0.5$	--
Mitigation system II	$\lambda_{up} = 0.3$	--	$\lambda_{down} = 0.6$	--
Mitigation system III	$\lambda_{up} = 0.4$	$e_{x\text{-}up} = 0.9$	$\lambda_{down} = 0.7$	$e_{x\text{-}down} = 0.8$
Mitigation system IV	$\xi_{up\ tail} = 0.65$	$\xi_{up\ fore} = 0.75$	$\xi_{do\ fore} = 0.85$	$\xi_{do\ tail} = 0.95$

Table 4.26 Overview of salt exchange coefficients in Coefficient Set 'mit', used in test cases, revised three-lift locks / mitigation systems

Test cases

A series of tests was done with the salt concentration of all basins initially set on 0; the salt concentration of the Pacific and Atlantic tailbays was prescribed (salt concentration values of Table 5.9 were selected). Water levels of Miraflores Lake and Gatun Lake, tidal movements in the tailbays, dimensions of locks, and dimensions of water saving basins were all prescribed (default values for water levels and tidal movement, see discussion in Section 5.2).

The purpose of the tests was to check the set up of water balance and salt balance in relation to the mitigation options in the simulation model. The results of the water-balance and salt-balance computations have been checked by computations 'by hand'. An overview of test cases is presented in Table 4.27. Test have been done both for revised 3-lift locks with 2 wsb's/lift and revised 3-lift locks with 3 wsb's/lift.

Test Case	*Coefficient Set*	*Day Pattern*	*Period*	*Output interval*	*Remarks*
Mit I-1	mit	mit I	Jan 1 – Jan 2, 1970	scenario	single ship, S = 235000
Mit II-1	mit	mit II	Jan 1 – Jan 2, 1970	scenario	single ship, S = 235000
Mit III-1	mit	mit III	Jan 1 – Jan 2, 1970	scenario	single ship, S = 235000
Mit IV-1	mit	mit IV	Jan 1 – Jan 2, 1970	scenario	single ship, S = 235000
Mit I-1r	mit	mit I-r	Jan 1 – Jan 2, 1970	scenario	single ship, S = 235000
Mit II-1r	mit	mit II-r	Jan 1 – Jan 2, 1970	scenario	single ship, S = 235000
Mit III-1r	mit	mit III-r	Jan 1 – Jan 2, 1970	scenario	single ship, S = 235000
Mit IV-1r	mit	mit IV-r	Jan 1 – Jan 2, 1970	scenario	single ship, S = 235000

Table 4.27 Test Cases mitigation options / revised three-lift locks

Conclusions

The water balance and salt balance are well computed for all four mitigation options: salt water migrates properly from the tailbays in the sea entrances to all higher basins, water saving basins are correctly used, the mitigation systems function properly, and the time-dependent exchange of salt water between forebays and lakes is correct.

5 Hydraulic boundary conditions for salt water intrusion simulations

The numerical programme SWINLOCKS is used to simulate the process of salt water intrusion through the locks of the Panama Canal. Simulations will be done for the revised 3-lift lock configuration of Post-Panamax Locks, both for 2 wsb's per lift (configuration E) and 3 wsb's per lift (configuration F), and for selected mitigation systems.

The purpose of the simulations is to study the effectiveness of the selected mitigation systems when applied at the Panama Canal, in relation to the water quantities, that are lost from the canal when a mitigation system is in operation. These losses may necessitate an extra supply of water to the Panama Canal from other fresh water resources in addition to the supply of water that is already required for operation of the Post-Panamax Locks. In any case the supply of water to the Panama Canal becomes unavoidable when - during dry periods - the water level of Gatun Lake drops below a minimum level for navigation.
For the present study ACP has selected a minimum operating level of Gatun Lake of PLD +25.0 m (PLD + 82.0 ft) and a maximum operating level of PLD +27.13 m (PLD + 89.0 ft).

The control of the water levels of Gatun Lake and Miraflores Lake is explained in next Section 5.1. An overview of data on tidal fluctuations and salt concentrations in seaside tailbays, which are used as input in salt water intrusion simulations, is presented in Section 5.2.

5.1 Water level control of Gatun Lake and Miraflores Lake

5.1.1 Present water levels and water volumes of lakes

Miraflores Lake receives water from Gatun Lake (through the lockages at Pedro Miguel) and from a few small streams. It looses water through the lockages at Miraflores, evapotranspiration, industrial water use, use as cooling water, ground water flow and spillage of water at Miraflores Spillway. At present the water level in Miraflores Lake is maintained at about PLD +16.6 m (+54.4 ft), 0.25 m higher than in the years up to 1965. ACP will maintain this water level also in the future after realization of the new shipping lane.

The water level of Gatun Lake fluctuates in dependence of either dry or wet season (maximum variation about 2.8 m). Water is supplied by Chagres River, Trinidad River and Gatun River; these rivers drain a watershed of 3500 km^2. Water losses occur as a result of lockages, evapotranspiration, industrial and municipal water use, groundwater flow, hydro power generation at Gatun Dam and spillage of water (at present water is spilled through Gatun Spillway when a water level of about PLD +26.7 m (PLD +87.5 ft) is exceeded). During the last decade the mean water level of Gatun Lake was about PLD +25.9 m (PLD +85.0 ft); the corresponding water volume amounts to 5.12 km^3.

The daily water level recordings of Gatun Lake have been averaged for all months in the period 1992 – 2001. The average values of month-averages (January, February, ... December) in this 10-year period and the corresponding water volumes are shown in Table 5.1.

Month	*Water level (m to PLD)*	*Volume (10^6 m^3)*	*Water level (ft to PLD)*	*Volume (10^6 ft^3)*
January	26.47	5407	86.85	190958
February	26.28	5326	86.23	188080
March	26.00	5205	85.30	183804
April	25.66	5062	84.19	178764
May	25.57	5024	83.89	177414
June	25.76	5104	84.52	180256
July	25.94	5179	85.10	182891
August	26.02	5213	85.36	184079
September	26.16	5274	85.83	186235
October	26.29	5330	86.26	188219
November	26.49	5418	86.93	191331
December	26.58	5456	87.22	192686

Table 5.1 Gatun Lake: present representative water levels and corresponding water volumes

The constant water level of Miraflores Lake of PLD +16.58 m (+54.4 ft) with corresponding water volume of 23.8 x 10^6 m^3 (840.65 x 10^6 ft^3) and the fluctuating water level of Gatun Lake with corresponding water volume shown in Table 5.1, are displayed in Figure 5.1. These water levels have been used in the validation of the simulation model (see Report A) and also in salt water intrusion simulations for different configurations of Post-Panamax Locks (see Reports B – E).

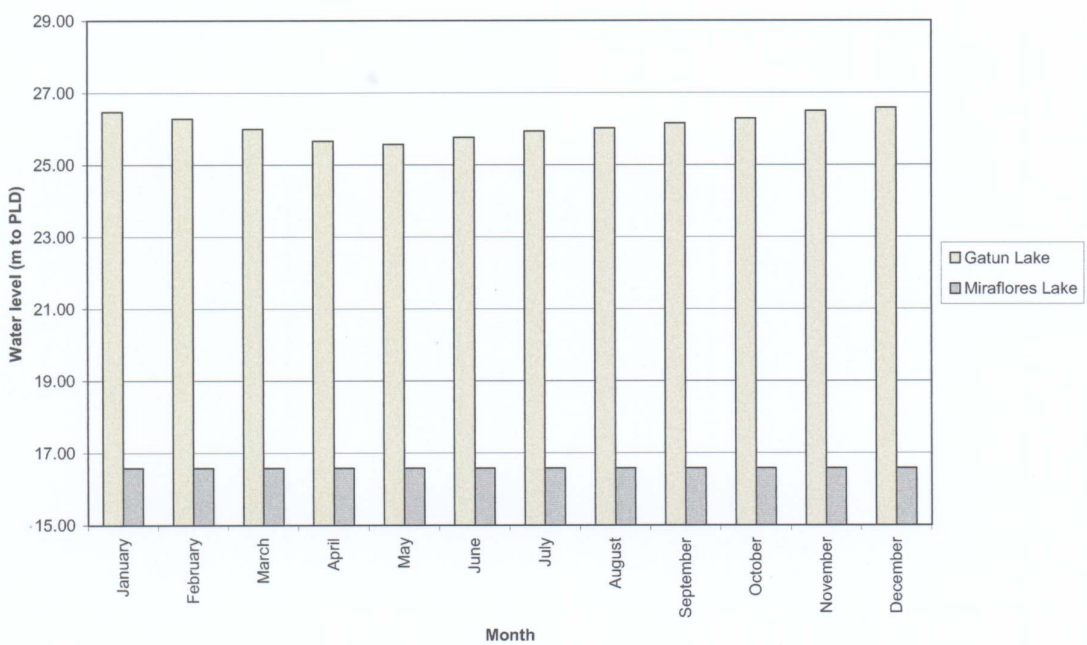


Figure 5.1 Present representative water levels of Gatun Lake and Miraflores Lake

The averaged water levels of Figure 5.1 are regarded as typical water levels representing the present real water level fluctuations of the lakes throughout the year. They are the net result of inflow and outflow of water in the present situation, including the water losses caused by the operation of the existing locks (traffic intensity: 18 ship transfers a day in west shipping lane and 18 ship transfers a day in east shipping lane) and including water releases.

5.1.2 Present water releases

The water levels of Miraflores Lake and Gatun Lake are controled by spillways. When the water level exceeds a maximum value, the surplus water is spilled. Water of Gatun Lake is also used for hydropower generation, water of Miraflores Lake is withdrawn for cooling purposes. These spillways and offtakes are such located that a part of the salt water that has been intruded through operation of the shipping locks, is discharged together with the released water.
We assume that the outflow of salt water through other offtakes is negligible.

In SWINLOCKS, the outflow of water from the lakes is included in the water level of the lakes, which is prescribed as a function of time (through an input table). The effect of the release of water on the salt concentration of the lakes is accounted for in the salt balance. For that reason the quantities of water that are released have to be provided as input in SWINLOCKS simulations.

The daily spilled water quantities at Miraflores Spillway and the water quantities used for cooling at Miraflores are shown in Table 5.2. These values concern monthly averaged values of the year 2001.

Month	*Spilled water (10^6 m^3 per day)*	*Cooling water (10^6 m^3 per day)*	*Totally released (10^6 m^3 per day)*
January	0.25	0.30	0.55
February	0.17	0.30	0.47
March	0.17	0.30	0.47
April	0.10	0.30	0.40
May	0.05	0.30	0.35
June	0.06	0.30	0.36
July	0.12	0.30	0.42
August	0.11	0.30	0.41
September	0.24	0.30	0.54
October	0.41	0.30	0.71
November	0.49	0.30	0.79
December	0.36	0.30	0.66

Table 5.2 Miraflores Lake: daily spilled / used water quantities in 2001

The values in Table 5.2 are not used as input in the simulation model, because they are not representative for a longer period of time. To get representative values we have adapted the water release quantities of Miraflores Lake as follows. Firstly, we have redistributed the totally released water quantity over the year 2001 using the distribution of averaged monthly releases of the ten-year period of Gatun Lake (but, a minimum value of 0.075 x 10^6 m^3/day and a maximum value of 0.3 x 10^6 m^3/day were maintained for water-cooling purposes at Miraflores Dam). Then we have corrected the redistributed 2001-values, because the year

2001 appeared to be a relatively dry year. The correction was made on the basis of the water-release quantity of Gatun Lake for the year 2001 and the average water-release quantity of Gatun Lake for the ten-year period 1992 - 2001, taking again into account a maximum value of 0.3 x 10^6 m^3/day for cooling purposes at Miraflores Dam. The obtained values are shown in Table 5.3.

Month	*Spilled water (10^6 m^3 per day)*	*Cooling water (10^6 m^3 per day)*	*Totally released (10^6 m^3 per day)*
January	0.54	0.30	0.84
February	0.04	0.19	0.23
March	0.02	0.15	0.17
April	0.01	0.15	0.16
May	0.07	0.21	0.28
June	0.39	0.30	0.69
July	0.69	0.30	0.99
August	0.85	0.30	1.15
September	1.11	0.30	1.41
October	1.10	0.30	1.40
November	1.62	0.30	1.92
December	1.77	0.30	2.07
Total (10^9 m^3/year)	0.25	0.09	0.35

Table 5.3 Miraflores Lake: present representative values of daily spilled water quantities and water quantities used for cooling

The daily spilled water quantities of Gatun Lake and water quantities used for hydropower generation have been averaged for all months in the period 1992 – 2001. The average values of month-averages (January, February, ... December) in this period are shown in Table 5.4.

Month	*Hydropower (10^6 m^3 per day)*	*Spilled water (10^6 m^3 per day)*	*Totally released (10^6 m^3 per day)*
January	2.57	2.04	4.61
February	0.60	0.00	0.60
March	0.20	0.00	0.20
April	0.16	0.00	0.16
May	0.94	0.00	0.94
June	3.63	0.00	3.63
July	5.55	0.00	5.55
August	6.06	0.52	6.58
September	7.49	0.83	8.32
October	7.03	1.20	8.23
November	7.38	4.22	11.60
December	5.69	6.94	12.63
Total (10^9 m^3/year)	1.45	0.48	1.93

Table 5.4 Gatun Lake: present representative values of daily spilled water quantities and water quantities used for hydropower

The averaged water release quantities of Gatun Lake and Miraflores Lake are shown in Figure 5.2, and are regarded as typical water release quantities representing the present real water release quantities of the lakes throughout the year.

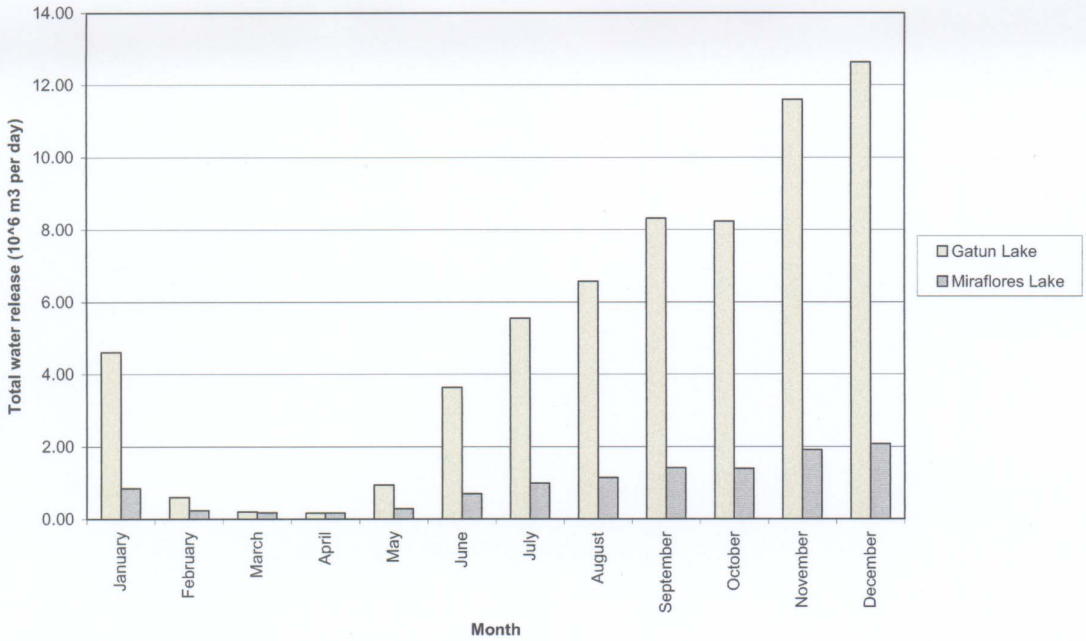


Figure 5.2 Present representative daily water releases of Gatun Lake and Miraflores Lake

The present water balance of Gatun Lake is shown in Figure 5.2a. Starting from the average water level variation of the lake (Figure 5.1) the change of water volume throughout the year has been computed (mean water volume 5.12 km^3).

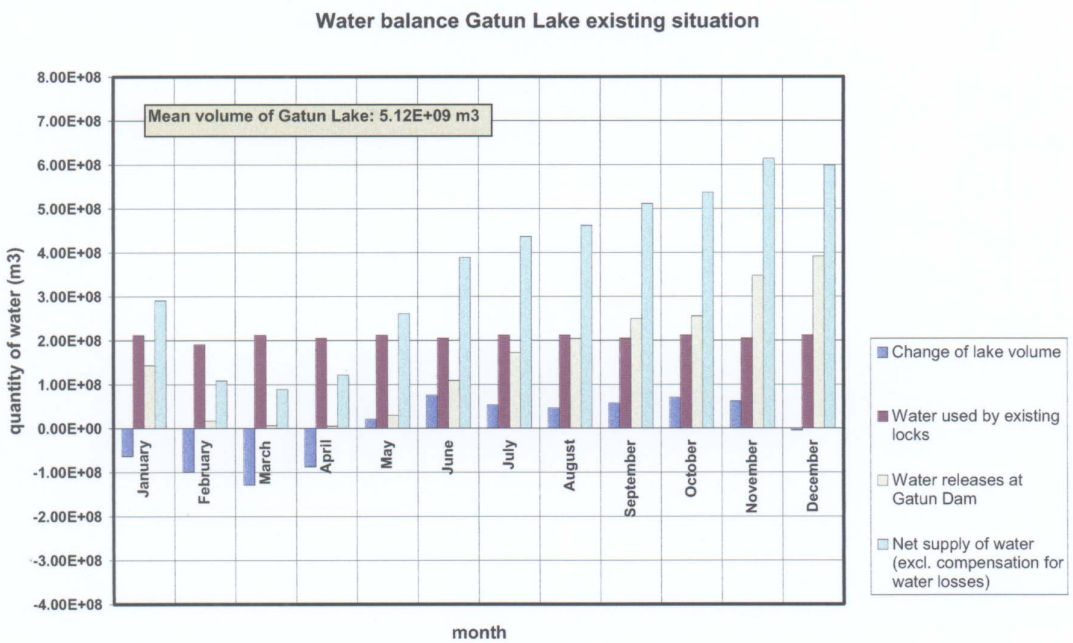


Figure 5.2a Present water balance of Gatun Lake

The water quantity that is used by the existing locks (36 ship transfers per day) and the quantity of water that is released at Gatun Dam are separately shown in Figure 5.2a. Both quantities sum up to 4.42 x 10^9 m^3 for one year, which is equal to 86% of the mean lake volume. It means that Gatun Lake is almost fully refreshed once per year.
The quantity of water that balances with these losses corresponds to the net supply of water to the lake (= the natural inflow of water from the catchment area minus evaporation and seepage losses and minus the quantity of water that is withdrawn for water consumption etc.).

Since the Post-Panamax Locks on the new shipping lane cause extra water losses, the present water balance of Gatun Lake is disturbed and an additional water quantity has to be supplied to Gatun Lake and / or a lesser water quantity released at Gatun Dam to maintain the present water level fluctuation of Gatun Lake. Doing so the water balance of Miraflores Lake is not affected by the new locks.

5.1.3 Future water levels of lakes and water releases

For the present study ACP has selected a minimum operating level of Gatun Lake of PLD +25.0 m (PLD + 82.0 ft) and a maximum operating level of PLD +27.13 m (PLD + 89.0 ft). This is a somewhat broader operational range than the range of present representative water levels, based on 10-year averages (Figure 5.1); a broader water level range is favorable since this enables a better utilization of the storage capacity of the lake.
The water level of Miraflores Lake will be maintained at the present water level of about PLD +16.6 m (PLD +54.4 ft).

Initially, ACP had selected a minimum water level of PLD +26.2 m (PLD +86.0 ft) in combination with a high water level of PLD +27.13 m (PLD + 89.0 ft) for Gatun Lake in phase II (phase II starts five years after opening of the new shipping lane, at the time that excavation works have made sufficient progress to enable a safe passage of Post-Panamax vessels).
This choice implies that the water level of Gatun Lake is bound within a relatively narrow band, at least when we assume that the *maximum operational* level is similar as at present, about PLD +26.7 m (PLD +87.5 ft). As a result the operational storage capacity of the lake is considerably smaller compared to the present situation. It means that water releases at Gatun Dam have to be reduced or stopped as soon as the water level drops below PLD +26.2 m. Consequently, a lesser water quantity is available for hydropower generation in the dry season.
Even, an extra quantity of water has to be supplied to the lake in the dry season in order to maintain the water level at PLD +26.2 m. The extra supplied water quantity has to be released again in the wet season to prevent that the maximum water level is exceeded; this water quantity can fully be utilized for hydropower generation.

Figure 5.3a shows the difference between the present, representative water level of Gatun Lake based on 10-year averages and the water level of Gatun Lake in the case that a minimum of PLD +26.2 m is maintained.

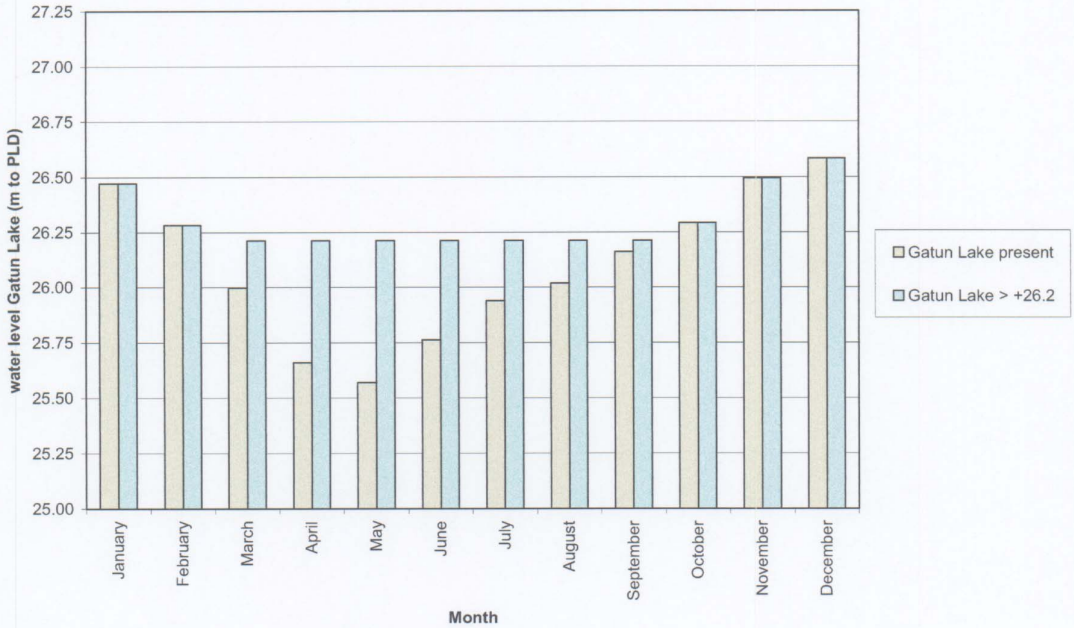


Figure 5.3a Present representative water level of Gatun Lake and water level in the case that a minimum level of PLD +26.2 m is maintained

The *extra* quantity of water that has to be supplied in the dry period to maintain the water level at PLD +26.2 m (and has to be released again in the wet season) equals the difference between the lake volume at the present water level and the lake volume at the desired water level. The incremental water volumes in subsequent months have to be considered and mutually compared in the analysis of the extra water supplies. The volume of the lake can be approximated using the relationship:

$Vol = 5.10^6 \times WL^{2.125}$, where Vol = volume (m^3), WL = water level (m to PLD).

The results of the analysis are shown in Table 5.5. The table presents the extra water quantities that are supplied in the dry season and are released again in the wet season, and the total releases and supplies in comparison to the present water releases (negative values are water supplies).

Month	*Totally released at present* (10^6 m^3 *per day*)	*Extra supplies (-) and releases (+) for water level* $\geq +26.2$ *m* (10^6 m^3 *per day*)	*Totally released (+) or supplied (-) wl* $\geq +26.2$ *m* (10^6 m^3 *per day*)
January	4.61	0.00	4.61
February	0.60	0.00	0.60
March	0.20	-2.89	-2.69
April	0.16	-4.63	-4.47
May	0.94	-1.18	-0.24
June	3.63	2.61	6.23
July	5.55	2.35	7.91
August	6.58	1.07	7.65
September	8.32	1.98	10.30
October	8.23	0.69	8.92
November	11.60	0.00	11.60
December	12.63	0.00	12.63

Table 5.5 Gatun Lake: present representative daily water releases and extra water supplies / releases in the case that a minimum water level of PLD +26.2 m is maintained

Present representative water releases of Gatun Lake and the water releases / water supplies in the case that a minimum water level of PLD +26.2 m is maintained are shown in next Figure 5.3b. Note that all quantities are still without the effects caused by operation of the Post-Panamax Locks and salt-water intrusion mitigation systems.

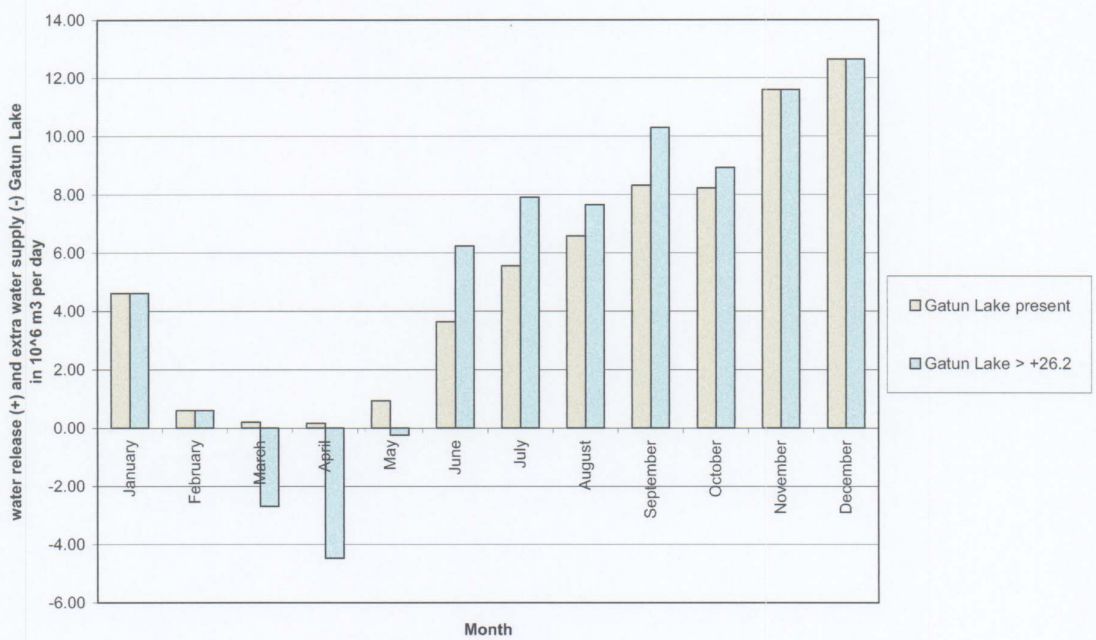


Figure 5.3b Present representative water releases of Gatun Lake and water releases in the case that a minimum water level of PLD +26.2 m is maintained

The extra supply of water to Gatun Lake can be prevented when a higher maximum operational water level is accepted. In that case the storage capacity of the lake increases,

giving room for a greater water level variation, similar as at present. The lowest water level can be kept than above PLD +26.2 m (PLD +86.0 ft). This case with an upward shift of water level is shown in next figures: Figure 5.4a presents the water level, Figure 5.4b the corresponding water releases of Gatun Lake in comparison to the present situation.

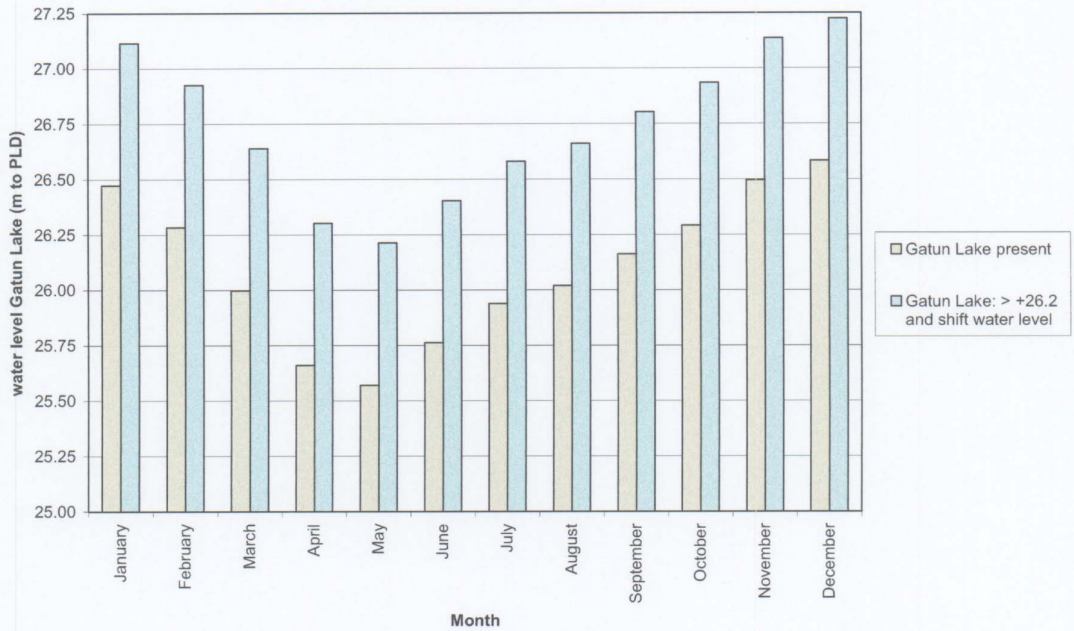


Figure 5.4a Present representative water level of Gatun Lake and water level in the case of an upward water level shift with a minimum of PLD +26.2 m

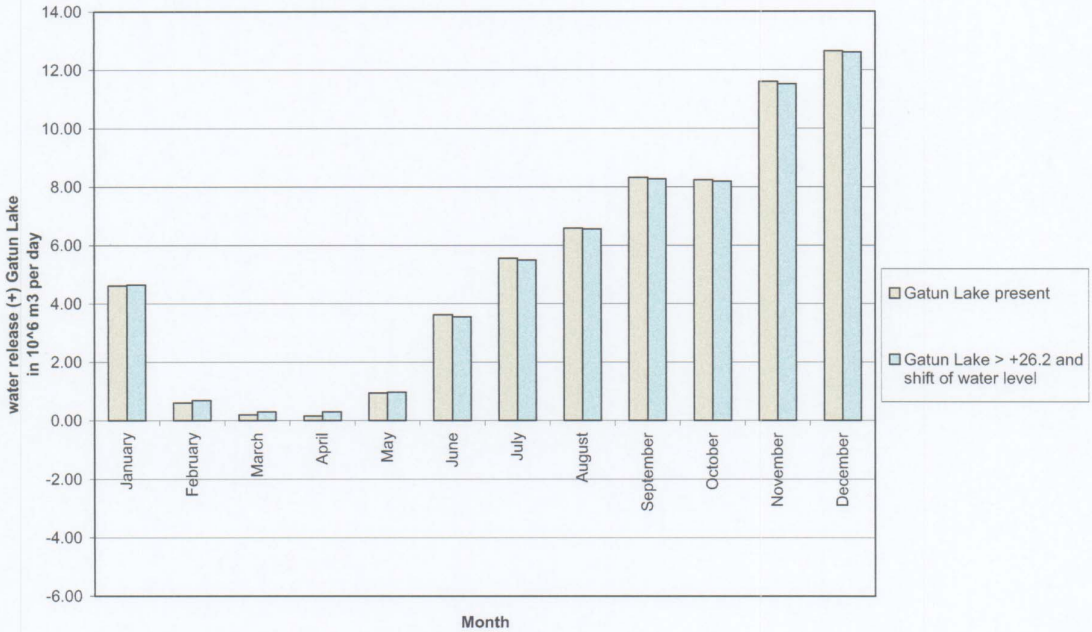


Figure 5.4b Present representative water releases of Gatun Lake and water releases in the case of an upward water level shift with a minimum of PLD +26.2 m

The water level control option shown in Figures 5.4a/b demonstrates that the supply of extra water to Gatun Lake for operation of the Post-Panamax Locks can (partly) be prevented when a sufficient operational water storage capacity is available. The option of Figures 5.4a/b is not applied in simulations with SWINLOCKS. Instead the concept of a proportionally reduced water release is applied, see hereafter, which offers the possibility to minimize the supply of extra water from new water resources.

Some initial simulations have been executed for the water level control option shown in Figures 5.3a/b, in which the water level of Gatun Lake is maintained between a minimum of PLD +26.2 m (+86.0 ft) and a maximum of PLD +26.7 m (+87.5 ft; maximum similar as at present). The higher minimum water level of Gatun Lake permits also a higher floor level of the lock chambers of the revised 3-lift locks. In SWINLOCKS simulations this higher floor level was taken into account. In order to make a distinction between results for the locks with higher floor level and results for the regular locks (see description in Section 4.2.1), the name of lock configurations with a higher floor level are provided with an asterix: configuration E* for locks with 2 wsb's per lift and configuration F* for locks with 3 wsb's per lift. Reference is made to Section 6.1 for a further description of these lock configurations.

In all other initial simulations the concept of a proportional reduction of the water releases (resulting in a minimum extra water supply) is applied. In these simulations the water level of Gatun Lake is controled between a minimum of PLD +25.0 m (PLD + 82.0 ft) and a maximum of PLD +27.13 m (PLD + 89.0 ft) throughout the year. This water level range selected by ACP, offers an ample operational water storage capacity. In SWINLOCKS simulations this storage capacity is optimally utilized: the release of water at Gatun Dam is reduced and scheduled in such a way (compared to the present water releases) that the supply of fresh water is minimized.

The applied water control method is as follows:
Let X be the total quantity of water per year that on average is released *at present* at Gatun Dam.
Let Y be the quantity of water per year that is needed to operate the new Post-Panamax Locks and possibly the mitigation systems. This quantity is dependent on the number of lockages, the use of water saving basins and the mode of operation of the mitigation systems.
The supply of fresh water to Gatun Lake is minimum when first the water releases are used to operate the new locks and mitigation systems, and secondly, if not sufficient, to supply water. The water quantity (X-Y) is the reduced water release per year; when this quantity is negative there is a supply of water. The water release per month is scheduled as follows:

$$\text{release}_{\text{month i}} = \left(1 - \frac{Y}{X}\right) . \text{ present release}_{\text{month i}}$$

With the above formula the present water releases per month are proportionally reduced. When Y > X there is no release of water, but a water supply. In that case the water supplies per month are scheduled throughout the year in proportion to the *present* water releases, meaning that most water is supplied in the wet season. This is favorable since, generally, more water is available in the wet season.

In simulations where the concept of a proportional reduction of the water releases is applied an average water level of PLD +26.1 m is selected for Gatun Lake, similar as the present average water level. When the water releases and extra water supplies throughout the year are known the water level variation about the mean value can be computed in an iterative procedure, using the relationship between water level and water volume:

$$Vol = 5.10^6 \times WL^{2.125}$$

where
Vol = volume of Gatun Lake (m^3)
WL = water level of Gatun Lake (m to PLD).

This method has been applied using an Excel spreadsheet.

The concept of a proportional reduction of the water releases at Gatun Dam, resulting in a minimum extra water supply to Gatun Lake can not be applied in the real situation since the actual rainfall and rainfall distribution over a year is not known in advance. Yet, the extra water supply can be minimized when water is only released when the water level threatens to exceed the upper limit level of Gatun Lake. When the spill capacity of Gatun Dam is sufficient to instantaneously discharge floods caused by intensive showers in the water shed area, the water level at which the release of water shall start, can be chosen close to the upper limit level of the lake. This has to be studied more in detail, also in relation to the use of water for electrical power generation at Gatun Dam.

5.1.4 Scenarios for the control of the water level of Gatun Lake

Overview of water level control scenarios used in simulations

Table 5.6a presents an overview of scenarios for the control of the water level of Gatun Lake; some of these scenarios have earlier been used and others are used in the present salt water intrusion simulations with SWINLOCKS. Salt water intrusion simulations are indicated with a combination of a letter (for the lock configuration) and a number (for the water level control scenario). Combinations in **bold** refer to simulations for revised 3-lift locks, which are executed in the present study, combinations in *italic* refer to earlier salt-water intrusion simulations (see Reports B, C and D). Table 5.6a does not yet include the simulations which are aimed to study the effect of salt water intrusion mitigation systems (these simulations are discussed in Chapter 6 and Chapter 7).

nario	*Description*	*B 3-lift locks 3 wsb's*	*C 2-lift locks 2 wsb's*	*D 1-lift locks 6 wsb's*	***E revised 3-lift locks 2 wsb's***	***F revised 3-lift locks 3 wsb's***
1	Wsb's in operation Gatun Lake: present representative water level variation, see Figure 5.1 Gatun Dam: present representative water releases, see Figure 5.2 Extra fresh water supply to Gatun Lake to compensate for PPL losses	*B1*	*C1*	*D1*	–	–
2	Wsb's switched off Gatun Lake: present representative water level variation, see Figure 5.1 Gatun Dam: present representative water releases, see Figure 5.2 Extra fresh water supply to Gatun Lake to compensate for PPL losses	*B2*	*C2*	*D2*	–	–
3	Wsb's in operation Gatun Lake: present representative water level variation, see Figure 5.1 Gatun Dam: present water releases are reduced to compensate for PPL losses If needed, extra fresh water supply to Gatun Lake to compensate for PPL losses	*B3*	*C3*	*D3*	**E3**	**F3**
4	Wsb's switched off Gatun Lake: present representative water level variation, see Figure 5.1 Gatun Dam: present water releases are reduced to compensate for PPL losses If needed, extra fresh water supply to Gatun Lake to compensate for PPL losses	*B4*	*C4*	*D4*	**E4**	**F4 = E4**
	Wsb's in operation Gatun Lake: water level > PLD +26.2 m (86.0 ft); maximum level PLD +26.7 m (87.5 ft) Gatun Dam: if needed, present water releases are reduced to maintain water level If needed, extra fresh water supply to Gatun Lake to maintain water level Gatun Dam: water releases are further reduced to compensate for PPL losses If needed, extra fresh water supply to Gatun Lake to compensate for PPL losses	–	–	–	**E*11**	**F*11**
12	Wsb's switched off Gatun Lake: water level > PLD +26.2 m (86.0 ft); maximum level PLD +26.7 m (87.5 ft) Gatun Dam: if needed, present water releases are reduced to maintain water level If needed, extra fresh water supply to Gatun Lake to maintain water level Gatun Dam: water releases are further reduced to compensate for PPL losses If needed, extra fresh water supply to Gatun Lake to compensate for PPL losses	–	–	–	**E*12**	**F*12 = E*12**
13	Wsb's in operation Gatun Lake: operating level between PLD +25.0 m (82.0 ft) and PLD +27.13 m (89.0 ft) Gatun Dam: proportional reduction of present water releases resulting in a minimum water supply to Gatun Lake	–	–	–	**E13**	**F13**
14	Wsb's switched off Gatun Lake: operating level between PLD +25.0 m (82.0 ft) and PLD +27.13 m (89.0 ft) Gatun Dam: proportional reduction of present water releases resulting in a minimum water supply to Gatun Lake	–	–	–	**E14**	**F14 = E14**

Table 5.6a Water level control scenarios Gatun Lake; different configurations of Post-Panamax Locks

For the sake of completeness we show in Table 5.6b also the water control scenarios, which have been applied in earlier salt water intrusion simulations focused on the effects of water recycling at the Pacific side of the canal (see Report E, part I):

Scenario	*Description*	*B* *3-lift locks 3 wsb's*	*C* *2-lift locks 2 wsb's*	*D* *1-lift locks 6 wsb's*	***E*** ***revised 3-lift locks 2 wsb's***	***F*** ***revised 3-lift locks 3 wsb's***
6	Wsb's switched off Gatun Lake: present representative water level variation, see Figure 5.1 Gatun Dam: present water releases are reduced to compensate for PPL losses If needed, recycling of water; lower pond > upper pond to compensate for PPL losses If needed, extra fresh water supply to Gatun Lake to compensate for PPL losses	*B6*	*C6*	–	–	–
7	Wsb's in operation Gatun Lake: present representative water level variation, see Figure 5.1 Gatun Dam: present water releases are reduced to compensate for PPL losses If needed, recycling of water; lower pond > Gatun Lake to compensate for PPL losses If needed, extra fresh water supply to Gatun Lake to compensate for PPL losses	*B7*	–	–	–	–
	Wsb's switched off Gatun Lake: present representative water level variation, see Figure 5.1 Gatun Dam: present water releases are reduced to compensate for PPL losses If needed, recycling of water; lower pond >Gatun Lake to compensate for PPL losses If needed, extra fresh water supply to Gatun Lake to compensate for PPL losses	*B8*	–	–	–	–
9	Wsb's in operation Gatun Lake: present representative water level variation, see Figure 5.1 Gatun Dam: present water releases are reduced to compensate for PPL losses If needed, recycling of water; tailbay > Gatun Lake to compensate for PPL losses If needed, extra fresh water supply to Gatun Lake to compensate for PPL losses	*B9*	–	–	–	–
10	Wsb's switched off Gatun Lake: present representative water level variation, see Figure 5.1 Gatun Dam: present water releases are reduced to compensate for PPL losses If needed, recycling of water; tailbay >Gatun Lake to compensate for PPL losses If needed, extra fresh water supply to Gatun Lake to compensate for PPL losses	*B10*	–	–	–	–

Table 5.6b Water level control scenarios Gatun Lake; recycling at Pacific side of canal

Discussion of water level control scenarios

In scenario 1 the present water level variation (Figure 5.1) and present water releases (Figure 5.2) are maintained; all extra 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 an instantaneous supply of fresh water from new water sources. Scenario 2 is like scenario 1, but in scenario 2 the wsb's are switched off. Scenarios 1 and 2 do not adversely effect the generation of electrical power at Gatun Dam.

In scenario 3 (wsb's in operation) and scenario 4 (wsb's switched off) the present water level variation is maintained and the extra water losses caused by operation of the new locks are instantaneously 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 resources.

Scenarios 5 – 10 concern the option of recycling of water at the Pacific side of the canal.
In scenarios 5, 7 and 9 (wsb's in operation) and 6, 8 and 10 (wsb's switched off) the extra water losses caused by the operation of the new locks are an instantaneously 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 is recycled; in the case that this is still insufficient the remaining portion is supplied to Gatun Lake from new water resources.

In scenarios 11 (wsb's in operation) and 12 (wsb's switched off) the water level of Gatun Lake is maintained at a minimum value of PLD + 26.2 m (see Figure 5.3a), the maximum water level is similar as at present (PLD +26.7 m). If needed the present water releases at Gatun Dam are instantaneously reduced and extra water supplied to maintain the water level at PLD + 26.2 m (see Figure 5.3b). Water releases are further reduced to compensate for the extra water losses caused by the operation of the Post-Panamax Locks or, if this is insufficient, extra water is instantaneously supplied to Gatun Lake from new water resources. Lock chamber floors are at a higher elevation in simulations in which scenarios 11 and 12 are applied (these simulations are indicated with an asterix in the name).

In scenarios 13 (wsb's in operation) and 14 (wsb's switched off) the water level of Gatun Lake varies between the extremes PLD +25.0 m (82.0 ft) and PLD +27.13 m (89.0 ft). The *present* water releases at Gatun Dam are in proportion reduced to compensate for the extra water losses caused by operation of the Post-Panamax Locks; the reduction of water releases is scheduled in such a way that the supply of fresh water from new water resources is minimum (see Section 5.1.3 for explanation of the water control method); the water level of Gatun Lake varies about an average value of PLD +26.1 m (+85.6 ft, similar as at present).

Extra water losses caused by operation of Post-Panamax Locks

The extra water losses caused by operation of the new locks are growing when the Post-Panamax traffic intensity increases. Table 5.7a presents the extra water losses of the Post-Panamax Locks (previous lock configurations and revised 3-lift lock configurations) for a single ship transfer from ocean to ocean. These values are based on a semi-convoy mode of operation and a mean water level difference between Gatun Lake and both oceans of 25.7 m. A mean water level difference of 25.7 m can be regarded as a representative value in the present situation. Each transiting ship causes then a water loss of (25.7 m / n) * l_{lock} * b_{lock} * 2 * (1-s), where n = number of lifts, and s = water saving rate of wsb's for each lift. The chamber length l_{lock} is inclusive the area of the gate recesses. The chamber width b_{lock} amounts to 61.0 m in the previous designs and 54.86 m in the revised 3-lift lock design. Notice that an uplocking ship causes a downward water flow (equal to the submerged volume of the ship), while a downlocking ship causes an upward flow. Since a ship moves up at one side of the canal and moves down at the other side, the resulting effect on the water volume of Gatun Lake is zero (apart from differences caused by tidal movements; in the long run however, the mean value of these differences is zero).
When a minimum water level of Gatun Lake is maintained of PLD +26.2 m (scenarios 11 and 12) the mean water level difference between Gatun Lake and both oceans is a little greater than 25.7 m, about 26.1 m. This difference is accounted for in SWINLOCKS simulations.

The total quantity of water that is lost each year by operation of the Post-Panamax Locks depends on the number of ships that is transferred. Table 5.7b presents the yearly losses of the considered lock configurations for a ship traffic intensity of 15 Post-Panamax vessels a day.

Post-Panamax Lock configuration	*Representative chamber length and width (m)*	*Number of wsb's per lift and water saving rate per lift*	*Extra water losses each ship transfer no wsb's (10^6 m^3/day)*	*Extra water losses each ship transfer in case of wsb's (10^6 m^3/day)*
B 3-lift locks / rolling gates	505 x 61	3 – 60%	0.53	0.21
C 2-lift locks / mitre gates	515 x 61	2 – 50%	0.81	0.40
D 1-lift locks / rolling gates	540 x 61	6 – 75%	1.69	0.42
E / E* **revised 3-lift locks / rolling gates**	490 x 54.86	2 – 50%	0.46	0.23
F / F* **revised 3-lift locks / rolling gates**	490 x 54.86	3 – 60%	0.46	0.18

Table 5.7a Extra water losses caused by a single ship transfer in third, new shipping lane with Post-Panamax Locks

Post-Panamax Lock configuration	*Representative chamber length and width (m)*	*Number of wsb's per lift and water saving rate per lift*	*Extra water losses per year for 15 PP-ships/day no wsb's (10^9 m^3)*	*Extra water losses per year for 15 PP-ships/day in case of wsb's (10^9 m^3)*
B 3-lift locks / rolling gates	505 x 61	3 – 60%	2.89	1.16
C 2-lift locks / mitre gates	515 x 61	2 – 50%	4.42	2.21
D 1-lift locks / rolling gates	540 x 61	6 – 75%	9.27	2.32
E / E* **revised 3-lift locks / rolling gates**	490 x 54.86	2 – 50%	2.52	1.26
F / F* **revised 3-lift locks / rolling gates**	490 x 54.86	3 – 60%	2.52	1.01

Table 5.7b Extra water losses per year caused by 15 Post-Panamax ship transfers per day in third, new shipping lane with Post-Panamax Locks

Note that the existing shipping locks in west and east shipping lane with a chamber length of 330 m and a chamber width of 33.5 m cause a total water loss of 2.49×10^9 m^3 per year (ship traffic intensity: 18 ship transfers per day in each shipping lane), which is greater than the losses caused by the operation of the Post-Panamax Locks (at 15 ship transfers per day),

provided that water saving basins are applied. The water losses have to be seen in relation to the water volume of Gatun Lake, which on average amounts to about 5.12 x 10^9 m^3.

The yearly water losses caused by operation of the locks are also shown in next Figure 5.5.

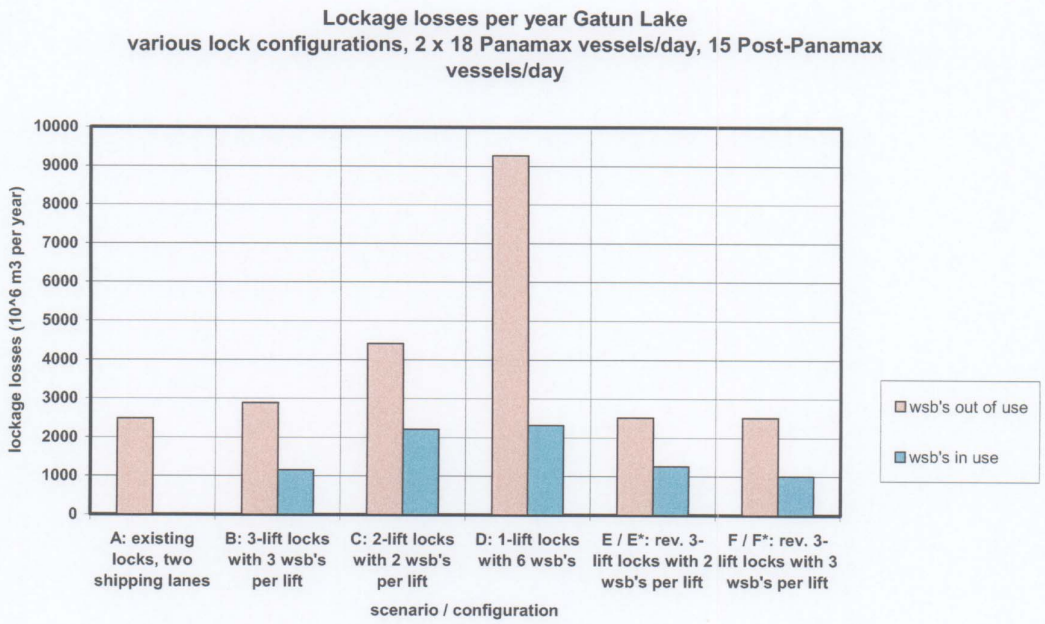


Figure 5.5 Gatun Lake: water losses per year caused by operation of existing and Post-Panamax Locks

Water level control scenarios Gatun Lake compared

The present representative water level of Gatun Lake (A) is shown as a function of time in Figure 5.6a together with the water levels which occur when alternative water level control scenarios are applied. The corresponding water releases and extra water supplies are shown in Figure 5.6b; the values of Figure 5.6b concern the summed water release and water supply quantities during a full year. The figures are valid for a ship traffic intensity of 15 Post-Panamax vessel transfers per day in the new shipping lane, in addition to 18 ship transfers per day in both west and east shipping lane. Beside the data of the revised 3-lift lock configurations E and F also the data of the earlier 3-lift lock configuration B with 3 wsb's per lift (CPP design, see Report C) is shown.

As can be seen in Figure 5.6b water control scenario 3 requires the supply of extra water to Gatun Lake in the dry season, while at the same time large quantities of water are released in the wet season. From the view point of conservation of water this is not desired. The same effect, but even stronger, occurs in scenario 11. The supply of water is prevented in scenario 13; this is realized by a proportional reduction of the water releases throughout the year. Notice that the outflow of water in scenario 13 is the same as the net outflow (water release minus water supply) in scenario 3 and scenario 11. To illustrate the differences between the scenarios 3, 11 and 13, Figure 5.6c and Figure 5.6e show the daily water releases and extra

water supplies throughout the year for lock configuration E (revised 3-lift locks with 2 wsb's per lift) and lock configuration F (revised 3-lift locks with 3 wsb's per lift) in comparison to the present water releases (A).

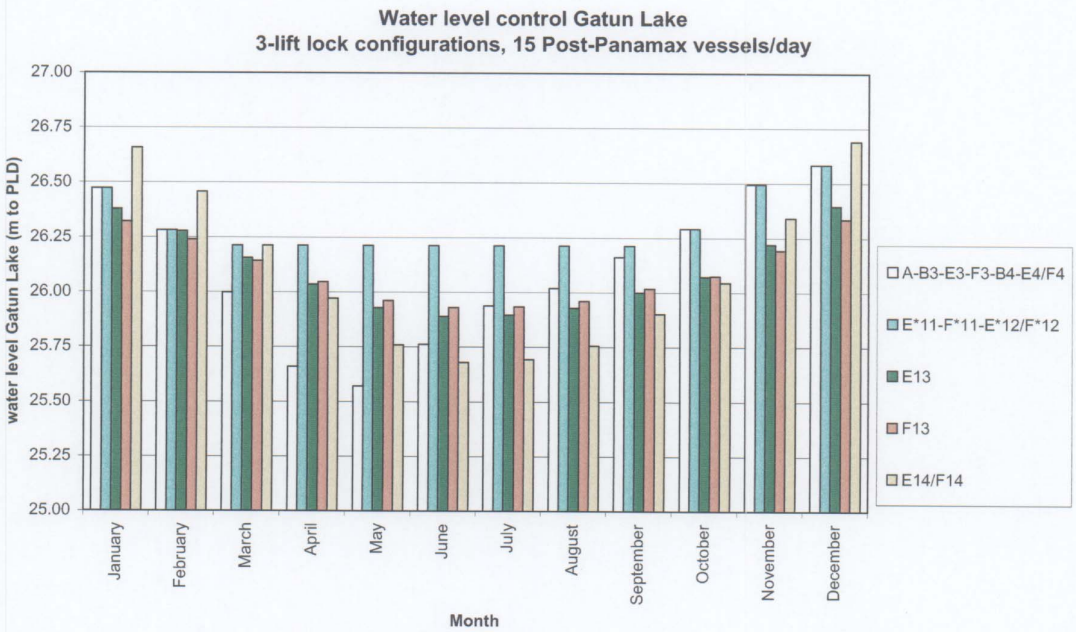


Figure 5.6a **Comparison of present representative water level of Gatun Lake (A) with water level in the case of alternative water level control scenarios (15 PP-vessels per day)**

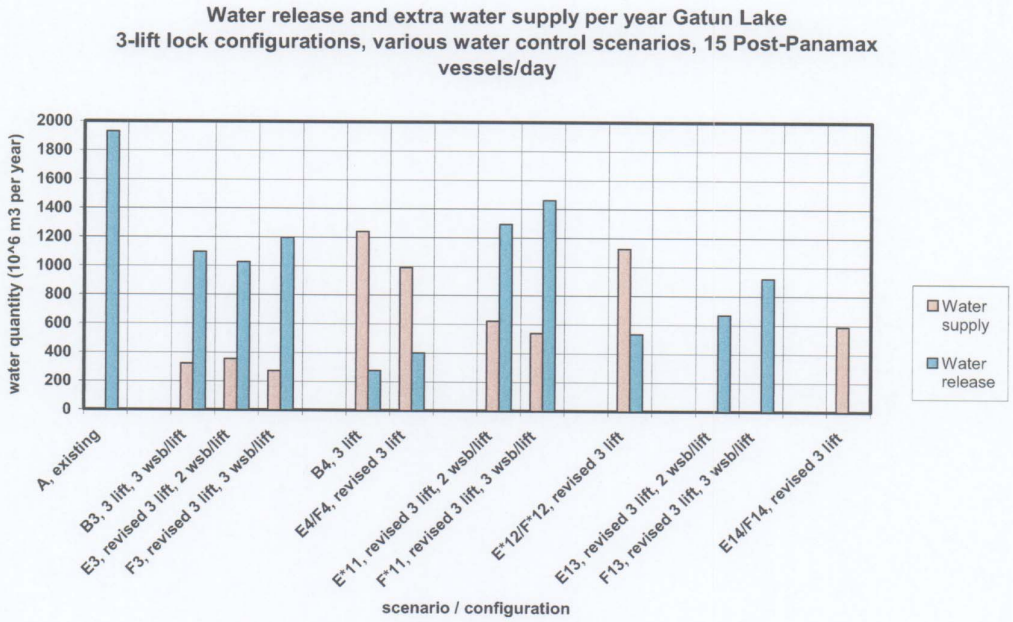


Figure 5.6b **Comparison of present representative water releases of Gatun Lake (A) with water releases and extra water supplies in the case of alternative water level control scenarios (15 PP-vessels per day)**

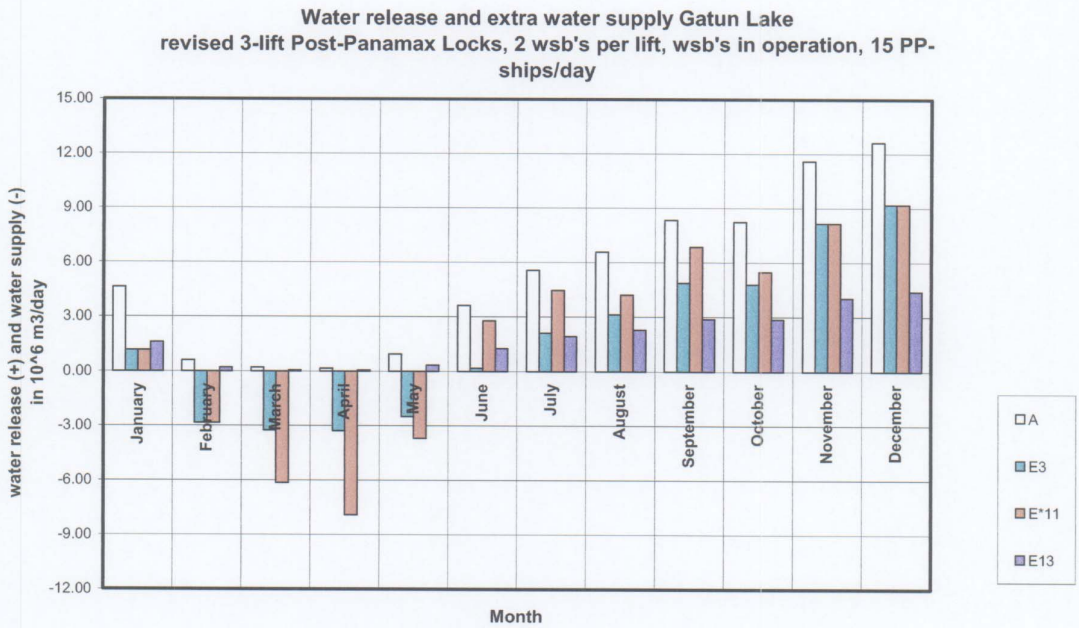


Figure 5.6c Daily water releases and extra water supplies Gatun Lake as a function of water control scenario, configuration E / E* (revised 3-lift locks, 2 wsb's per lift) , wsb's in operation (15 PP-vessels per day)

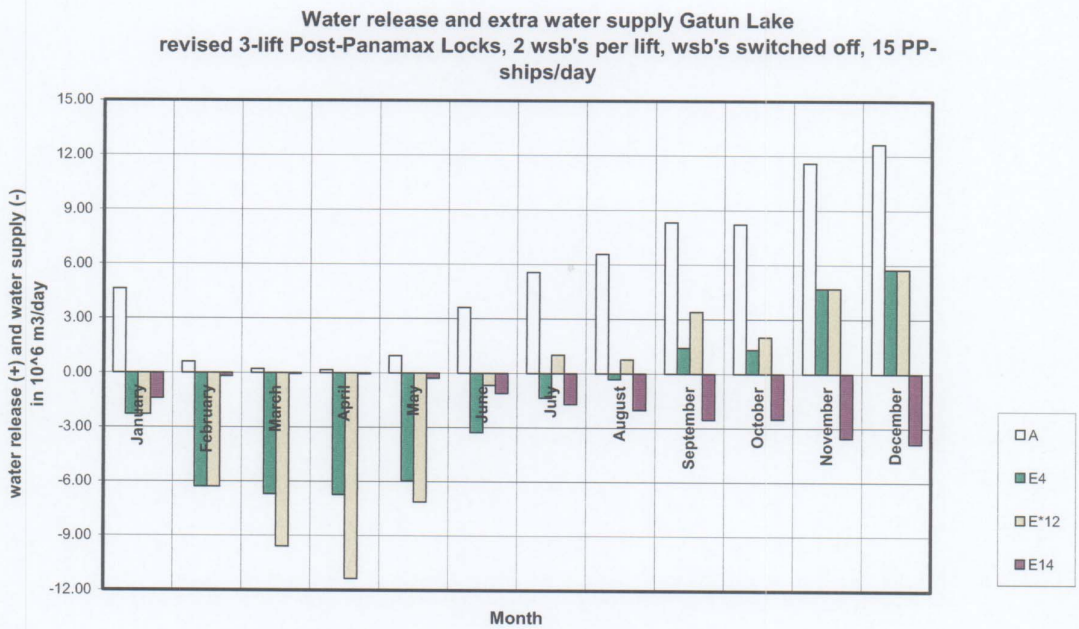


Figure 5.6d Daily water releases and extra water supplies Gatun Lake as a function of water control scenario, configuration E / E* (revised 3-lift locks, 2 wsb's per lift), wsb's switched off (15 PP-vessels per day)

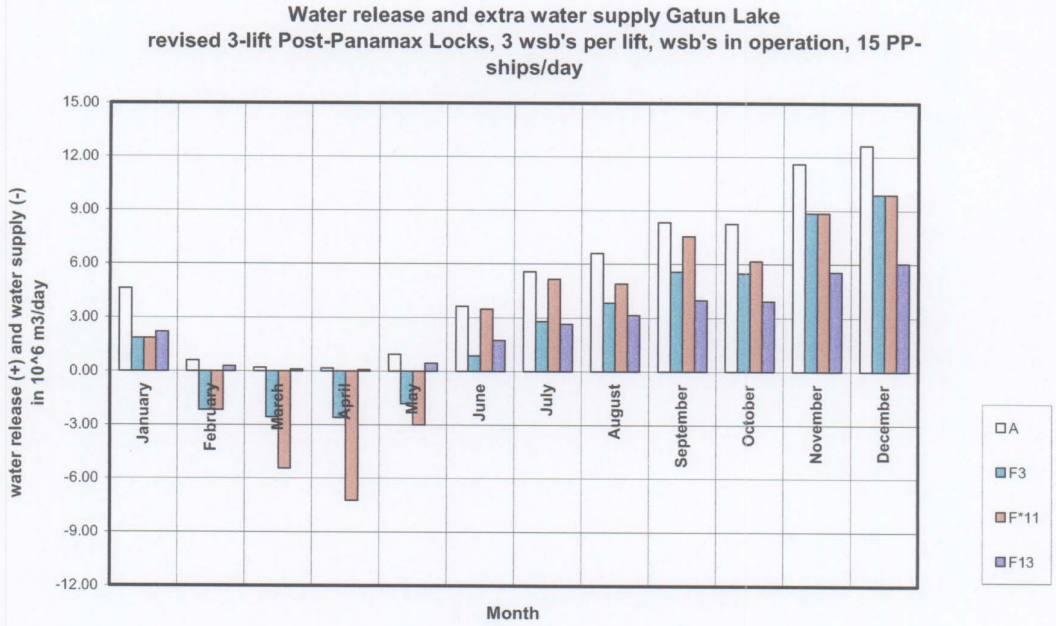


Figure 5.6e **Daily water releases and extra water supplies Gatun Lake as a function of water control scenario, configuration F / F* (revised 3-lift locks, 3 wsb's per lift) , wsb's in operation (15 PP-vessels per day)**

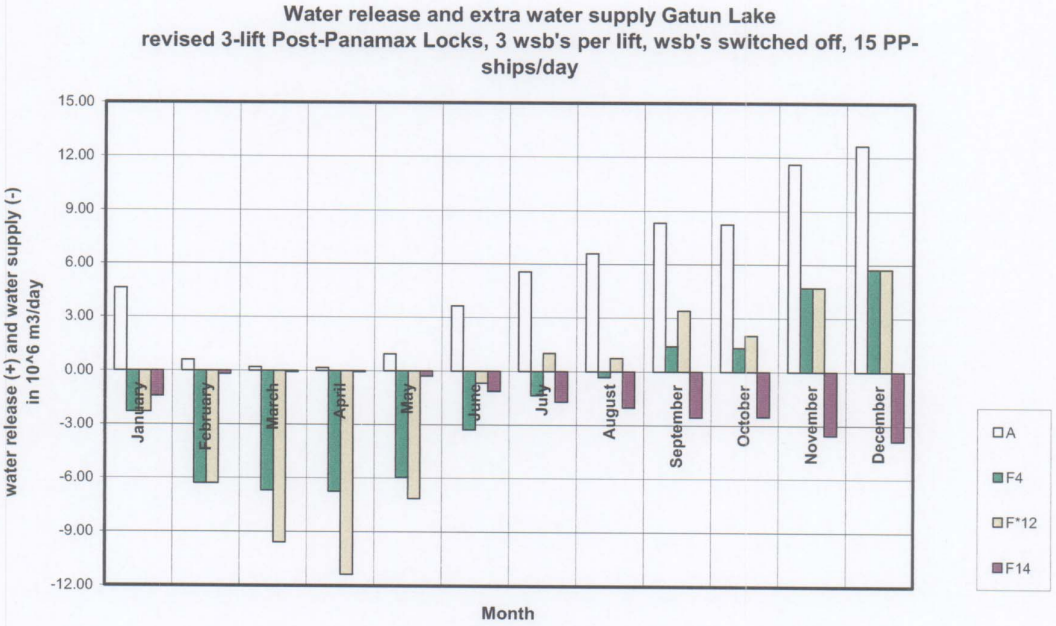


Figure 5.6f **Daily water releases and extra water supplies Gatun Lake as a function of water control scenario, configuration F / F* (revised 3-lift locks, 3 wsb's per lift), wsb's switched off (15 PP-vessels per day)**

In scenarios 4, 12 and 14 the wsb's of the Post-Panamax Locks are switched off. As a consequence a larger quantity of water is lost from Gatun Lake due to the operation of the locks. Figure 5.6b presents the water releases and extra water supplies (total quantities for a full year) that are required in this case. As can be seen the extra water supply quantity is considerable in scenario 4, and is even higher in scenario 12. Despite the high water supply quantities, still water is released in the wet season. In scenario 14 the release of water in the wet season is fully blocked, which results in a strong reduction of the extra water supply in the dry season. Notice that the supply of water in scenario 14 equals the net inflow of water (extra water supply minus water release) in scenarios 4 and 12. The daily water releases and extra water supplies throughout the year, when wsb's are switched off, are shown in Figure 5.6d for lock configuration E (revised 3-lift locks with 2 wsb's per lift) and in Figure 5.6f for lock configuration F (revised 3-lift locks with 3 wsb's per lift) in comparison to the present water releases (A). These figures illustrate that in scenario 14 extra water supplies are needed in the wet season, instead of the dry season, which is favourable in view of the availability of fresh water. Note that water quantities of lock configuration E are equal to those of lock configuration F when wsb's are switched off.

In the case that water saving basins are used, a lesser quantity of water is lost from Gatun Lake and this offers the possibility that a part of the thus saved water is used for the operation of a salt water intrusion mitigation system. This may reduce the supply of extra fresh water to the lake, needed to operate the mitigation system. It is emphasized however, that, in general, a lesser supply of fresh water to Gatun Lake is unfavorable in view of a refreshment of the water in the lake; it will adversely effect the salt concentration of the lake. The mitigation system has to compensate the effects caused by a lesser fresh water supply. This will be analysed in Chapter 7.

In scenarios 3 and 4 the average water level of Gatun Lake (about PLD +26.1 m) and the water level variation about this mean value is similar as at present, see Figure 5.6a. In scenarios 11 and 12 the average water level is higher, about PLD +26.3 m, but the water level variation is smaller, due to the selected small operational water level range.
In scenarios 13 and 14 an average water level of PLD +26.1 m is selected, and the variation of the water level is controled by a careful release of water at Gatun Dam (aimed to prevent or to minimize the supply of extra water to Gatun Lake). In scenarios 13 and 14 the water releases / extra water supplies are dependent of the number of ships that pass the canal (similar as in scenarios 3, 4 ,11 and 12), but the water level variation is also a function of the number of ships, see Section 5.1.3 for explanation.
It is possible to select a higher mean water level for Gatun Lake in scenarios 13 and 14 than PLD +26.1 m (the maximum water level still remains below the upper limit level of PLD +27.13 m). A higher mean water level has the advantage that there is a greater back up of water for a dry year. However, the lock operation losses will be somewhat greater: in the case of a mean water level of e.g. PLD +26.4 m instead of PLD +26.1 m the water losses increase with about 1%.

Water control scenarios 13 and 14 ask for an active and careful planning of the water releases at Gatun Dam. This may put stronger demands on the operation of Gatun Dam. Moreover, since a considerably smaller quantity of water is available at Gatun Dam for the generation of electrical power, a search for additional sources of energy may be necessary.

5.2 Tide variations and salt concentrations of seaside tailbays

The tide variation at the Pacific side of the Panama Canal is relatively strong (the sea level near Balboa varies between the extremes PLD -3.44 m and PLD +3.60 m; mean sea level PLD +0.30 m, mean low spring tide PLD – 2.32 m).
The tide variation at the Atlantic side is small compared to the tide variation at the Pacific side (the tide near Colon varies between the extremes PLD -0.38 m and PLD +0.56 m; mean sea level PLD +0.06 m, mean low tide PLD –0.12 m).
The water level variation in the sea entrances is predicted as a function of time in the simulation model SWINLOCKS. To that purpose sinusoidal functions are applied. The resultant tide shape may not fully be conform the real water level fluctuation near the locks, but in the long run the tidal period and the tidal amplitude are the quantities that count, rather than the real course of the tidal movement.

The tidal movement in the tailbays at the Pacific side is predicted with:

$$h_{tailbay} = 0.305 + A.\sin\omega_1 t + B.\sin\omega_2 t$$

with:

$h_{tailbay}$	= tidal movement (m to PLD)
A	= amplitude 1st component = 1.8 m
B	= amplitude 2nd component = 0.575 m
ω_1	= frequency 1st component = ($2\pi/44760$)
ω_2	= frequency 2nd component = ($2\pi/43233$)
t	= time (s)

giving a minimum value of PLD –2.07 m and a maximum value of PLD +2.68 m (see Figure 5.7a).

The tidal movement in the tailbays at the Atlantic side is predicted with:

$$h_{tailbay} = 0.06 + A.\sin\omega_1 t + B.\sin\omega_2 t$$

with:

A	= amplitude 1st component = 0.16 m
B	= amplitude 2nd component = 0.04 m

giving a minimum value of PLD –0.14 m and a maximum value of PLD +0.26 m (see Figure 5.7b).

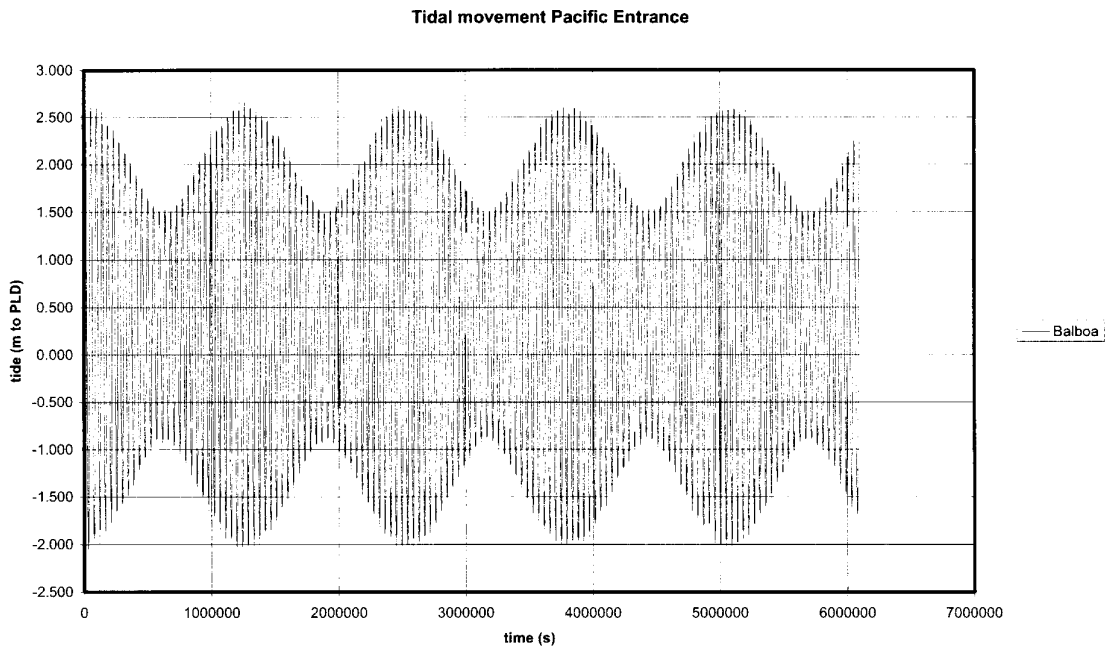


Figure 5.7a Tailbays at Pacific side: prediction of tidal movement in SWINLOCKS

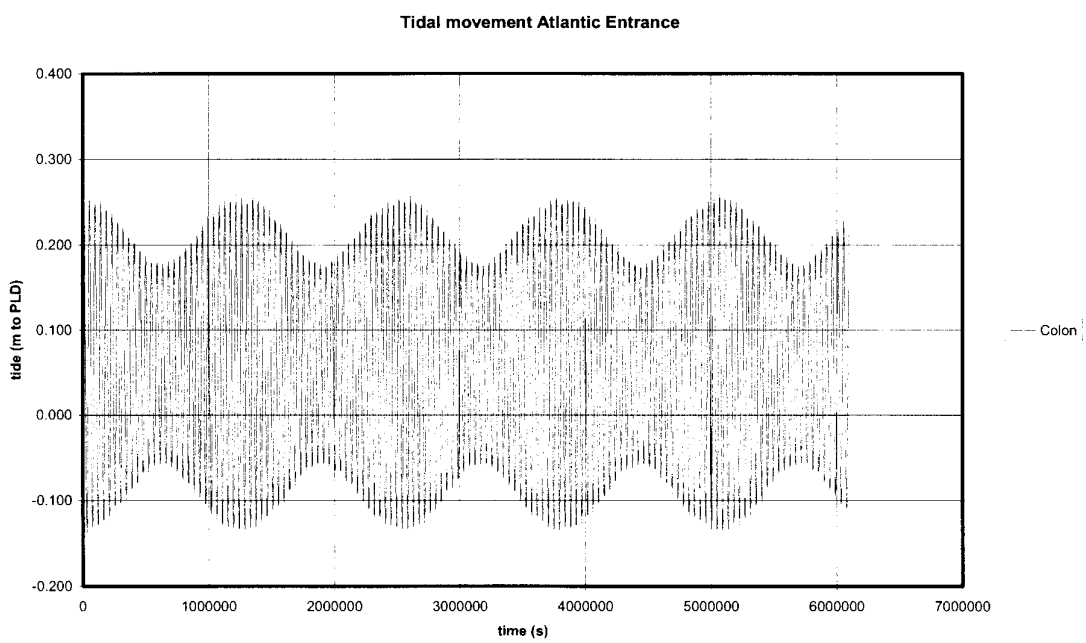


Figure 5.7b Tailbays at Atlantic side: prediction of tidal movement in SWINLOCKS

The salt concentration in the tailbays at the seaside of the locks fluctuates as a function of the season; this holds in particular for the tailbays at the Pacific side (see also Report A). The salt concentration in the tailbays at the Pacific side varies between about 28 ppt (wet season) and 34 ppt (dry season); the effect of a lower temperature in the dry season (21 °C

versus 28 °C in the wet season) is not separately taken into account in the simulation model. Instead, we have increased the salinity level in the dry season, using the relationships which exist between temperature, density and salinity. The salt concentration in the tailbays at the Atlantic side varies slightly about a value of 31 ppt. The following salt concentrations are used in the present salt water intrusion simulations:

Month	*Salt concentration tailbays Pacific side (ppt)*	*Salt concentration tailbays Atlantic side (ppt)*
January	31	30
February	34	31
March	37	32
April	37	32
May	35	32
June	33	31
July	31	30
August	28	30
September	28	30
October	28	30
November	28	30
December	28	30

Table 5.9 Temperature compensated salt concentration of seaside tailbays

The salt concentrations presented in the above table are also shown in next Figure 5.8.

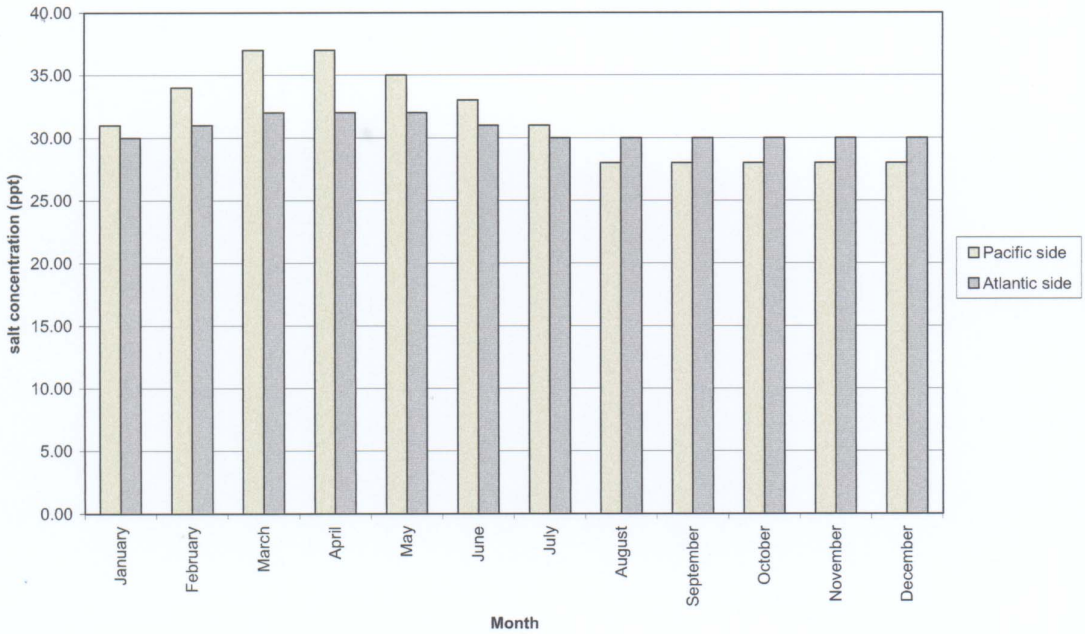


Figure 5.8 Temperature compensated salt concentration of seaside tailbays

6 Initial simulations for revised 3-lift locks and selected mitigation systems

6.1 Introduction

The salt water intrusion simulations with SWINLOCKS focus on the revised 3-lift Post-Panamax Lock configuration with either two wsb's per lift or three wsb's per lift, in addition to the existing locks.

A series of initial simulations is executed for the revised 3-lift locks without any mitigation system in operation (see Table 6.3). These simulations are done using water control scenario 3 (wsb's in operation), scenario 4 (wsb's switched off), scenario 13 (wsb's in operation) and scenario 14 (wsb's switched off). Simulations are also done for scenario 11 (wsb's in operation) and scenario 12 (wsb's switched off), but in these simulations the lock chamber floors of the revised 3-lift locks are at a higher elevation (see Table 6.2), which is related to the selected high lower limit level of PLD +26.2 m of Gatun Lake in these scenarios. The simulations for revised 3-lift locks with higher chamber floors are indicated with an asterix in their name. An overview of scenarios is shown in Table 5.6a.

Next, initial simulations are executed for the revised 3-lift locks with each of four selected and modeled mitigation systems (mitigation systems I – IV, see Chapter 4) in operation; in these simulations water control scenarios 15 – 18 (see Table 6.7) are applied. These water control scenarios are similar to water control scenario 13 (they all have in common that fresh water supplies to Gatun Lake are minimized by an active control of water releases at Gatun Dam), but additional water is used for the operation of the mitigation systems.

In the initial simulations the effect of salt water intrusion mitigation systems on the salt concentration levels of Gatun Lake and Miraflores Lake is studied for a ship traffic intensity of 15 Post-Panamax ship transfers a day in the new shipping lane. The present ship traffic intensity in the existing two shipping lanes (18 ship transfers a day in each of the two lanes) is maintained. Table 6.1 presents an overview of the number of ships per lane and the mixture of vessel types applied in the simulations. Apart from ship type X (beam 45.7 m, S = 235000 m^3), which replaces the wider ship type VIII (beam 54.0 m, S = 285,000 m^3), these mixtures are similar as applied in earlier computations, see Reports B, C and D.
With the selection of a ship traffic intensity of 15 Post-Panamax vessels a day in the new shipping lane and 36 Panamax vessels per day in the existing west and east shipping lanes the present results can be linked with the results of former simulations for other lock systems (reference is made to earlier reports, see Section 1.3). The latest traffic projections of ACP indicate however a lesser traffic intensity in the existing shipping lanes of 28 – 30 ship transfers per day when the new lane is in operation.

The results of the initial simulations are sufficient for an adequate, mutual comparison of the effects of the four mitigation systems (in terms of salt water intrusion and extra water loss).

On the basis of these results the programme for further simulations is set up. The further simulations are discussed in Chapter 7.

Vessel type	*Water displacement S (m^3)*	*15 PP-ships per day in new lane*	*10 PP-ships per day in new lane*	*5 PP-ships per day in new lane*
Existing shipping lane West				
type I	15,000	8	8	8
type II	45,000	4	4	4
type III	90,000	6	6	6
Total		**18**	**18**	**18**
Existing shipping lane East				
type I	15,000	8	8	8
type II	45,000	4	4	4
type III	90,000	6	6	6
Total		**18**	**18**	**18**
Future third shipping lane				
type IV	120,000	5	2	0
type X	235,000	10	8	5
Total		**15**	**10**	**5**

Table 6.1 SWINLOCKS simulations: ship transfers in existing shipping lanes and third, new lane with Post-Panamax Locks

lock / forebay	*floor level of revised 3-lift locks (m to PLD)*	*floor level in scenarios 11 and 12 (m to PLD)*
Lock U	-19.09	-19.09
Lock V	-9.98	-9.57
Lock W	-0.87	-0.06
Gatun W forebay	+8.23	+9.15
Gatun Z forebay	+8.23	+9.15
Lock Z	-0.23	+0.58
Lock Y	-8.69	-8.28
Lock X	-17.15	-17.15

Table 6.2 Floor level of lock chambers of revised 3-lift locks in scenarios 11 and 12

6.2 Initial simulations for revised 3-lift locks without mitigation systems

6.2.1 Set up of simulations for revised 3-lift locks without mitigation system

Table 6.3 presents an overview of simulations for the revised 3-lift locks with 2 or 3 wsb's per lift in operation or switched off, but without mitigation systems. The ship traffic intensity is 15 Post-Panamax vessels a day in the new shipping lane and 18 vessels a day in both west and east shipping lane (see Table 6.1). In *earlier studies* a ship traffic intensity of

15 Post-Panamax vessels was assumed for year 50 after opening of the new lane (in year 2060). At present the expectations for ship traffic development of the Panama Canal are different, so that dates in the simulations are not relevant anymore. However, in order to be consistent with the earlier studies, simulations are executed for the 5-year period 2056-2060. The dates of the simulations have, in fact, no relevant effect on the results of the simulations.

Tidal fluctuations and salt concentrations of seaside tailbays are in conformation with Section 5.2. Salt exchange coefficients are as explained in Section 4.5, and are similar as in earlier simulations for 3-lift locks (with and without wsb's).

The water level of Miraflores Lake is kept constant at PLD +16.58 m (PLD +54.4 ft). The water level of Gatun Lake varies as a function of time; Figure 5.6a shows the water level variation in the various applied water control scenarios.
The water releases of Miraflores Lake are shown in Figure 5.2 and Table 5.3. The water releases and extra water supplies of Gatun Lake are shown in Figures 5.6c-f for scenarios 3, 4, 11, 12, 13 and 14 respectively; the same quantities are presented in Tables 6.4a-b.

Water control scenario Gatun Lake	*Description*	***E revised 3-lift locks 2 wsb's / lift***	***F revised 3-lift locks 3 wsb's / lift***
		case	*case*
3	Wsb's in operation Gatun Lake: present representative water level variation, see Figure 5.1 Gatun Dam: present water releases are reduced to compensate for PPL losses If needed, extra fresh water supply to Gatun Lake to compensate for PPL losses	E3-15PP	F3-15PP
4	Wsb's switched off Gatun Lake: present representative water level variation, see Figure 5.1 Gatun Dam: present water releases are reduced to compensate for PPL losses If needed, extra fresh water supply to Gatun Lake to compensate for PPL losses	E4-15PP	F4-15PP = E4-15PP
11	Wsb's in operation Gatun Lake: water level > PLD +26.2 m (86.0 ft); maximum level PLD +26.7 m (87.5 ft) Gatun Dam: if needed, present water releases are reduced to maintain water level If needed, extra fresh water supply to Gatun Lake to maintain water level Gatun Dam: water releases are further reduced to compensate for PPL losses If needed, extra fresh water supply to Gatun Lake to compensate for PPL losses	E*11-15PP	F*11-15PP
12	Wsb's switched off Gatun Lake: water level > PLD +26.2 m (86.0 ft); maximum level PLD +26.7 m (87.5 ft) Gatun Dam: if needed, present water releases are reduced to maintain water level If needed, extra fresh water supply to Gatun Lake to maintain water level Gatun Dam: water releases are further reduced to compensate for PPL losses If needed, extra fresh water supply to Gatun Lake to compensate for PPL losses	E*12-15PP	F*12-15PP = E*12-15PP
13	Wsb's in operation Gatun Lake: operating level between PLD +25.0 m (82.0 ft) and PLD +27.13 m (89.0 ft) Gatun Dam: proportional reduction of present water releases resulting in a minimum water supply to Gatun Lake	E13-15PP	F13-15PP
14	Wsb's switched off Gatun Lake: operating level between PLD +25.0 m (82.0 ft) and PLD +27.13 m (89.0 ft) Gatun Dam: proportional reduction of present water releases resulting in a minimum water supply to Gatun Lake	E14-15PP	F14-15PP = E14-15PP

Note:
Simulations with an asterix concern revised 3-lift locks with a higher lock chamber floor, see Table 6.2

Table 6.3 Initial simulations for revised 3-lift locks; no mitigation system, 15 PP ships a day

Month	*scenario 3*		*scenario 4*		*scenario 11*		*scenario 12*		*scenario 13*		*scenario 14*	
	released	*supplied*	*released*	*supplied*	*released*	*supplied*	*released*	*supplied*	*released*	*supplied*	*released*	*supplied*
January	1.16	0.00	0.00	2.29	1.16	0.00	0.00	2.29	1.60	0.00	0.00	1.41
February	0.00	2.85	0.00	6.30	0.00	2.85	0.00	6.30	0.21	0.00	0.00	0.18
March	0.00	3.25	0.00	6.70	0.00	6.14	0.00	9.59	0.07	0.00	0.00	0.06
April	0.00	3.29	0.00	6.74	0.00	7.92	0.00	11.37	0.06	0.00	0.00	0.05
May	0.00	2.51	0.00	5.96	0.00	3.69	0.00	7.14	0.33	0.00	0.00	0.29
June	0.18	0.00	0.00	3.27	2.78	0.00	0.00	0.67	1.26	0.00	0.00	1.11
July	2.10	0.00	0.00	1.35	4.46	0.00	1.01	0.00	1.93	0.00	0.00	1.70
August	3.13	0.00	0.00	0.32	4.20	0.00	0.75	0.00	2.29	0.00	0.00	2.01
September	4.87	0.00	1.42	0.00	6.85	0.00	3.40	0.00	2.89	0.00	0.00	2.54
October	4.78	0.00	1.33	0.00	5.47	0.00	2.02	0.00	2.86	0.00	0.00	2.51
November	8.14	0.00	4.69	0.00	8.14	0.00	4.69	0.00	4.03	0.00	0.00	3.54
December	9.19	0.00	5.74	0.00	9.19	0.00	5.74	0.00	4.39	0.00	0.00	3.86

Table 6.4a Gatun Lake: mean daily released and supplied water quantities in 10^6 m^3/day; 15 Post-Panamax ships a day, revised 3-lift locks with 2 wsb's per lift

Month	*scenario 3*		*scenario 4*		*scenario 11*		*scenario 12*		*scenario 13*		*scenario 14*	
	released	*supplied*	*released*	*supplied*	*released*	*supplied*	*released*	*supplied*	*released*	*supplied*	*released*	*supplied*
January	1.85	0.00	0.00	2.29	1.85	0.00	0.00	2.29	2.20	0.00	0.00	1.41
February	0.00	2.16	0.00	6.30	0.00	2.16	0.00	6.30	0.29	0.00	0.00	0.18
March	0.00	2.56	0.00	6.70	0.00	5.45	0.00	9.59	0.10	0.00	0.00	0.06
April	0.00	2.60	0.00	6.74	0.00	7.23	0.00	11.37	0.08	0.00	0.00	0.05
May	0.00	1.82	0.00	5.96	0.00	3.00	0.00	7.14	0.45	0.00	0.00	0.29
June	0.87	0.00	0.00	3.27	3.47	0.00	0.00	0.67	1.73	0.00	0.00	1.11
July	2.79	0.00	0.00	1.35	5.15	0.00	1.01	0.00	2.65	0.00	0.00	1.70
August	3.82	0.00	0.00	0.32	4.89	0.00	0.75	0.00	3.14	0.00	0.00	2.01
September	5.56	0.00	1.42	0.00	7.54	0.00	3.40	0.00	3.97	0.00	0.00	2.54
October	5.47	0.00	1.33	0.00	6.16	0.00	2.02	0.00	3.93	0.00	0.00	2.51
November	8.83	0.00	4.69	0.00	8.83	0.00	4.69	0.00	5.54	0.00	0.00	3.54
December	9.88	0.00	5.74	0.00	9.88	0.00	5.74	0.00	6.04	0.00	0.00	3.86

Table 6.4b Gatun Lake: mean daily released and supplied water quantities in 10^6 m^3/day; 15 Post-Panamax ships a day, revised 3-lift locks with 3 wsb's per lift

6.2.2 Results of simulations for revised 3-lift locks without mitigation system

The computed volume-averaged salt concentrations (in ppt) of Miraflores Lake and Gatun Lake are presented in Table 6.5. The salt concentrations of the lakes fluctuate as a function of wet and dry season and the scenarios for control of the water level of Gatun Lake. Salt concentration fluctuations of some selected cases are shown in Annex A: 'Selected figures

initial SWINLOCKS simulations'. Simulations have been executed for a period of five year. The figures show that stable salt concentration values occur already after about three years.

The computed maximum and minimum salt concentration values of Miraflores Lake and Gatun Lake in the last year of the considered period are presented in Table 6.5. For reasons of comparison also the present salinity levels of the lakes are shown (Case A) and the salinity levels computed for the former, bigger 3-lift locks (CPP design) for water control scenarios 3 and 4, and 15 Post-Panamax vessels a day (Cases B3-50 and B4-50, see Report C).

Case / water control scenario	*Volume-averaged salt concentration (ppt) Miraflores Lake*		*Volume-averaged salt concentration (ppt) Gatun Lake*	
	minimum	*maximum*	*minimum*	*maximum*
Existing situation				
A	0.64	1.42	0.010	0.027
3-lift locks – 3 wsb's/lift				
B3-50	0.82	2.15	0.38	0.86
B4-50	0.81	1.92	0.36	0.52
Revised 3-lift locks – 2 wsb's/lift				
E3-15PP	0.76	1.97	0.28	0.62
E4-15PP	0.76	1.84	0.27	0.43
E*11-15PP	0.74	1.95	0.24	0.54
E*12-15PP	0.74	1.82	0.24	0.38
E13-15PP	0.85	2.08	0.45	0.68
E14-15PP	0.90	2.02	0.52	0.58
Revised 3-lift locks – 3 wsb's/lift				
F3-15PP	0.77	2.02	0.29	0.69
F4-15PP = E4-15PP	0.76	1.84	0.27	0.43
F*11-15PP	0.75	2.01	0.25	0.61
F*12-15PP = E*12-15PP	0.74	1.82	0.24	0.38
F13-15PP	0.83	2.10	0.41	0.71
F14-15PP = E14-15PP	0.90	2.02	0.52	0.58

Table 6.5 Maximum and minimum volume-averaged salt concentration of Miraflores Lake and Gatun Lake; present (A), 3-lift locks (B) and revised 3-lift locks with 2 wsb's (E) and 3 wsbs's (F) per lift, 15 PP-vessels a day, various water control scenarios

The values in Table 6.5 have been plotted in Figure 6.1 (Miraflores Lake) and Figure 6.2 (Gatun Lake). Since the water control scenarios of Gatun Lake have influence on the salt concentration, the results have to be considered in relation to the water releases at Gatun Dam and the extra water supplies to Gatun Lake. The water releases and extra water supplies *per year* are shown in Figure 6.3. From this figure it can be read that a quantity of 1.93×10^9 m^3 per year is released *at present* at Gatun Dam (1.45×10^9 m^3 used for hydropower and 0.48×10^9 m^3 spilled, see Table 5.4). The totally released water quantity is smaller when the 3-lift Post-Panamax locks are in operation; this is true for all applied water control scenarios and lock configurations. Scenarios 13 and 14 are most efficient in view of water

conservation: in these scenarios the supply of extra water from new water resources is minimum. This is realized by a lesser water release in the wet season as can be read from Figures 6.4 and 6.5, which present the daily water releases and water supplies throughout the year.

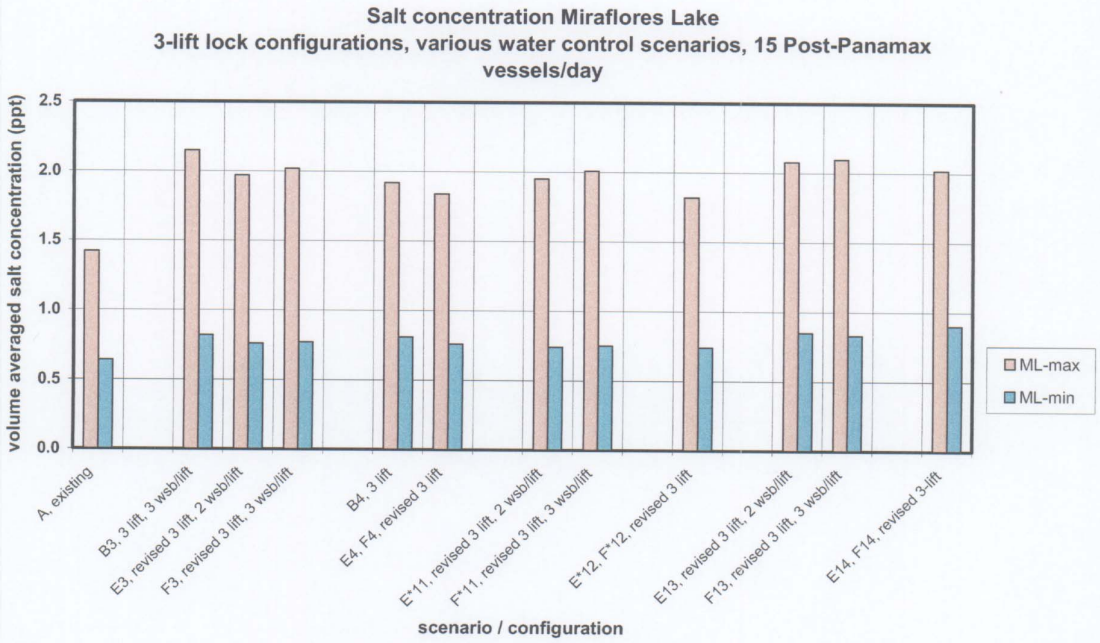


Figure 6.1 **Miraflores Lake: volume-averaged salt concentration (in ppt), maximum and minimum values, 15 PP-vessels/day, various water control scenarios**

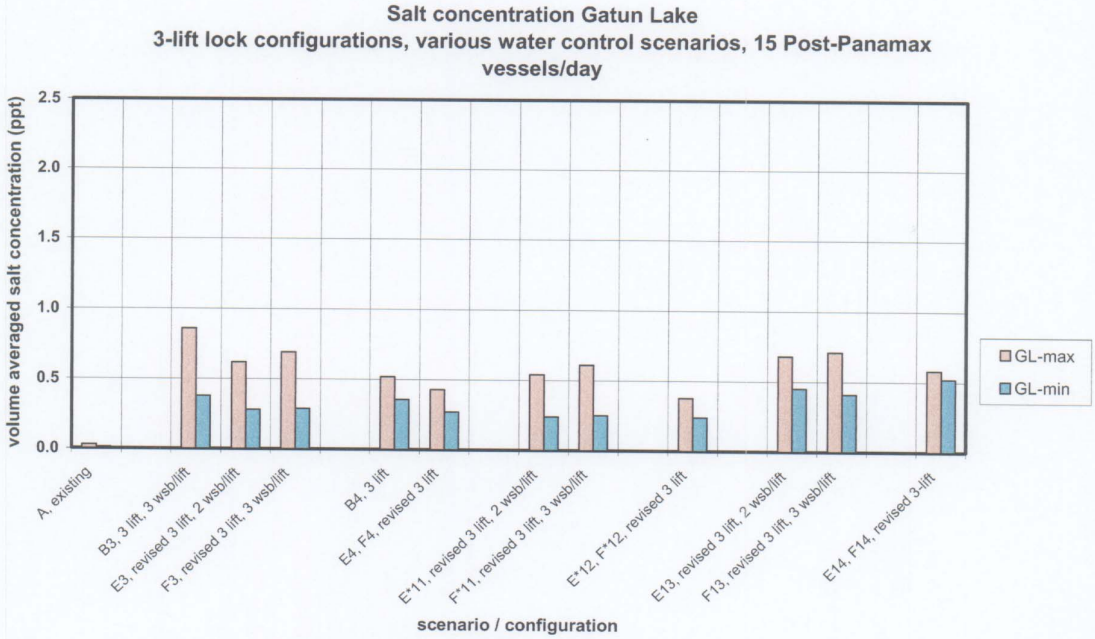


Figure 6.2 **Gatun Lake: volume-averaged salt concentration (in ppt), maximum and minimum values, 15 PP-vessels/day, various water control scenarios**

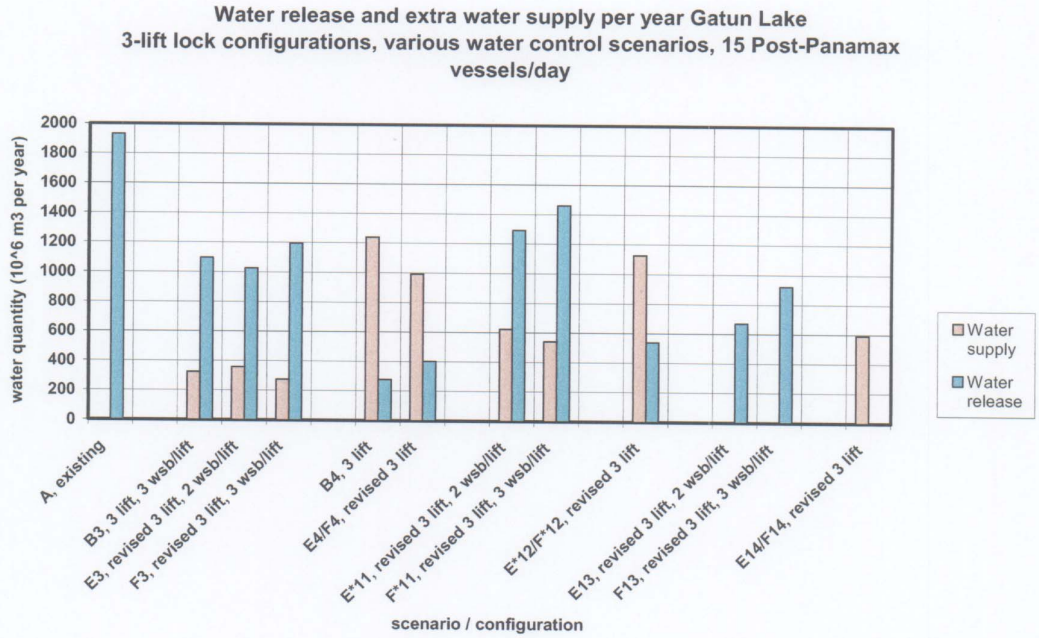


Figure 6.3 Gatun Lake: water releases and extra water supplies in 10^6 m^3 per year, 15 PP-vessels/day, various water control scenarios

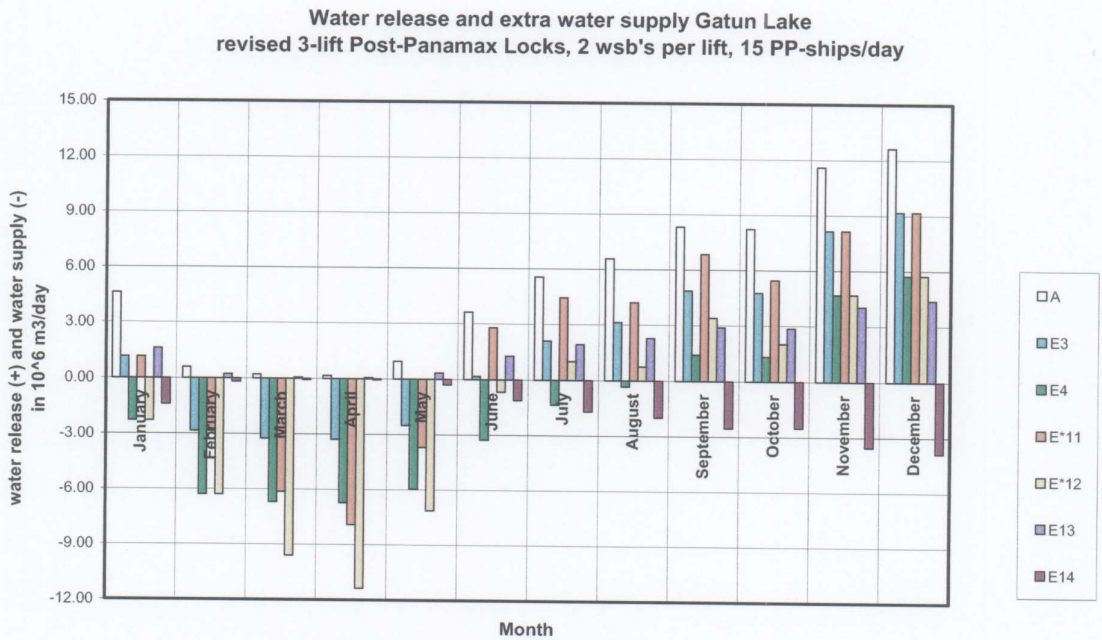


Figure 6.4 Gatun Lake: daily water releases and extra water supplies in 10^6 m^3/day, revised 3-lift locks 2 wsb's/lift (E), 15 PP-vessels/day, various water control scenarios

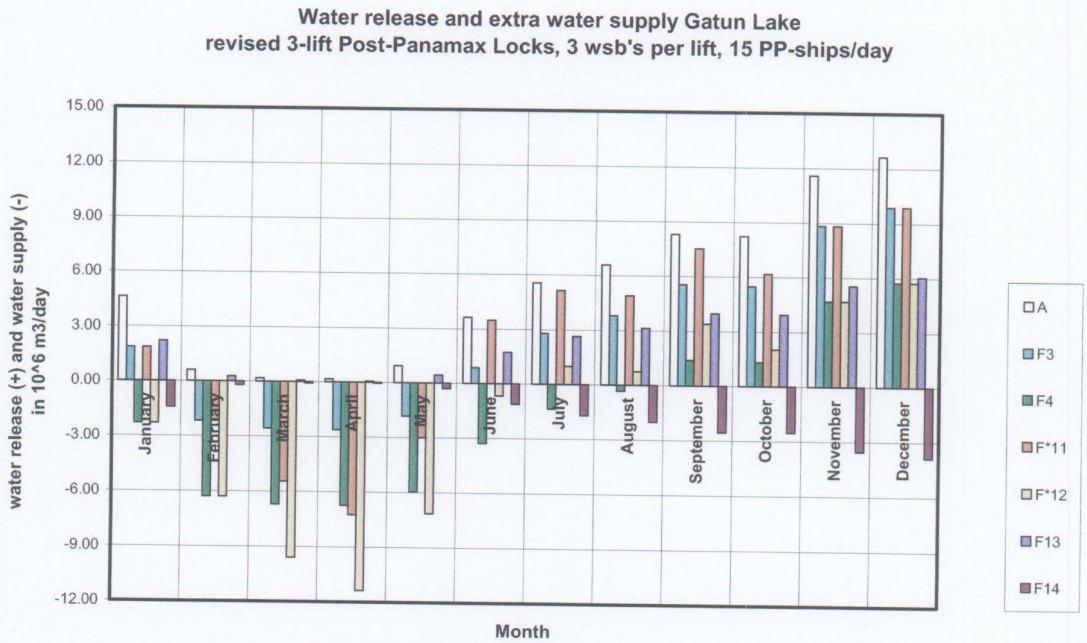


Figure 6.5 **Gatun Lake: daily water releases and extra water supplies in 10^6 m^3/day, revised 3-lift locks 3 wsb's/lift (F), 15 PP-vessels/day, various water control scenarios**

6.2.3 Analysis and conclusions

From a mutual comparison of the results of the salt water intrusion simulations next conclusions can be drawn:

- As may be expected, the revised 3-lift Post-Panamax locks with smaller dimensions than the locks in the earlier CPP design (configuration B, see Section 4.3) cause a lesser salt water intrusion. The reduction of the volume-averaged salt concentration of Gatun Lake is about 20% when no water saving basins are applied, the reduction of the volume-averaged salt concentration of Miraflores Lake (indirect effect) is smaller: compare results of 'B4, 3-lift' with results of 'E4 / F4, revised 3-lift' in Figures 6.1 and 6.2 respectively. As is shown in Figure 6.3 the net yearly supply of water to Gatun Lake (= extra water supply – water release) is also considerably smaller.
  When water saving basins are in operation the reduction of the salt concentration of Gatun Lake is even more evident, about 25%: compare results of 'B3, 3-lift, 3 wsb/lift' with results of 'E3, rev. 3-lift, 2 wsb/lift' and results of 'F3, rev. 3-lift, 3 wsb/lift' in Figures 6.1 and 6.2. From the viewpoint of water conservation the revised 3-lift locks with 3 wsb's per lift are a better option than the original 3-lift locks with 3 wsb's per lift or the revised 3-lift locks with 2 wsb's per lift, see Figure 6.3.
- When the water level of Gatun Lake is maintained above PLD + 26.2 m (this occurs in water level control scenario 11 (wsb's) and water level control scenario 12 (no wsb's)), extra fresh water has to be supplied in the dry season to keep the water level of Gatun Lake above the lower limit value, but the same quantity of water has to be released in the wet season. Additional fresh water has to be supplied to compensate for the lock operation losses. However, the net inflow or outflow of water (= extra water supply –

water release) is the same as in scenario 3 (wsb's) and scenario 4 (no wsb's) respectively, see Figure 6.3. The result of the extra water supply and extra water release in scenarios 11 and 12 (providing extra flushing of Gatun Lake) is a somewhat lesser salt concentration of mainly Gatun Lake: compare the results of scenario 11 (E*11, F*11) with results of scenario 3 (E3, F3), and the results of scenario 12 (E*12, F*12) with results of scenario 4 (E4, F4) in Figures 6.1 and 6.2. Probably, also the higher floor level of lock chambers in simulations with scenarios 11 and 12 plays a favourable role.
The option of a minimum water level of PLD +26.2 m for Gatun Lake is however, no longer be considered by ACP, since the deepening of the shipping channel in the lake has become the preferred alternative.

- When the extra water supply to Gatun Lake is minimized, which is realized in scenario 13 (wsb's) and scenario 14 (no wsb's) by a proportional release of water throughout the year (see Figures 6.4 and 6.5), the salt concentration of the lakes is somewhat higher, but in particular the minimum salt concentration values, which occur at the end of the wet season, are higher. Compare the results of scenario 13 (E13, F13) with results of scenario 3 (E3, F3), and the results of scenario 14 (E14, F14) with results of scenario 4 (E4, F4) in Figures 6.1 and 6.2. The higher concentration values at the end of the wet season are caused by the fact that a lesser quantity of salt water is spilled at Gatun Dam.
- As can be read from Figure 6.3 no extra fresh water has to be supplied to Gatun Lake in the case of scenario 13, but compared to scenario 3 a lesser quantity of water is available for hydropower generation at Gatun Dam.
- The application of water saving basins is the reason that the salt water intrusion increases compared to locks *without* water saving basin facilities. The advantage of wsb's is of course that a lesser quantity of fresh water has to be supplied to Gatun Lake to compensate for the lock operation losses. But generally it is true that: the more water is saved by the wsb's, the higher the salt water intrusion into Gatun Lake; compare results of scenario 3 (B3, E3, F3) with results of scenario 4 (B4, E4, F4), results of scenario 11 (E*11, F*11) with results of scenario 12 (E*12, F*12), and results of scenario 13 (E13, F13) with results of scenario 14 (E14, F14), see Figures 6.1 and 6.2.
- Maximum and minimum salt concentration values of Gatun Lake (volume-averaged) are considerably higher than at present, see Figure 6.2. This is true for all lock configurations and water control scenarios considered.
- The indirect effect of the Post-Panamax locks, which by-pass Miraflores Lake, on the salt concentration of Miraflores Lake is relatively small, see Figure 6.1. Extra salt water intrudes through Pedro Miguel Locks; the salt load varies with the salt concentration of Gatun Lake and varies thus with the configuration of Post-Panamax Locks and the applied water control scenario of Gatun Lake.
  The effects of a specific combination of Post-Panamax locks and water control scenario on the salt concentration of Miraflores Lake are relatively smaller than the effects of this combination on the salt concentration of Gatun Lake. Maximum and minimum salt concentration values of Miraflores Lake (volume-averaged) are up to a factor 1.5 higher than at present, see Figure 6.1.

The above conclusions hold for a ship traffic intensity of 15 Post-Panamax vessels per day in the new shipping lane, but general tendencies will also apply to lower traffic levels.

6.3 Initial simulations for revised 3-lift locks and selected mitigation systems

6.3.1 Set up of simulations for revised 3-lift locks with mitigation systems

Initial simulations have been executed for revised 3-lift locks with 2 wsb's per lift (E) and 3 wsb's per lift (F) in combination with selected mitigation systems I, II, III and IV. The modeling of these mitigation systems is extensively described in Section 4.4.

The quantities of water that are used in the operation of the mitigation system are expressed as $\lambda.V_{refmit}$, where V_{refmit} is the 'normal' water loss (= $\Delta h/3$ * lock area, see Figure 3.2), and λ is a multiplication factor. In mitigation system I (Figures 2.4a/b) and mitigation system II (Figures 2.5a/b) the maximum water quantity is equal to V_{refmit} (λ = 1.0). In mitigation system III (Figure 2.12) the maximum quantity of water that is needed to drain the salt pit depends in particular on the sailing direction of the ship; reference is made to Section 4.5.2 for an explanation. For all three systems it applies that the effectiveness reduces when a lesser quantity of water is used.
Mitigation system IV (pneumatic barrier, Figure 2.13) operates without any extra water loss.

In the initial simulations we start from a *maximum* effectiveness of each of the mitigation systems. This implies that a maximum quantity of water is applied in the operation of mitigation systems I, II and III. For mitigation systems I and II it means: $\lambda_{uplockage} = \lambda_{downlockage}$ = 1.0, for mitigation system III it means: $\lambda_{uplockage}$ = 0.5 and $\lambda_{downlockage}$ = 1.25, see Section 4.5.2. A maximum effectiveness means for mitigation system IV that an optimal air discharge is applied; with optimal air discharge the exchange of salt water with fresh water may be reduced with 80% in the period that lock gates are open. This is in the simulation model effectuated by the selection of ξ = 0.2 in the salt balance formulas (ξ = 1.0 means no effect, ξ = 0.2 means maximum effect, see Section 4.5.2).
Pneumatic barriers are assumed both at the entrance to the lower locks and the entrance to the upper locks.
The choice of multiplication factors is summarized in Table 6.6.

	$\lambda_{uplockage}$	$\xi_{uplockage}$	$\lambda_{downlockage}$	$\xi_{downlockage}$
Mitigation System I	1.0	-	1.0	-
Mitigation System II	1.0	-	1.0	-
Mitigation System III	0.5	-	1.25	-
Mitigation System IV	-	0.2	-	0.2

Table 6.6 Initial simulations: multiplication factors of mitigation systems I, II, III and IV

The salt exchange coefficients used in simulations are different for each of the selected four mitigation systems. Exchange coefficients in mitigation systems I and II are depending on the density flow phenomena in the lock chambers, but not (or almost not) on the quantity of water that is used in the operation of the system. Contrary, exchange coefficients in mitigation system III are bound up with the quantity of water that is used in the operation of the salt pit, and exchange coefficients in mitigation system IV are bound up with the

quantity of air that is applied. The exchange coefficients used in the initial simulations are such selected that the effectiveness of the mitigation systems is *maximum*, see Section 4.5.2 for the selection of exchange coefficients.

Table 6.7 presents an overview of simulations (water control scenarios 15 – 18) for the revised 3-lift locks with 2 or 3 wsb's per lift in operation, in combination with respectively mitigation system I, II, III and IV.
In scenarios 15 – 18 the water level of Gatun Lake varies between the extremes PLD +25.0 m (82.0 ft) and PLD +27.13 m (89.0 ft). The present water releases at Gatun Dam *in the wet season* are reduced to compensate for the extra losses caused by the operation of the Post-Panamax Locks *and* the operation of the mitigation system; the reduction in the wet season is scheduled in such a way that the supply of fresh water from new water resources in the dry season is minimum (similar as in scenario 13); the water level of Gatun Lake varies about an average value of PLD +26.1 m (PLD +85.6 ft); the water level variation remains between the limit values PLD +25.0 m (PLD +82.0 ft) and PLD + 27.13m (PLD + 89.0 ft).

The mitigation system is first deployed at each uplockage and downlockage operation, and than solely at each downlockage operation. In the latter case the extra water loss caused by operation of the mitigation system is reduced; it may also be advantageous in view of a delay for shipping. All simulations are executed for a 5-year period (the period 2056-2060 has been selected, similar as in earlier studies).

The ship traffic intensity is 15 Post-Panamax vessels a day in the new shipping lane and 18 vessels a day in both west shipping lane and east shipping lane (see Table 6.1).

The λ and ξ values used in the simulations form a part of the case name. For example: case name 'E15-15PP, mit I, up1.0+down1.0' means that the simulation is executed for Post-Panamax lock configuration E (revised 3-lift locks with 2 wsb's per lift), water control scenario 15, a ship traffic intensity of 15 Post-Panamax ships in the new lane, and operation of mitigation system I both at uplockage ($\lambda_{uplockage} = 1.0$) and downlockage ($\lambda_{downlockage} = 1.0$).

Tidal fluctuations and salt concentrations of seaside tailbays are in conformation with Section 5.2.

The water level of Miraflores Lake is kept constant at PLD +16.58 m (PLD +54.4 ft). The water releases of Miraflores Lake are shown in Figure 5.2 and Table 5.3.

In water control scenarios 15 – 18 the water level and the water releases / extra water supplies of Gatun Lake vary as a function of time and are dependent on the number of Post-Panamax ship transits in the new shipping lane, the number of water saving basins and the mode of operation of the mitigation system. Figures 6.6a/b present the water level variation throughout the year and the daily water releases / extra water supplies of Gatun Lake for configuration E (revised 3-lift locks with 2 wsb's per lift) in water control scenarios 15 – 18. For reasons of comparison the water level variation and water releases of Gatun Lake in scenario 13 are also shown. Figures 6.7a/b present the same quantities for configuration F (revised 3-lift locks with 3 wsb's per lift).

Scenario	*Description*	***E*** ***revised*** ***3-lift locks*** ***2 wsb's / lift***	***F*** ***revised*** ***3-lift locks*** ***3 wsb's / lift***
		case	***case***
15	Wsb's in operation - **Mitigation system I in operation** Gatun Lake: operating level between PLD +25.0 m (82.0 ft) and PLD +27.13 m (89.0 ft) Gatun Dam: proportional reduction of present water releases resulting in a minimum water supply to Gatun Lake	E15-15PP, mit I, up1.0+down1.0 E15-15PP, mit I, down1.0	F15-15PP, mit I, up1.0+down1.0 F15-15PP, mit I, down1.0
16	Wsb's in operation - **Mitigation system II in operation** Gatun Lake: operating level between PLD +25.0 m (82.0 ft) and PLD +27.13 m (89.0 ft) Gatun Dam: proportional reduction of present water releases resulting in a minimum water supply to Gatun Lake	E16-15PP, mit II, up1.0+down1.0 E16-15PP, mit II, down1.0	F16-15PP, mit II, up1.0+down1.0 F16-15PP, mit II, down1.0
17	Wsb's in operation - **Mitigation system III in operation** Gatun Lake: operating level between PLD +25.0 m (82.0 ft) and PLD +27.13 m (89.0 ft) Gatun Dam: proportional reduction of present water releases resulting in a minimum water supply to Gatun Lake	E17-15PP, mit III, up0.5+down1.25 E17-15PP, mit III, down1.25	F17-15PP, mit III, up0.5+down1.25 F17-15PP, mit III, down1.25
18	Wsb's in operation - **Mitigation system IV in operation** Gatun Lake: operating level between PLD +25.0 m (82.0 ft) and PLD +27.13 m (89.0 ft) Gatun Dam: proportional reduction of present water releases resulting in a minimum water supply to Gatun Lake	E18-15PP, mit IV, up0.2+down0.2 E18-15PP, mit IV, down0.2	F18-15PP, mit IV, up0.2+down0.2 F18-15PP, mit IV, down0.2

Table 6.7 Initial simulations for revised 3-lift locks; mitigation systems I – IV; 15 PP ships a day, water control scenarios 15 - 18

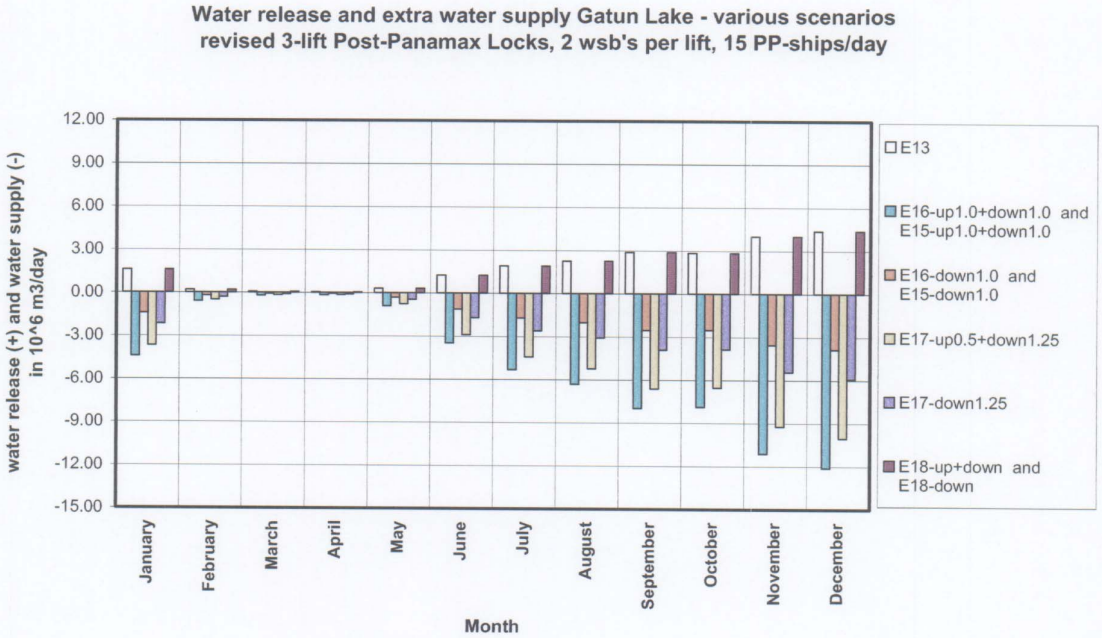


Figure 6.6a Gatun Lake: daily water releases and extra water supplies in 10^6 m^3/day , revised 3-lift locks 2 wsb's/lift (E), 15 PP-vessels/day

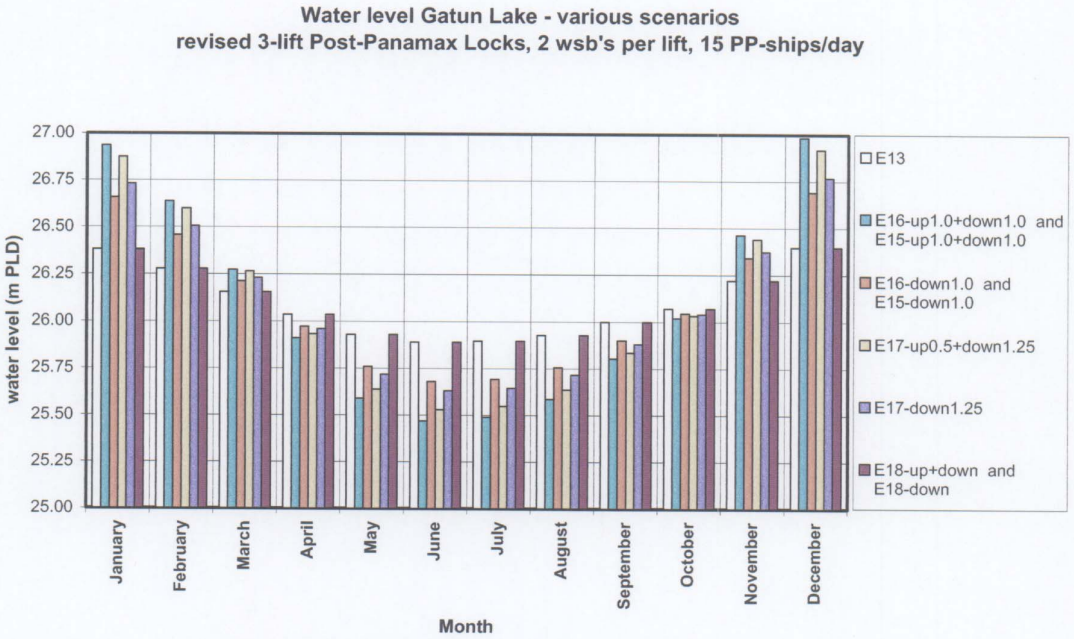


Figure 6.6b Gatun Lake: water level variation in m PLD, revised 3-lift locks 2 wsb's/lift (E), 15 PP-vessels/day

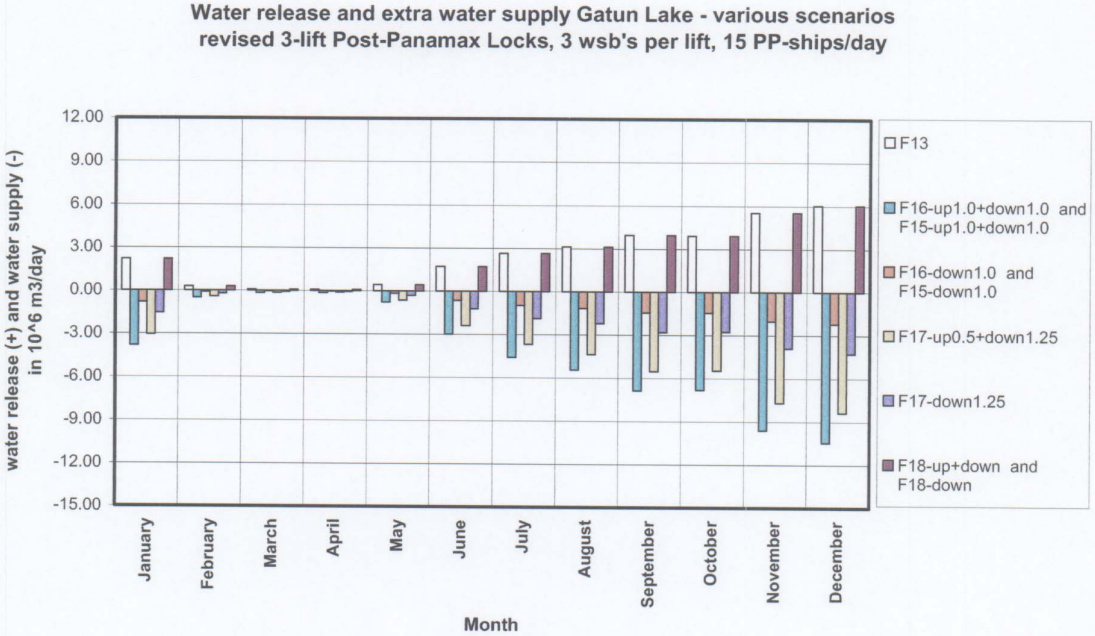


Figure 6.7a Gatun Lake: daily water releases and extra water supplies in 10^6 m^3/day, revised 3-lift locks 3 wsb's/lift (F), 15 PP-vessels/day

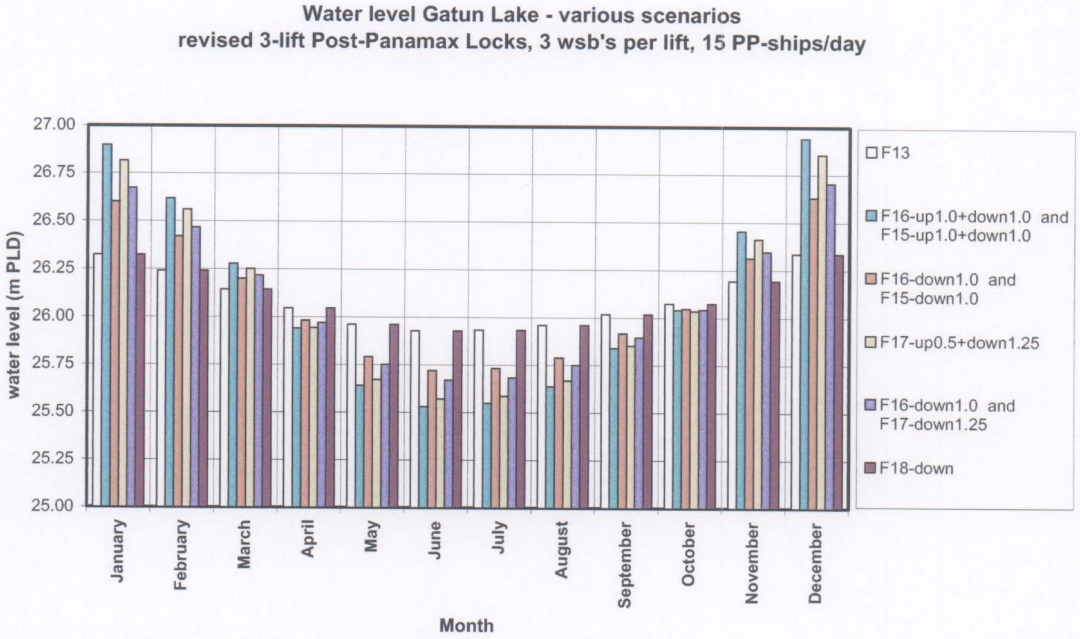


Figure 6.7b Gatun Lake: water level variation in m PLD, revised 3-lift locks 3 wsb's/lift (F), 15 PP-vessels/day

6.3.2 Results of simulations for revised 3-lift locks with mitigation systems

The results of the simulations are presented as maximum and minimum salt concentration values (*volume-averaged*) of Gatun Lake and Miraflores Lake. For a few selected cases the variation of the concentration as a function of wet and dry season is shown in figures of Annex A: 'Selected figures initial SWINLOCKS simulations'. As appears from the graphs stable salt concentration variations are obtained in the simulations after a period of about three years. Generally, other cases show a similar variation pattern of the salt concentration.

The maximum and minimum salt concentration values of Miraflores Lake and Gatun Lake, found in the last year of the considered five-year period, are presented in Table 6.8a and Figures 6.8a/b for revised 3-lift locks with 2 wsb's per lift (E) and in Table 6.8b and Figures 6.9a/b for revised 3-lift locks with 3 wsb's per lift (F). For reasons of comparison also the salt concentration values are shown for the existing situation (A), and for the revised 3-lift locks without mitigation system (E13: 2 wsb's per lift; F13: 3 wsb's per lift).

The corresponding yearly water releases and extra water supplies of Gatun Lake are shown in Figure 6.8c for lock configuration E and in Figure 6.9c for lock configuration F.

Case / water control scenario	*Volume-averaged salt concentration (ppt) Miraflores Lake*		*Volume-averaged salt concentration (ppt) Gatun Lake*	
	minimum	*maximum*	*minimum*	*maximum*
Existing situation				
A	0.64	1.42	0.010	0.027
Revised 3-lift locks – 2 wsb's/lift				
E13-15PP, no mitigation	0.85	2.08	0.45	0.68
E14-15PP, no mitigation, no wsb's	0.90	2.02	0.52	0.58
E15-15PP, mit I, up1.0+down1.0	0.69	1.64	0.14	0.17
E15-15PP, mit I, down1.0	0.72	1.71	0.21	0.24
E16-15PP, mit II, up1.0+down1.0	0.67	1.61	0.11	0.13
E16-15PP, mit II, down1.0	0.69	1.64	0.15	0.17
E17-15PP, mit III, up0.5+down1.25	0.72	1.69	0.19	0.22
E17-15PP, mit III, down1.25	0.76	1.78	0.28	0.32
E18-15PP, mit IV, up0.2+down0.2	0.77	1.88	0.29	0.45
E18-15PP, mit IV, down0.2	0.81	1.98	0.37	0.56

Table 6.8a Maximum and minimum volume-averaged salt concentration of Miraflores Lake and Gatun Lake; present (A) and revised 3-lift locks with 2 wsb's (E) per lift, mitigation systems I – IV, 15 PP-vessels a day, water control scenarios 13 - 18

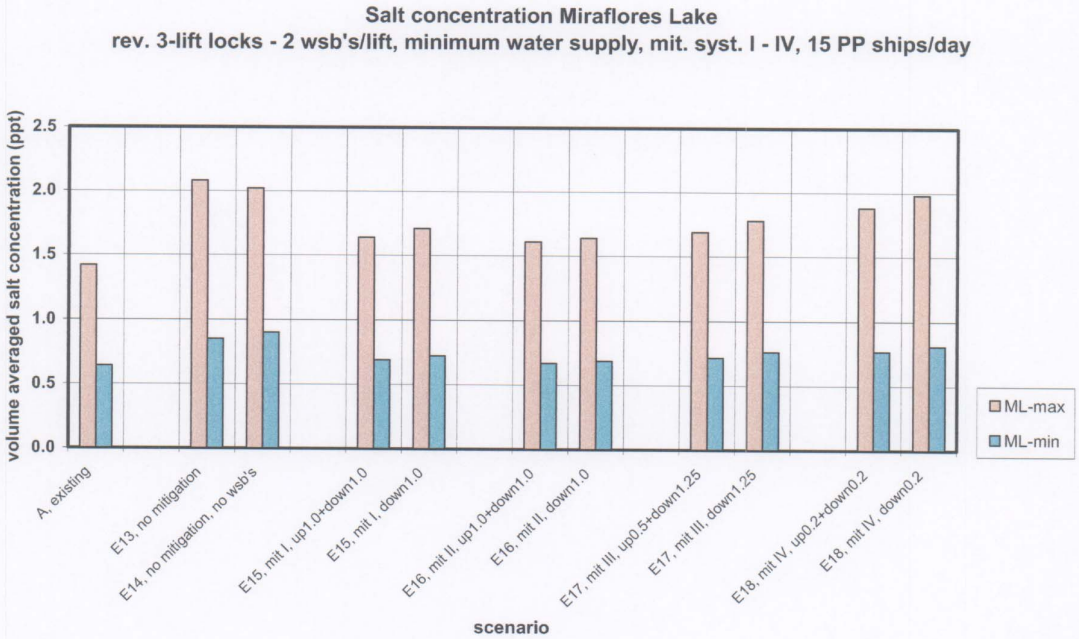


Figure 6.8a Miraflores Lake: volume-averaged salt concentration (in ppt), maximum and minimum values, revised 3-lift locks with 2 wsb's per lift (E), 15 PP-vessels/day, water control scenarios 13 - 18

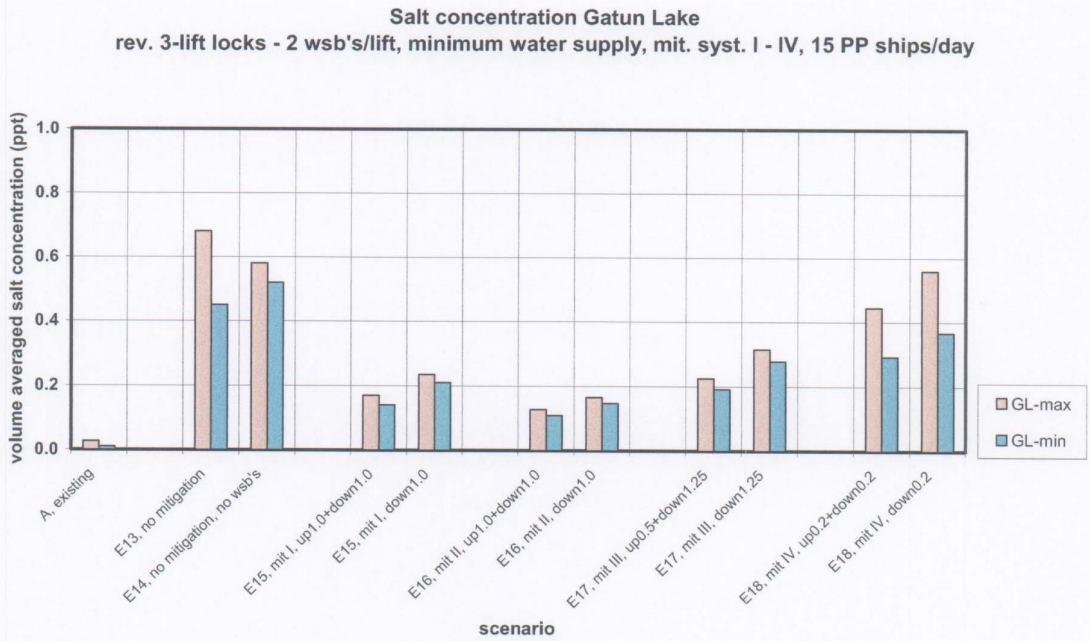


Figure 6.8b **Gatun Lake: volume-averaged salt concentration (in ppt), maximum and minimum values, revised 3-lift locks with 2 wsb's per lift (E), 15 PP-vessels/day, water control scenarios 13 - 18**

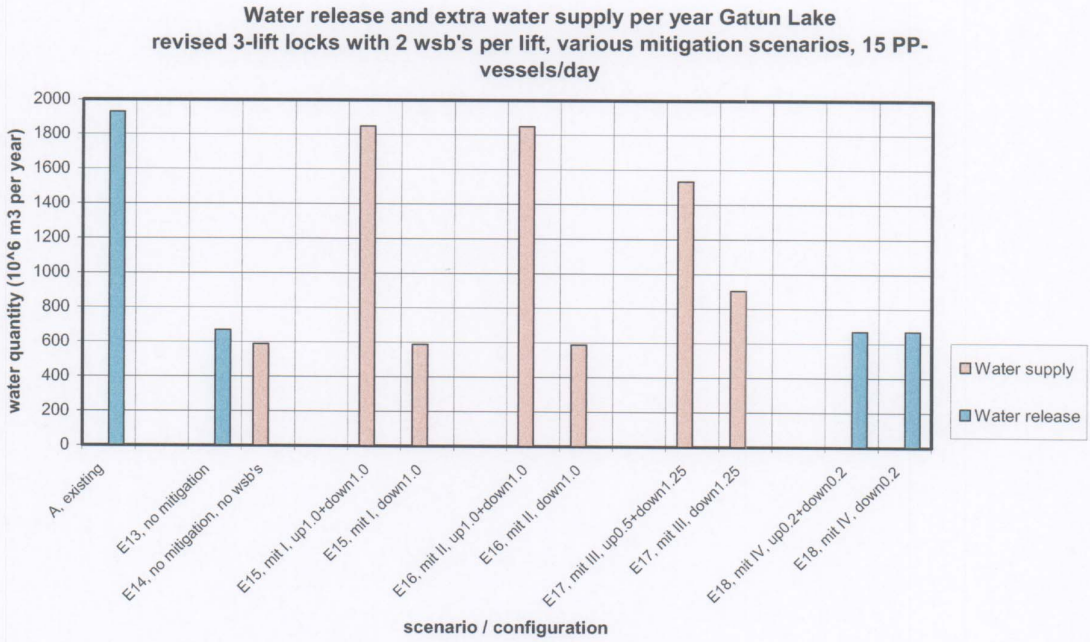


Figure 6.8c **Gatun Lake: water releases and extra water supplies in 10^6 m^3 per year, revised 3-lift locks with 2 wsb's per lift (E), 15 PP-vessels/day, water control scenarios 13 - 18**

Case / water control scenario	*Volume-averaged salt concentration (ppt) Miraflores Lake*		*Volume-averaged salt concentration (ppt) Gatun Lake*	
	minimum	*maximum*	*minimum*	*maximum*
Existing situation				
A	0.64	1.42	0.010	0.027
Revised 3-lift locks – 3 wsb's/lift				
F13-15PP, no mitigation	0.83	2.10	0.41	0.71
F14-15PP = E14-15PP	0.90	2.02	0.52	0.58
F15-15PP, mit I, up1.0+down1.0	0.70	1.66	0.16	0.19
F15-15PP, mit I, down1.0	0.75	1.75	0.25	0.28
F16-15PP, mit II, up1.0+down1.0	0.68	1.62	0.12	0.14
F16-15PP, mit II, down1.0	0.70	1.67	0.17	0.20
F17-15PP, mit III, up0.5+down1.25	0.74	1.73	0.23	0.27
F17-15PP, mit III, down1.25	0.80	1.84	0.34	0.38
F18-15PP, mit IV, up0.2+down0.2	0.76	1.90	0.28	0.48
F18-15PP, mit IV, down0.2	0.80	2.01	0.35	0.60

Table 6.8b Maximum and minimum volume-averaged salt concentration of Miraflores Lake and Gatun Lake; present (A) and revised 3-lift locks with 3 wsb's (F) per lift, mitigation systems I – IV, 15 PP-vessels a day, water control scenarios 13 - 18

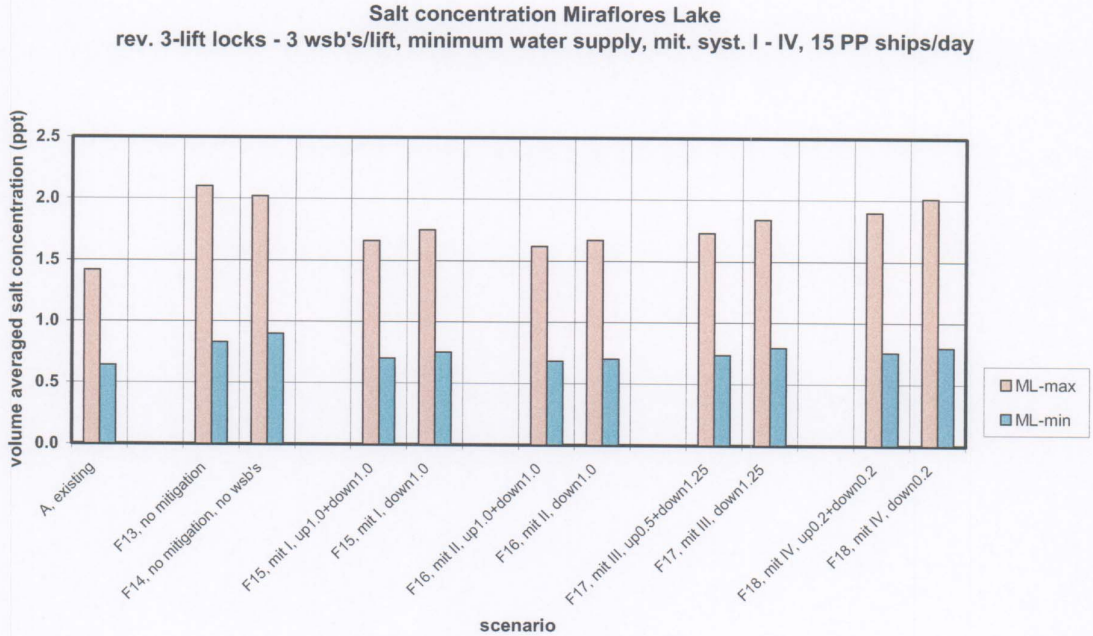


Figure 6.9a Miraflores Lake: volume-averaged salt concentration (in ppt), maximum and minimum values, revised 3-lift locks with 3 wsb's per lift (F), 15 PP-vessels/day, water control scenarios 13 - 18

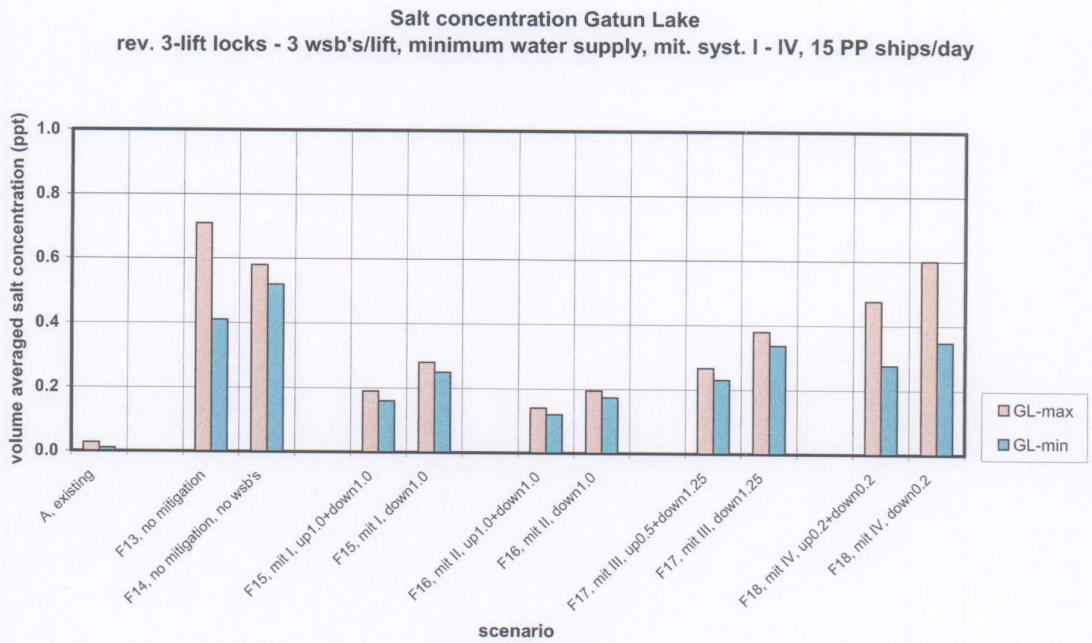


Figure 6.9b **Gatun Lake: volume-averaged salt concentration (in ppt), maximum and minimum values, revised 3-lift locks with 3 wsb's per lift (F), 15 PP-vessels/day, water control scenarios 13 - 18**

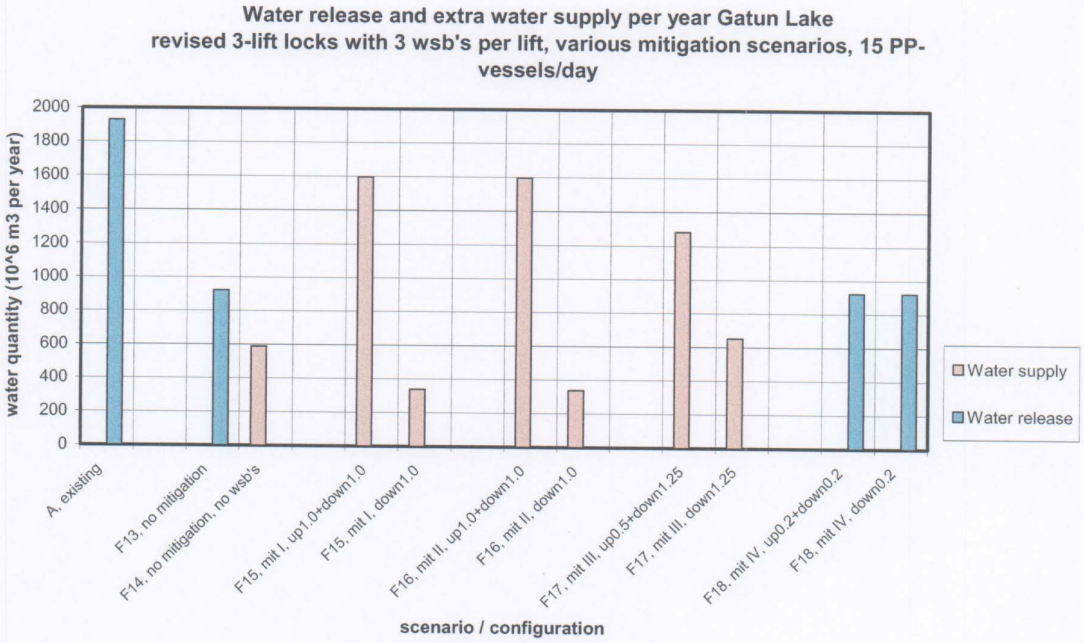


Figure 6.9c **Gatun Lake: water releases and extra water supplies in 10^6 m^3 per year, revised 3-lift locks with 3 wsb's per lift (F), 15 PP-vessels/day, water control scenarios 13 - 18**

6.3.3 Analysis and conclusions

The analysis of the results of the simulations leads to the following observations and conclusions:

- All mitigation systems I – IV reduce the salt load on Gatun Lake; consequently the salt concentration of the lake is also reduced. The mitigation systems have a limited, indirect effect on the salt concentration of Miraflores Lake: the concentration is reduced, but to a smaller extent than the salt concentration of Gatun Lake.
- The effect of the mitigation systems is somewhat better when mitigation systems are combined with the revised 3-lift locks with 2 wsb's per lift (configuration E) than combined with the revised 3-lift locks with 3 wsb's per lift (configuration F). This is caused by a better 'flushing' of the lock chambers in the case of 2 wsb's per lift (greater lockage loss), but also the greater extra fresh water supply to Gatun Lake or the lesser water release at Gatun Dam plays a role (compare Figure 6.8 c and Figure 6.9c).
- From the viewpoint of salt water intrusion mitigation, mitigation system II (flushing of middle and upper lock chamber) is the best option, immediately followed by mitigation system I (stepwise flushing of all three lock chambers), see Figure 6.8b and Figure 6.9b. Mitigation system III (salt pit at upstream side of upper lock) has a somewhat smaller effect than earlier expected (Chapter 3), but the effectiveness can be improved when the depth of the salt pit is enlarged. This appears from Delft3D simulations which have been executed for a salt pit with 17.0 m depth and a salt pit with 26.4 m depth, see Section 4.5. In the present SWINLOCKS simulations a moderate depth of 17.0 m was adopted in order not to drive up too much the excavation cost. Mitigation system IV (pneumatic barrier at the entrance to both the lower lock chamber and the upper lock chamber) has a relatively small effect, as was expected, but has the advantage of a zero water loss.
- When the mitigation systems are solely applied at downlockage of ships the effect of the mitigation systems is still considerable; in particular this is true for mitigation systems II and I. The advantage of this mode of operation is that water losses are strongly reduced.
- With a ship traffic intensity of 15 Post-Panamax vessels a day the volume-averaged salt concentration of Gatun Lake is forced back below the fresh-water limit of about 0.45 ppt salinity, but remains higher than the present salt concentration. Locally, however, the salt concentration may still be far above the fresh water limit (see also Chapter 8).
- The above conclusions apply to mitigation systems which are operated at a maximum effectiveness, which means that the greatest quantity of water is used in the operation of the mitigation system; consequently the water loss caused by operation of the mitigation systems is relatively high (apart from mitigation system IV, pneumatic barrier, that uses air and is operated without a loss of water).
- The above conclusions apply to a water control scenario of Gatun Lake that is aimed to minimize the supply of extra fresh water from new water resources (water control scenarios 13, 15 – 18).
- The effectiveness of the best mitigation systems II and I may be improved when these systems are combined with mitigation system IV; an additional effect of combining system II (or system I) with system IV may be that there is a lesser need to operate system II (or system I), which may save water. This will be studied in Chapter 7.
- The volume-averaged salt concentration of Gatun Lake may further be reduced when the water control scenario of Gatun Lake is not focused on a minimization of the supply of extra fresh water from new water resources. In the alternative approach it is assumed

that sufficient extra fresh water is available throughout the year; this approach will be studied in Chapter 7 (water control scenarios 3, 4, 21 – 24).

6.4 Programme for further simulations

To complete the study on the effects of mitigation systems I – IV for the revised 3-lift Post-Panamax locks a programme for further simulations has been set up. The programme is indicated in next tables together with the initial simulations, which have already been executed. Initial simulations are indicated in black, further simulations are indicated in red. The full programme comprises 108 simulations, and has been discussed with ACP by e-mail. ACP has studied the results of the initial simulations presented in previous sections, and has a preference for mitigation system I, possibly in combination with mitigation system IV (system I: relatively high effectiveness, no additional investments needed for the Post-Panamax locks, system can be used as needed with varying intensity).
ACP plans also to control the water releases of Gatun Lake in such a way that the supply of extra water, needed for the operation of the Post-Panamax locks and mitigation systems, is minimum. For that reason this water control scenario is the preferred scenario in the programme of simulations, but scenarios in which the supply of extra water is fully free are also applied in the simulations.

The programme of simulations is organized in three groups:

A Simulations in which the extra fresh water supply to Gatun Lake is minimized; the present water releases at Gatun Dam are proportionally reduced throughout the year to compensate for the extra water losses caused by operation of the Post-Panamax Locks and mitigation systems; the reduction of water releases is scheduled in such a way that the supply of fresh water from new water resources is minimum (see Section 5.1.3 for an explanation of the water control method); the water level of Gatun Lake is kept between the adopted limits PLD +25.0 m (+82.0 ft) and PLD + 27.13 m (+89.0 ft).

B Simulations in which the extra fresh water supply to Gatun Lake is *not* minimized (free extra water supply when needed; starting point is that sufficient extra fresh water is available throughout the year); the present representative, 10-year averaged water level variation throughout the year is maintained; this water level varies also between the adopted limits PLD +25.0 m (+82.0 ft) and PLD + 27.13 m (+89.0 ft).

C Simulations in which the water level of Gatun Lake is maintained above PLD +26.2 m (+86.0 ft); these simulations have already been executed as part of the initial simulations programme. The water control scenario in which the water level of Gatun Lake is maintained above PLD +26.2 m will not be applied in combination with mitigation systems, since this option is no longer considered by ACP.

With the proposed programme the effects of the mitigation systems are studied for next conditions:

- revised 3-lift locks without wsb's, 2 wsb's per lift and 3 wsb's per lift
- 15, 10 and 5 Post-Panamax vessels a day
- solely operation of mitigation system I, II, III or IV (preference for mitigation system I)
- operation of mitigation systems at uplockage and downlockage versus operation of mitigation system at downlockage only

- intensive use of mitigation system I (at each downlockage) versus a less intensive use of mitigation system I (resulting in a smaller effectiveness but a lesser water loss)
- keel clearance of ship 10 ft instead of 5 ft (this requires a 5 ft lower lock chamber floor elevation in simulations)
- a combination of mitigation system I (stepwise flushing of all three lock chambers) and mitigation system IV (pneumatic barrier)
- real hydraulic conditions as occurred in the period 1992 - 2001

Simulations with real hydraulic conditions as occurred in the period 1992 – 2001, are useful to check the influence of real water level variations of the lakes in comparison to averaged water level variations and related water releases. The event of an extremely dry year 1997 followed in 1998 by a strong drop of the water level of Gatun Lake below PLD + 25.0 m, may also occur in the future. When no sufficient back up water is available in reserve reservoirs to overcome such a long dry period, shipping in the new lane and eventually also in the existing west and east lanes has to be restricted to a limited draft or even stopped during the period that the water level is too low for a safe navigation.

To get insight into the effect of real water level variations of the lakes on salt concentration variations, some simulations will be executed for the revised 3-lift locks for hydraulic conditions as occurred in the period 1992 – 2001. However, the water balance of Gatun Lake in these simulations is different compared to the water balance in the 1992 – 2001 period, since extra water losses occur, which are caused by the operation of the new locks and mitigation systems. To compensate for these losses the real water releases are proportionally reduced throughout the year (see Section 5.1.3 for explanation), or if not sufficient, extra water is supplied. Consequently, the water level variation of Gatun Lake throughout the year deviates from the real water level variation in the 1992 – 2001 period (but the mean value of the water level in a year is kept the same).

The full programme of simulations (initial and further simulations) is shown in next tables. Initial simulations are indicated in black, further simulations are indicated in red.

A Minimum extra fresh water supply to Gatun Lake

Scenarios 13, 14, 15-18, 19, 25:
Gatun Lake: the water level is kept between the adopted limits PLD +25.0 m (+82.0 ft) and PLD + 27.13 m (+89.0 ft), mean water level: PLD +26.1 m (+85.6 ft).
Gatun Dam: water releases throughout the year are proportionally reduced resulting in a minimum extra fresh water supply from new water resources to Gatun Lake.

Note: 1:2 in next tables means: mitigation action each second lockage
1:3 in next tables means: mitigation action each third lockage
mark + in name $E^{+}13$ etc. in next tables means: revised 3-lift locks with 5 ft lower lock chamber floors (corresponding to 10 ft keel clearance instead of 5 ft clearance)

SOLELY OPERATION OF MITIGATION SYSTEM I, II, III OR IV

15 Post-Panamax vessels per day	No mitigation	Mitigation system I	Mitigation system II	Mitigation system III	Mitigation system IV
Rev 3-lift locks, 2 wsb's/lift	E13-15PP	E15-15PP, mit I, up1.0+down1.0	E16-15PP, mit II, up1.0+down1.0	E17-15PP, mit III, up0.5+down1.25	E18-15PP, mit IV, up0.2+down0.2
		E15-15PP, mit I, down1.0	E16-15PP, mit II, down1.0	E17-15PP, mit III, down1.25	E18-15PP, mit IV, down0.2
		E15-15PP, mit I, down1.0, 1:2			
		E15-15PP, mit I, down1.0, 1:3			
	$E^{+}13$-15PP				
		$E^{+}15$-15PP, mit I, down1.0			
	E14-15PP no wsb's	E25-15PP, no wsb's mit I, down1.0			
	$E^{+}14$-15PP no wsb's				
Rev 3-lift locks, 3 wsb's/lift	F13-15PP	F15-15PP, mit I, up1.0+down1.0	F16-15PP, mit II, up1.0+down1.0	F17-15PP, mit III, up0.5+down1.25	F18-15PP, mit IV, up0.2+down0.2
		F15-15PP, mit I, down1.0	F16-15PP, mit II, down1.0	F17-15PP, mit III, down1.25	F18-15PP, mit IV, down0.2
		F15-15PP, mit I, down1.0, 1:2			
		F15-15PP, mit I, down1.0, 1:3			
	$F^{+}13$-15PP				
		$F^{+}15$-15PP, mit I, down1.0			
	F14-15PP = E14-15PP	F25-15PP = E25-15PP			
	$F^{+}14$-15PP = $E^{+}14$-15PP				

Table 6.9a SWINLOCKS simulations, minimum extra fresh water supply, 15 PP-ships/day

10 Post-Panamax vessels per day	No mitigation	Mitigation system I	Mitigation system II	Mitigation system III	Mitigation system IV
Rev 3-lift locks, 2 wsb's/lift	E13-10PP	E15-10PP, mit I, down1.0	E16-10PP, mit II, down1.0	E17-10PP, mit III, down1.25	
		E15-10PP, mit I, down1.0, 1:3			
	E14-10PP no wsb's	E25-10PP, no wsb's mit I, down1.0			
Rev 3-lift locks, 3 wsb's/lift	F13-10PP	F15-10PP, mit I, down1.0	F16-10PP, mit II, down1.0	F17-10PP, mit III, down1.25	F18-10PP, mit IV, down0.2
		F15-10PP, mit I, down1.0, 1:3			
	F14-10PP = E14-10PP	F25-10PP = E25-10PP			

Table 6.9b SWINLOCKS simulations, minimum extra fresh water supply, 10 PP-ships/day

5 Post-Panamax vessels per day	No mitigation	Mitigation system I	Mitigation system II	Mitigation system III	Mitigation system IV
Rev 3-lift locks, 2 wsb's/lift	E13-5PP	E15-5PP, mit I, down1.0	E16-5PP, mit II, down1.0	E17-5PP, mit III, down1.25	
		E15-5PP, mit I, down1.0, 1:3			
	E14-5PP no wsb's	E25-5PP, no wsb's mit I, down1.0			
Rev 3-lift locks, 3 wsb's/lift	F13-5PP	F15-5PP, mit I, down1.0	F16-5PP, mit II, down1.0	F17-5PP, mit III, down1.25	F18-5PP, mit IV, down0.2
		F15-5PP, mit I, down1.0, 1:3			
	F14-5PP = E14-5PP	F25-5PP = E25-5PP			

Table 6.9c SWINLOCKS simulations, minimum extra fresh water supply, 5 PP-ships/day

COMBINATION OF MITIGATION SYSTEMS I AND IV

15 Post-Panamax vessels per day	Mitigation system I in combination with mitigation system IV
Rev 3-lift locks, 2 wsb's/lift	E19-15PP, mit I, down1.0 + mit IV, down0.2
	E19-15PP, mit I, down1.0, 1:2 + mit IV, down0.2
	E19-15PP, mit I, down1.0, 1:3 + mit IV, down0.2
Rev 3-lift locks, 3 wsb's/lift	F19-15PP, mit I, down1.0 + mit IV, down0.2
	F19-15PP, mit I, down1.0, 1:2 + mit IV, down0.2
	F19-15PP, mit I, down1.0, 1:3 + mit IV, down0.2

Table 6.10a **SWINLOCKS simulations, minimum extra fresh water supply, mitigation system I + mitigation system IV, 15 PP-ships/day**

10 Post-Panamax vessels per day	Mitigation system I in combination with mitigation system IV
Rev 3-lift locks, 2 wsb's/lift	E19-10PP, mit I, down1.0 + mit IV, down0.2
	E19-10PP, mit I, down1.0, 1:3 + mit IV, down0.2
Rev 3-lift locks, 3 wsb's/lift	F19-10PP, mit I, down1.0 + mit IV, down0.2
	F19-10PP, mit I, down1.0, 1:3 + mit IV, down0.2

Table 6.10b **SWINLOCKS simulations, minimum extra fresh water supply, mitigation system I + mitigation system IV, 10 PP-ships/day**

5 Post-Panamax vessels per day	Mitigation system I in combination with mitigation system IV
Rev 3-lift locks, 2 wsb's/lift	E19-5PP, mit I, down1.0 + mit IV, down0.2
	E19-5PP, mit I, down1.0, 1:3 + mit IV, down0.2
Rev 3-lift locks, 3 wsb's/lift	F19-5PP, mit I, down1.0 + mit IV, down0.2
	F19-5PP, mit I, down1.0, 1:3 + mit IV, down0.2

Table 6.10c **SWINLOCKS simulations, minimum extra fresh water supply, mitigation system I + mitigation system IV, 5 PP-ships/day**

HYDRAULIC CONDITIONS AS IN PERIOD 1992 – 2001

15 / 10 / 5 Post-Panamax vessels per day	No mitigation	Mitigation system I
Rev 3-lift locks, 2 wsb's/lift	E13-15PP, real cond.	E15-15PP, mit I, down1.0, real cond.
		E15-10PP, mit I, down1.0, real cond.
		E15-5PP, mit I, down1.0, real cond.
	E14-15PP, no wsb's, real cond.	
Rev 3-lift locks, 3 wsb's/lift	F13-15PP, real cond.	F15-15PP, mit I, down1.0, real cond.
		F15-10PP, mit I, down1.0, real cond.
		F15-5PP, mit I, down1.0, real cond.
	F14-15PP-real = E14-15PP-real	

Table 6.11 **SWINLOCKS simulations, minimum extra fresh water supply, real hydraulic conditions, 15, 10 and 5 PP-ships/day**

B Free extra fresh water supply to Gatun Lake

Scenarios 3, 4, 21-24:
Gatun Lake: present representative water level; this water level varies between the adopted limits PLD +25.0 m (+82.0 ft) and PLD + 27.13 m (+89.0 ft)
Gatun Dam: present water releases are instantaneously reduced to compensate for water losses caused by operation of revised 3-lift Post-Panamax locks and mitigation systems; if needed immediate extra fresh water supply to Gatun Lake

SOLELY OPERATION OF MITIGATION SYSTEM I, II, III or IV

15 Post-Panamax vessels per day	No mitigation	Mitigation system I	Mitigation system II	Mitigation system III	Mitigation system IV
Rev 3-lift locks, 2 wsb's/lift	E3-15PP	E21-15PP, mit I, down1.0	E22-15PP, mit II, down1.0		
	E4-15PP no wsb's				
Rev 3-lift locks, 3 wsb's/lift	F3-15PP	F21-15PP, mit I, down1.0	F22-15PP, mit II, down1.0	F23-15PP, mit III, down1.25	F24-15PP, mit IV, down0.2
	F4-15PP = E4-15PP				

Table 6.12a SWINLOCKS simulations, free extra fresh water supply, 15 PP-ships/day

10 Post-Panamax vessels per day	No mitigation	Mitigation system I	Mitigation system II	Mitigation system III	Mitigation system IV
Rev 3-lift locks, 2 wsb's/lift	E3-10PP	E21-10PP, mit I, down1.0	E22-10PP, mit II, down1.0		
	E4-10PP no wsb's				
Rev 3-lift locks, 3 wsb's/lift	F3-10PP	F21-10PP, mit I, down1.0	F22-10PP, mit II, down1.0	F23-10PP, mit III, down1.25	F24-10PP, mit IV, down0.2
	F4-10PP = E4-10PP				

Table 6.12b SWINLOCKS simulations, free extra fresh water supply, 10 PP-ships/day

5 Post-Panamax vessels per day	No mitigation	Mitigation system I	Mitigation system II	Mitigation system III	Mitigation system IV
Rev 3-lift locks, 2 wsb's/lift	E3-5PP	E21-5PP, mit I, down1.0	E22-5PP, mit II, down1.0		
	E4-5PP no wsb's				
Rev 3-lift locks, 3 wsb's/lift	F3-5PP	F21-5PP, mit I, down1.0	F22-5PP, mit II, down1.0	F23-5PP, mit III, down1.25	F24-5PP, mit IV, down0.2
	F4-5PP = E4-5PP				

Table 6.12c SWINLOCKS simulations, free extra fresh water supply, 5 PP-ships/day

C Water level Gatun Lake > PLD +26.2 m

Scenarios 11 and 12:
Gatun Lake: water level > PLD +26.2 m (+86.0 ft); maximum level PLD +26.7 m (+87.5 ft)
Gatun Dam: if needed, present water releases are instantaneously reduced to maintain water level above PLD +26.2 m and to compensate for water losses caused by operation of revised 3-lift Post-Panamax locks; if needed immediate extra fresh water supply to Gatun Lake.

NO MITIGATION SYSTEM

15 Post-Panamax vessels per day	No mitigation
Rev 3-lift locks, 2 wsb's/lift	E*11-15PP
	E*12-15PP wsb's switched off
Rev 3-lift locks, 3 wsb's/lift	F*11-15PP
	F*12-15PP = E*12-15PP

Table 6.13 **SWINLOCKS simulations, water level Gatun Lake > PLD +26.2 m, no mitigation system, 15 PP-ships/day**

7 Further simulations for revised 3-lift locks and selected mitigation systems

7.1 Further simulations, minimum water supply

7.1.1 Set up of further simulations, minimum water supply

The programme of simulations is shown in Tables 6.9a/b/c (solely operation of mitigation system I, II, III or IV), Tables 6.10a/b/c (combination of mitigation systems I and IV) and Table 6.11 (hydraulic conditions as in period 1992 – 2001). In all these simulations the supply of extra fresh water to Gatun Lake is minimized; the water level of Gatun Lake is kept between the adopted limits PLD +25.0 m (+82.0 ft) and PLD +27.13 m (+89.0 ft).

In some simulations (Table 6.9a) the keel clearance of the Post-Panamax ships in lock chambers is 3.05 m (10 ft) instead of 1.52 m (5 ft); the latter value is adopted by ACP as a starting condition for the present study, but it may appear from other studies that a clearance of 5 ft is not safe enough in view of water movements, water surface draw down and hawser forces. In simulations where a keel clearance of 3.05 m (10 ft) is adopted, is the floor of the lock chambers on a 5 ft lower elevation, see next Table 7.1. Simulations with a lower floor level are indicated with a + in their names, for example E^{+}13-15PP.

lock / forebay	*floor level of revised 3-lift locks, 1.52 m (5.0 ft) keel clearance (m to PLD)*	*floor level of revised 3-lift locks, 3.05 m (10.0 ft) keel clearance (m to PLD)*
Lock U	-19.09	-20.61
Lock V	-9.98	-11.50
Lock W	-0.87	-2.40
Gatun W forebay	+8.23	+6.71
Gatun Z forebay	+8.23	+6.71
Lock Z	-0.23	-1.75
Lock Y	-8.69	-10.21
Lock X	-17.15	-18.67

Table 7.1 Floor level of lock chambers of revised 3-lift locks: 5 ft and 10 ft minimum keel clearance

In all simulations a maximum effectiveness of the mitigation system is prescribed (see Section 6.3.1 for water use and exchange coefficients). Mitigation systems are operated at downlockage of each ship. In some simulations mitigation system I is only operated each *second* downlockage or each *third* downlockage. In addition, some simulations with mitigation system I are executed for revised 3-lift locks without water saving basins. Mitigation system I is also operated together with mitigation system IV. All simulations are

executed for a 5-year period (the period 2056-2060 has been selected, similar as in earlier studies).

The ship traffic intensity is 15, 10 or 5 Post-Panamax vessels a day in the new shipping lane and 18 vessels a day in both west shipping lane and east shipping lane (see Table 6.1).

Tidal fluctuations and salt concentrations of seaside tailbays are in conformation with Section 5.2.

The water level of Miraflores Lake is kept constant at PLD +16.58 m (PLD +54.4 ft). The water releases of Miraflores Lake are shown in Figure 5.2 and Table 5.3.

In water control scenarios 13, 14, 15 – 18, 19 and 25 the water level and the water releases / extra water supplies of Gatun Lake vary as a function of time and are dependent on the number of Post-Panamax ship transits in the new shipping lane, the number of water saving basins and the mode of operation of the mitigation system. As an example Figures 7.1a/b present the water level variation and water releases / extra water supplies throughout the year of Gatun Lake for configuration E (revised 3-lift locks with 2 wsb's per lift) and for *15 Post-Panamax vessels per day* (water control scenarios 15, 14 and 25). Note that water levels, water releases and extra water supplies in scenario 19 (mitigation system I + mitigation system IV) are similar to those in scenario 15 (mitigation system I), since mitigation system IV, pneumatic barrier, does not cause water losses. Clearly, scenario 25 (revised 3-lift locks without wsb's in combination with mitigation system I), mitigation system I operated after each ship downlockage, is the most unfavorable scenario from the viewpoint of water losses. Scenario 15 (revised 3-lift locks with 2 wsb's per lift in combination with mitigation system I) is more favorable: when the mitigation system is operated after each second or third downlockage, the required extra supply of water is small or nil and in the latter case water can even be released at Gatun Dam.

Figures 7.2a/b present the same quantities for configuration F (revised 3-lift locks with 3 wsb's per lift) and for *15 Post-Panamax vessels per day* (water control scenarios 15, 14 and 25).

Similar charts as presented for 15 Post-Panamax vessels per day can be made for 10 and 5 Post-Panamax vessels per day (they are not taken up in this report). In the discussion of results the totally released and supplied water quantities per year are shown, also for simulations with real conditions as occurred in the period 1992-2001.

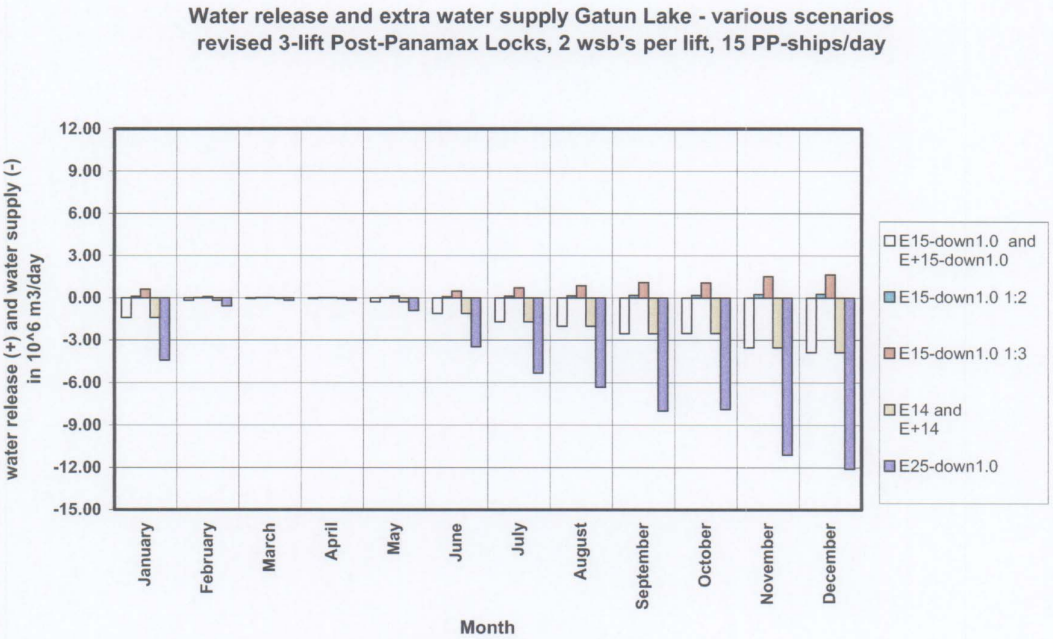


Figure 7.1a **Gatun Lake: daily water releases and extra water supplies in 10^6 m^3/day, revised 3-lift locks 2 wsb's/lift (E), 15 PP-vessels/day, minimum water supply**

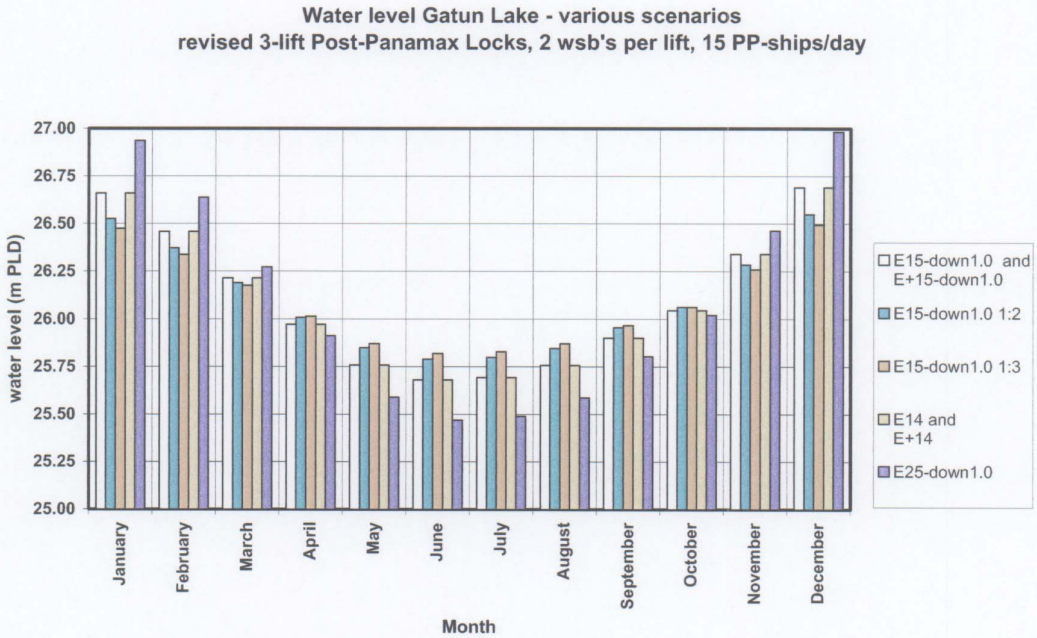


Figure 7.1b **Gatun Lake: water level variation in m PLD, revised 3-lift locks 2 wsb's/lift (E), 15 PP-vessels/day, minimum water supply**

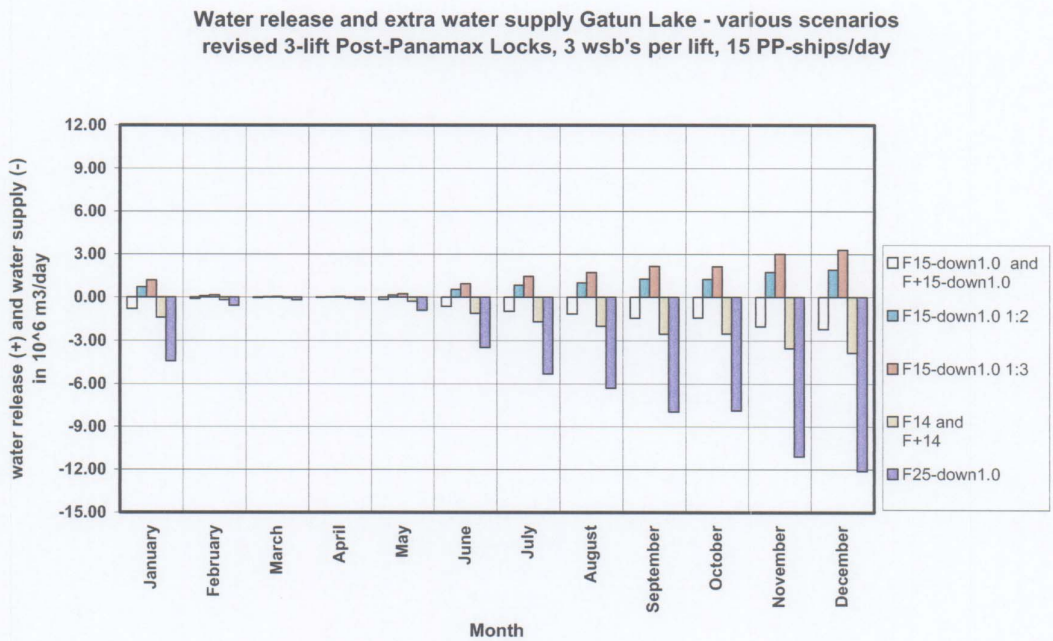


Figure 7.2a **Gatun Lake: daily water releases and extra water supplies in 10^6 m^3/day, revised 3-lift locks 3 wsb's/lift (F), 15 PP-vessels/day, minimum water supply**

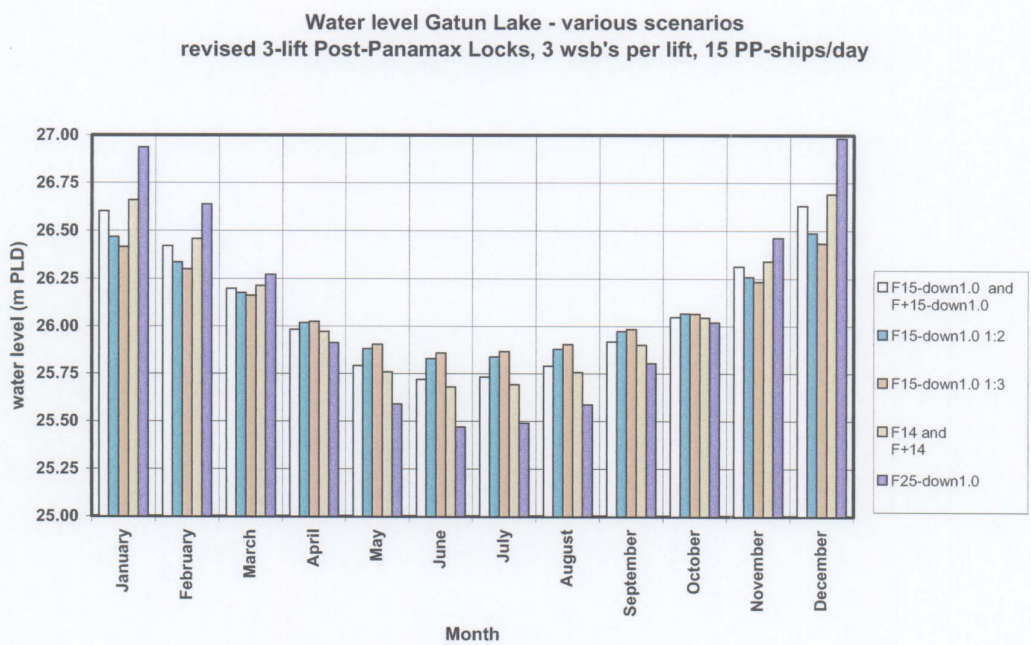


Figure 7.2b **Gatun Lake: water level variation in m PLD, revised 3-lift locks 3 wsb's/lift (F), 15 PP-vessels/day, minimum water supply**

7.1.2 Results of further simulations, minimum water supply

The results of the simulations are discussed as follows:

- Minimum water supply; solely operation of mitigation systems I, II, III or IV; 15 PP-ships/day
- Minimum water supply; solely operation of mitigation systems I, II, III or IV; combined operation of mitigation systems I and IV; 15, 10 and 5 PP-ships/day
- Real hydraulic conditions 1992-2001; minimum water supply; solely operation of mitigation system I; 15, 10 and 5 PP-ships/day.

The results of the simulations are presented as maximum and minimum salt concentration values (volume-averaged) of Gatun Lake and Miraflores Lake. The values found in the last year of the considered five-year period are presented in tables and graphs. Also the corresponding total water release and the total extra water supply per year are shown in graphs. For reasons of comparison the results of the initial simulations are included in the tables and charts. For a few cases the variation of the salt concentration of Miraflores Lake and Gatun Lake as a function of wet and dry season are shown in Annex A.

Minimum water supply; solely operation of mitigation systems I, II, III or IV; 15 PP-ships/day

Results of simulations for revised 3-lift locks with 2 wsb's per lift (E) are presented in Table 7.2 and Figures 7.3a/b/c, results of simulations for revised 3-lift locks with 3 wsb's per lift (F) are presented in Table 7.3 and Figures 7.4a/b/c. The present situation (A) is also shown.

Case / water control scenario	*Volume-averaged salt concentration (ppt) Miraflores Lake*		*Volume-averaged salt concentration (ppt) Gatun Lake*	
	minimum	*maximum*	*minimum*	*maximum*
Existing situation				
A	0.64	1.42	0.010	0.027
Revised 3-lift locks – 2 wsb's/lift				
E13-15PP, no mitigation	0.85	2.08	0.45	0.68
E⁺13-15PP, no mitigation	0.86	2.09	0.45	0.69
E14-15PP, no mitigation, no wsb's	0.90	2.02	0.52	0.58
E25-15PP, mit I, down1.0, no wsb's	0.67	1.60	0.11	0.12
E⁺14-15PP, no mitigation, no wsb's	0.90	2.03	0.52	0.59
E15-15PP, mit I, up1.0+down1.0	0.69	1.64	0.14	0.17
E15-15PP, mit I, down1.0	0.72	1.71	0.21	0.24
E15-15PP, mit I, down1.0, 1:2	0.89	2.01	0.50	0.56
E15-15PP, mit I, down1.0, 1:3	0.87	2.01	0.47	0.58
E⁺15-15PP, mit I, down1.0	0.74	1.73	0.23	0.26
E16-15PP, mit II, up1.0+down1.0	0.67	1.61	0.11	0.13
E16-15PP, mit II, down1.0	0.69	1.64	0.15	0.17
E17-15PP, mit III, up0.5+down1.25	0.72	1.69	0.19	0.22
E17-15PP, mit III, down1.25	0.76	1.78	0.28	0.32
E18-15PP, mit IV, up0.2+down0.2	0.77	1.88	0.29	0.45
E18-15PP, mit IV, down0.2	0.81	1.98	0.37	0.56
E19-15PP, mit I, down1.0 + mit IV, down0.2	0.71	1.68	0.18	0.20
E19-15PP, mit I, down1.0, 1:2 + mit IV, down0.2	0.84	1.92	0.42	0.47
E19-15PP, mit I, down1.0, 1:3 + mit IV, down0.2	0.82	1.92	0.39	0.48

Table 7.2 Maximum and minimum volume-averaged salt concentration of Miraflores Lake and Gatun Lake; present (A), revised 3-lift locks with 2 wsb's (E) per lift, minimum water supply, 15 PP-vessels a day, water control scenarios 13, 14, 15 – 18, 19, 25

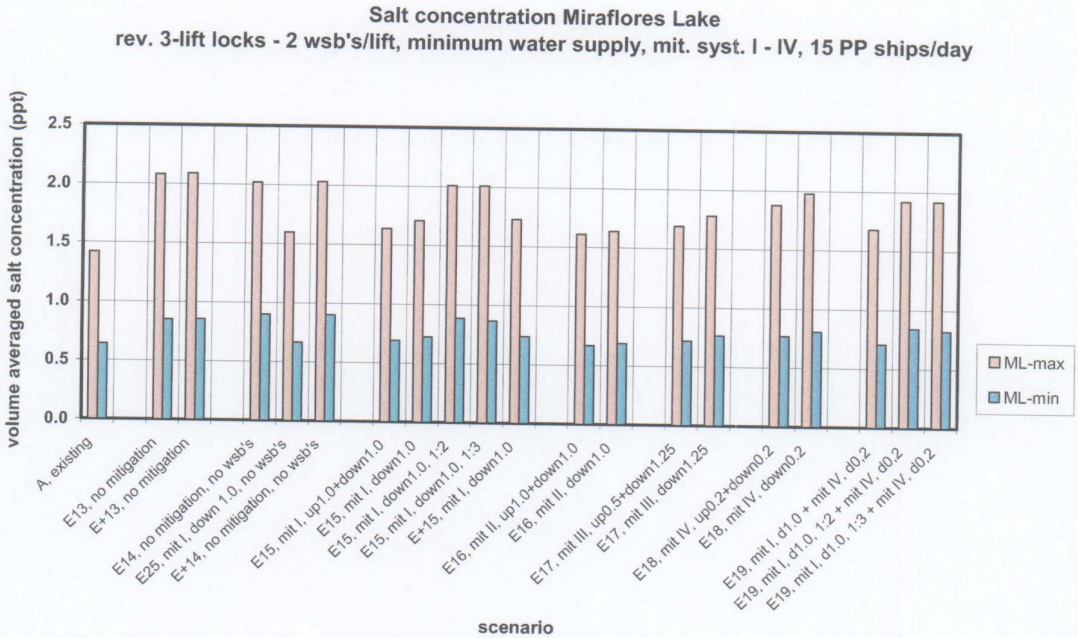


Figure 7.3a **Miraflores Lake: volume-averaged salt concentration (in ppt), maximum and minimum values, revised 3-lift locks with 2 wsb's per lift (E), 15 PP-vessels/day, minimum water supply, water control scenarios 13, 14, 15 – 18, 19, 25**

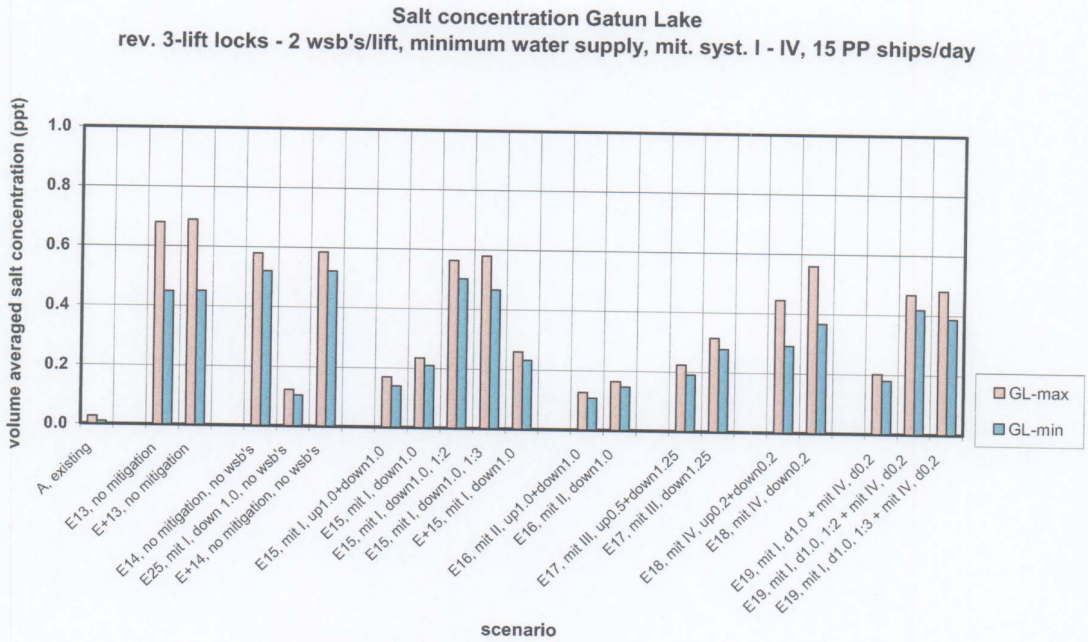


Figure 7.3b **Gatun Lake: volume-averaged salt concentration (in ppt), maximum and minimum values, revised 3-lift locks with 2 wsb's per lift (E), 15 PP-vessels/day, minimum water supply, water control scenarios 13, 14, 15 – 18, 19, 25**

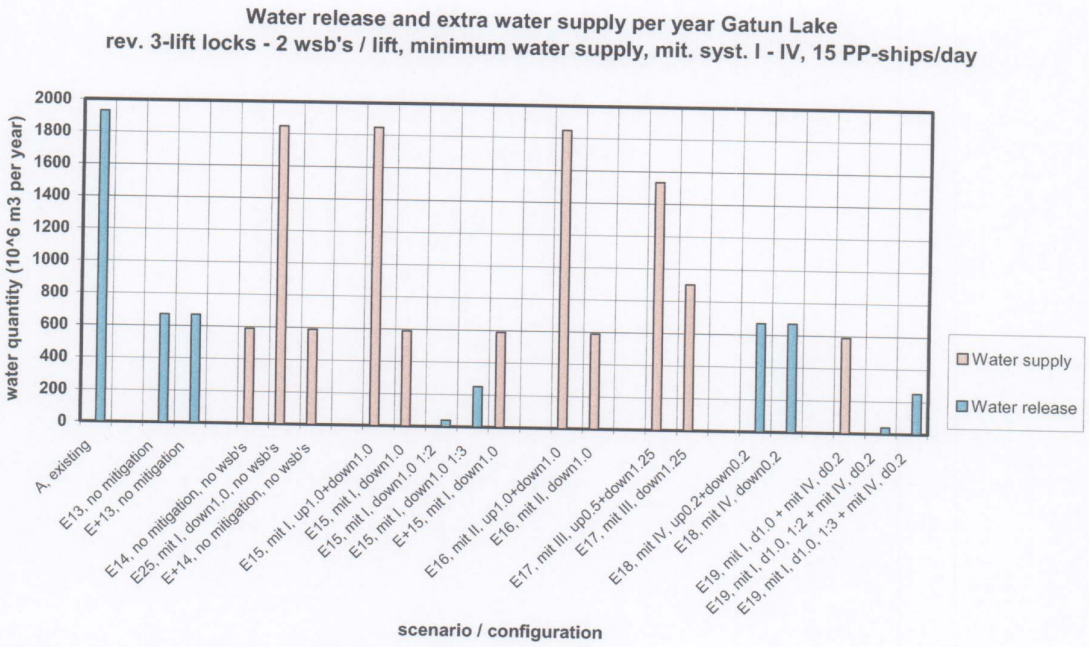


Figure 7.3c **Gatun Lake: water releases and extra water supplies in 10^6 m^3 per year, revised 3-lift locks with 2 wsb's per lift (E), 15 PP-vessels/day, minimum water supply, water control scenarios 13, 14, 15 – 18, 19, 25**

Case / water control scenario	*Volume-averaged salt concentration (ppt) Miraflores Lake*		*Volume-averaged salt concentration (ppt) Gatun Lake*	
	minimum	*maximum*	*minimum*	*maximum*
Existing situation				
A	0.64	1.42	0.010	0.027
Revised 3-lift locks – 3 wsb's/lift				
F13-15PP, no mitigation	0.83	2.10	0.41	0.71
F^{+}13-15PP, no mitigation	0.84	2.11	0.42	0.73
F14-15PP = E14-15PP	0.90	2.02	0.52	0.58
F25-15PP = E25-15PP	0.67	1.60	0.11	0.12
F^{-}14-15PP = E^{-}14-15PP	0.90	2.03	0.52	0.59
F15-15PP, mit I, up1.0+down1.0	0.70	1.66	0.16	0.19
F15-15PP, mit I, down1.0	0.75	1.75	0.25	0.28
F15-15PP, mit I, down1.0, 1:2	0.84	1.96	0.42	0.53
F15-15PP, mit I, down1.0, 1:3	0.83	1.99	0.41	0.57
F^{+}15-15PP, mit I, down1.0	0.76	1.78	0.28	0.31
F16-15PP, mit II, up1.0+down1.0	0.68	1.62	0.12	0.14
F16-15PP, mit II, down1.0	0.70	1.67	0.17	0.20
F17-15PP, mit III, up0.5+down1.25	0.74	1.73	0.23	0.27
F17-15PP, mit III, down1.25	0.80	1.84	0.34	0.38
F18-15PP, mit IV, up0.2+down0.2	0.76	1.90	0.28	0.48
F18-15PP, mit IV, down0.2	0.80	2.01	0.35	0.60
F19-15PP, mit I, down1.0 + mit IV, down0.2	0.73	1.72	0.22	0.25
F19-15PP, mit I, down1.0, 1:2 + mit IV, down0.2	0.80	1.89	0.35	0.45
F19-15PP, mit I, down1.0, 1:3 + mit IV, down0.2	0.79	1.91	0.34	0.48

Table 7.3 Maximum and minimum volume-averaged salt concentration of Miraflores Lake and Gatun Lake; present (A), revised 3-lift locks with 3 wsb's (F) per lift, minimum water supply, 15 PP-vessels a day, water control scenarios 13, 14, 15 – 18, 19, 25

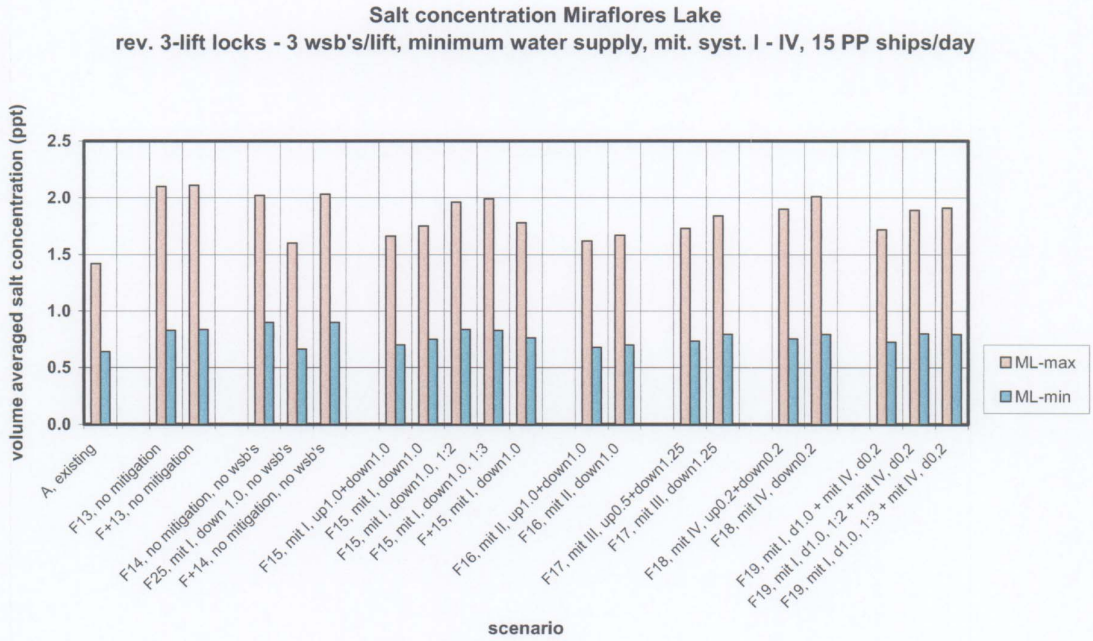


Figure 7.4a **Miraflores Lake: volume-averaged salt concentration (in ppt), maximum and minimum values, revised 3-lift locks with 3 wsb's per lift (F), 15 PP-vessels/day, minimum water supply, water control scenarios 13, 14, 15 – 18, 19, 25**

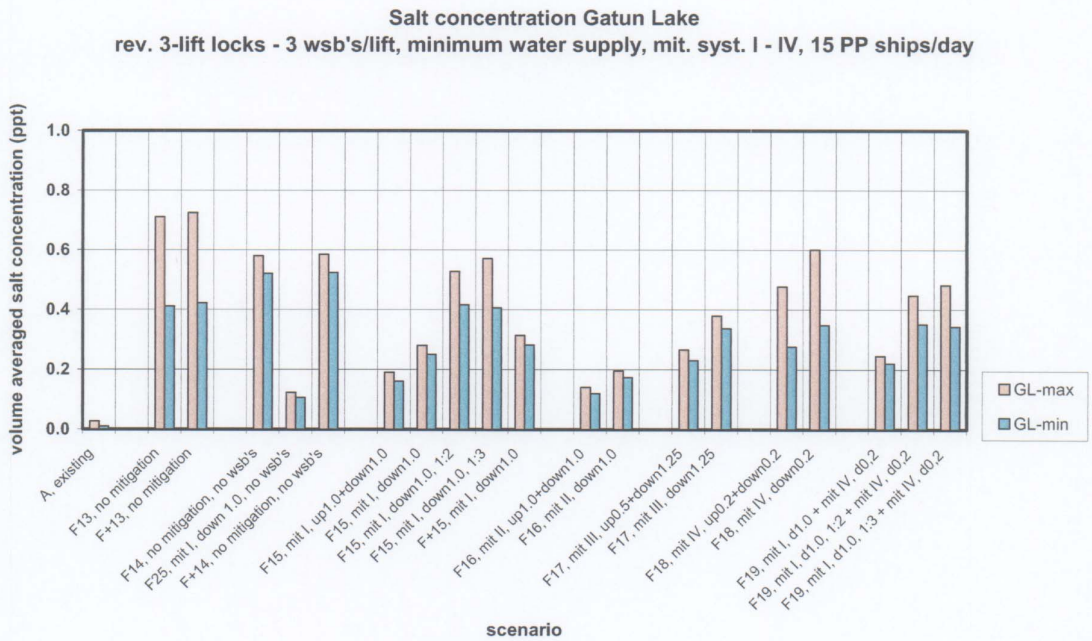


Figure 7.4b **Gatun Lake: volume-averaged salt concentration (in ppt), maximum and minimum values, revised 3-lift locks with 3 wsb's per lift (F), 15 PP-vessels/day, minimum water supply, water control scenarios 13, 14, 15 – 18, 19, 25**

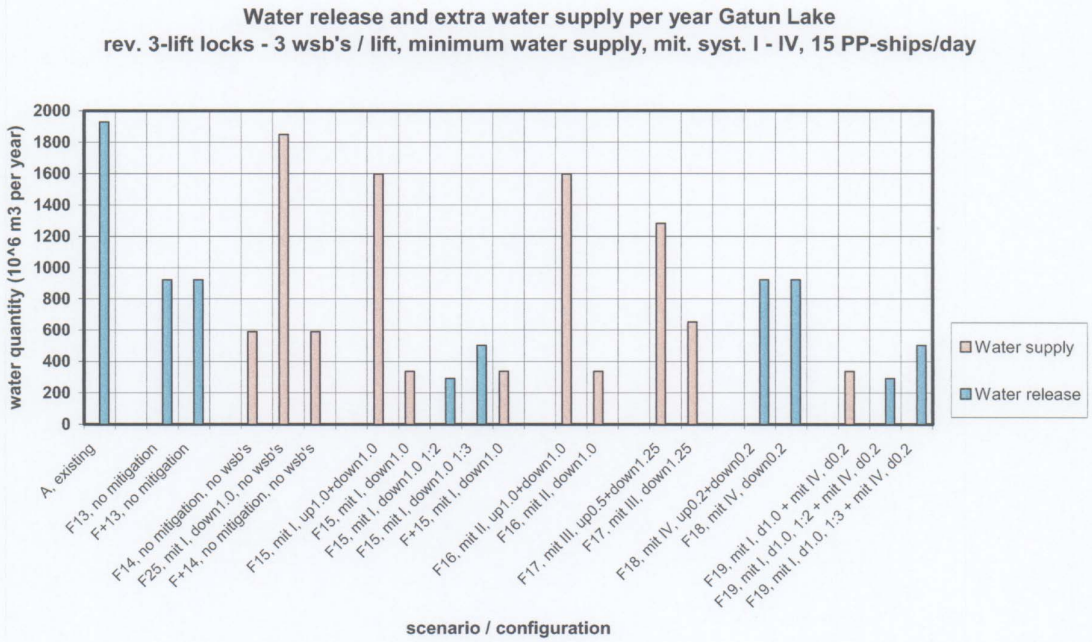


Figure 7.4c **Gatun Lake: water releases and extra water supplies in 10^6 m^3 per year, revised 3-lift locks with 3 wsb's per lift (F), 15 PP-vessels/day, minimum water supply, water control scenarios 13, 14, 15 – 18, 19, 25**

Minimum water supply; solely operation of mitigation systems I, II, III or IV; combined operation of mitigation systems I and IV; 15, 10 and 5 PP-ships/day

Results of simulations for revised 3-lift locks with 2 wsb's per lift (E) are presented in Table 7.4 and Figures 7.5a/b/c, results of simulations for revised 3-lift locks with 3 wsb's per lift (F) are presented in Table 7.5 and Figures 7.6a/b/c.

Case / water control scenario	*Volume-averaged salt concentration (ppt) Miraflores Lake*		*Volume-averaged salt concentration (ppt) Gatun Lake*	
	minimum	*maximum*	*minimum*	*maximum*
Revised 3-lift locks – 2 wsb's/lift				
E13-15PP, no mitigation	0.85	2.08	0.45	0.68
E13-10PP, no mitigation	0.69	1.74	0.15	0.29
E13-5PP, no mitigation	0.63	1.59	0.05	0.11
E14-15PP, no mitigation, no wsb's	0.90	2.02	0.52	0.58
E14-10PP, no mitigation, no wsb's	0.71	1.71	0.19	0.24
E14-5PP, no mitigation, no wsb's	0.62	1.54	0.03	0.05
E25-15PP, mit I, down1.0, no wsb's	0.67	1.60	0.11	0.12
E25-10PP, mit I, down1.0, no wsb's	0.65	1.58	0.09	0.10
E25-5PP, mit I, down1.0, no wsb's	0.62	1.53	0.03	0.04
E15-15PP, mit I, down1.0	0.72	1.71	0.21	0.24
E15-10PP, mit I, down1.0	0.66	1.60	0.10	0.12
E15-5PP, mit I, down1.0	0.68	1.67	0.03	0.05
E15-15PP, mit I, down1.0, 1:3	0.87	2.01	0.47	0.58
E15-10PP, mit I, down1.0, 1:3	0.66	1.65	0.11	0.18
E15-5PP, mit I, down1.0, 1:3	0.62	1.56	0.04	0.08
E16-15PP, mit II, down1.0	0.69	1.64	0.15	0.17
E16-10PP, mit II, down1.0	0.65	1.58	0.08	0.10
E16-5PP, mit II, down1.0	0.61	1.53	0.02	0.04
E17-15PP, mit III, down1.25	0.76	1.78	0.28	0.32
E17-10PP, mit III, down1.25	0.77	1.83	0.18	0.20
E17-5PP, mit III, down1.25	0.62	1.55	0.04	0.06
E18-15PP, mit IV, down0.2	0.81	1.98	0.37	0.56
E19-15PP, mit I, down1.0 + mit IV, down0.2	0.71	1.68	0.18	0.20
E19-10PP, mit I, down1.0 + mit IV, down0.2	0.67	1.59	0.09	0.11
E19-5PP, mit I, down1.0 + mit IV, down0.2	0.62	1.53	0.03	0.05
E19-15PP, mit I, down1.0, 1:3 + mit IV, down0.2	0.82	1.92	0.39	0.48
E19-10PP, mit I, down1.0, 1:3 + mit IV, down0.2	0.66	1.62	0.09	0.15
E19-5PP, mit I, down1.0, 1:3 + mit IV, down0.2	0.62	1.56	0.04	0.07

Table 7.4 Maximum and minimum volume-averaged salt concentration of Miraflores Lake and Gatun Lake; revised 3-lift locks with 2 wsb's (E) per lift, minimum water supply, 15, 10 and 5 PP-vessels a day, water control scenarios 13, 14, 15 – 18, 19, 25

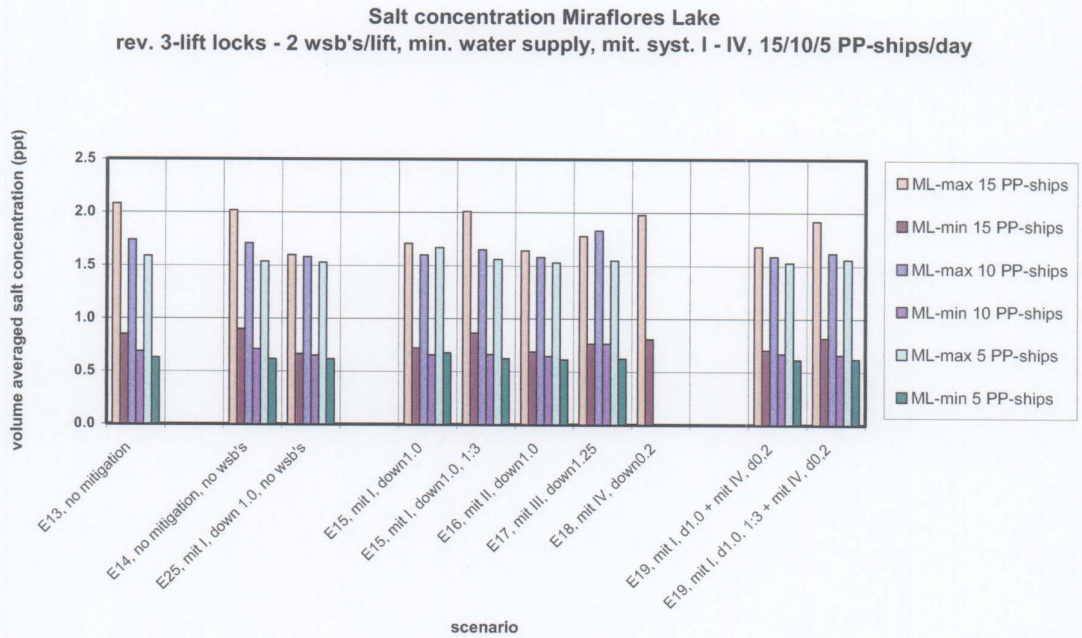


Figure 7.5a **Miraflores Lake: volume-averaged salt concentration (in ppt), maximum and minimum values, revised 3-lift locks with 2 wsb's per lift (E), 15, 10 and 5 PP-vessels/day, minimum water supply, water control scenarios 13, 14, 15 – 18, 19, 25**

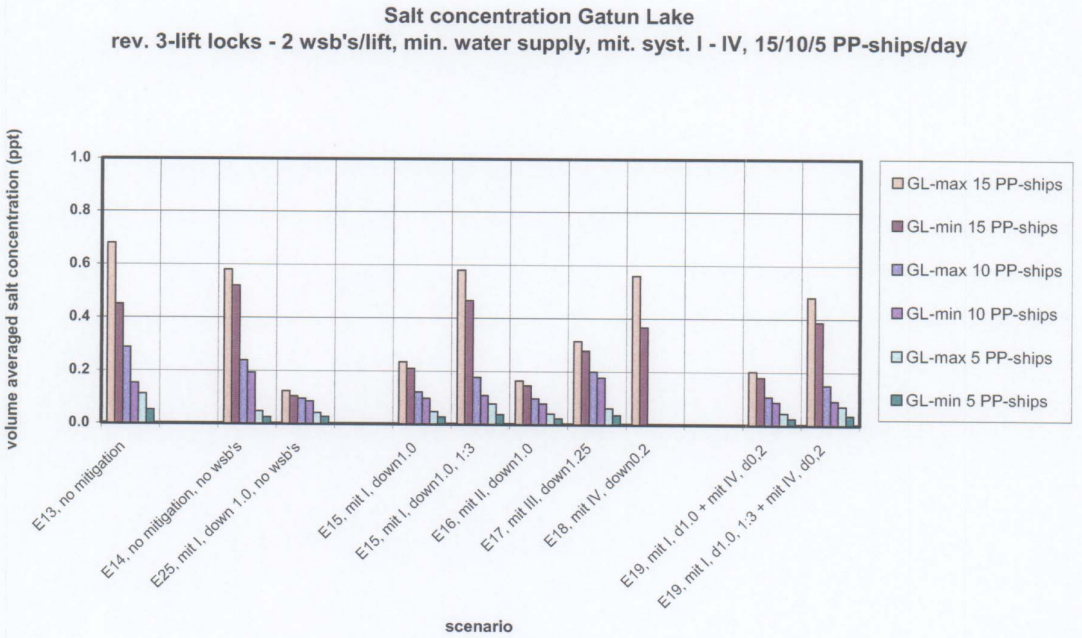


Figure 7.5b **Gatun Lake: volume-averaged salt concentration (in ppt), maximum and minimum values, revised 3-lift locks with 2 wsb's per lift (E), 15, 10 and 5 PP-vessels/day, minimum water supply, water control scenarios 13, 14, 15 – 18, 19, 25**

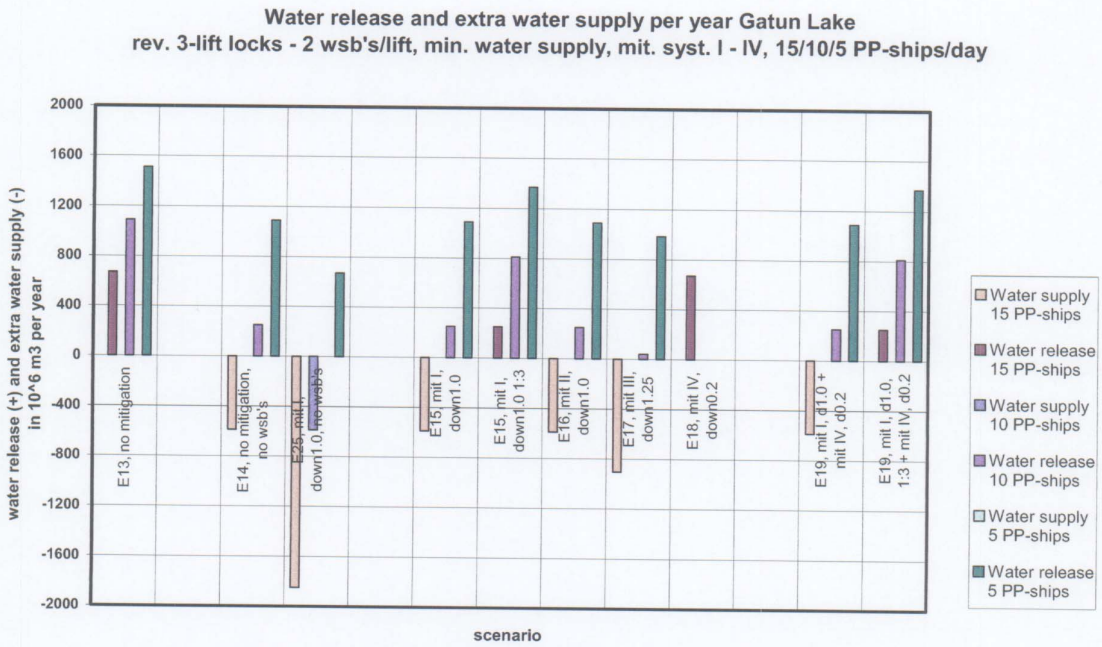


Figure 7.5c **Gatun Lake: water releases and extra water supplies in 10^6 m^3 per year, revised 3-lift locks with 2 wsb's per lift (E), 15, 10 and 5 PP-vessels/day, minimum water supply, water control scenarios 13, 14, 15 – 18, 19, 25**

Case / water control scenario	*Volume-averaged salt concentration (ppt) Miraflores Lake*		*Volume-averaged salt concentration (ppt) Gatun Lake*	
	minimum	*maximum*	*minimum*	*maximum*
Revised 3-lift locks – 3 wsb's/lift				
F13-15PP, no mitigation	0.83	2.10	0.41	0.71
F13-10PP, no mitigation	0.69	1.78	0.17	0.34
F13-5PP, no mitigation	0.64	1.62	0.06	0.15
F14-15PP = E14-15PP	0.90	2.02	0.52	0.58
F14-10PP = E14-10PP	0.71	1.71	0.19	0.24
F14-5PP = E14-5PP	0.62	1.54	0.03	0.05
F25-15PP = E25-15PP	0.67	1.60	0.11	0.12
F25-10PP = E25-10PP	0.65	1.58	0.09	0.10
F25-5PP = E25-5PP	0.62	1.53	0.03	0.04
F15-15PP, mit I, down1.0	0.75	1.75	0.25	0.28
F15-10PP, mit I, down1.0	0.65	1.60	0.09	0.12
F15-5PP, mit I, down1.0	0.62	1.54	0.03	0.05
F15-15PP, mit I, down1.0, 1:3	0.83	1.99	0.41	0.57
F15-10PP, mit I, down1.0, 1:3	0.67	1.67	0.11	0.20
F15-5PP, mit I, down1.0, 1:3	0.63	1.58	0.04	0.10
F16-15PP, mit II, down1.0	0.70	1.67	0.17	0.20
F16-10PP, mit II, down1.0	0.64	1.58	0.07	0.10
F16-5PP, mit II, down1.0	0.61	1.53	0.02	0.04
F17-15PP, mit III, down1.25	0.80	1.84	0.34	0.38
F17-10PP, mit III, down1.25	0.70	1.68	0.17	0.20
F17-5PP, mit III, down1.25	0.62	1.56	0.04	0.07
F18-15PP, mit IV, down0.2	0.80	2.01	0.35	0.60
F18-10PP, mit IV, down0.2	0.68	1.73	0.14	0.28
F18-5PP, mit IV, down0.2	0.63	1.61	0.06	0.13
F19-15PP, mit I, down1.0 + mit IV, down0.2	0.73	1.72	0.22	0.25
F19-10PP, mit I, down1.0 + mit IV, down0.2	0.65	1.59	0.08	0.11
F19-5PP, mit I, down1.0 + mit IV, down0.2	0.62	1.54	0.03	0.05
F19-15PP, mit I, down1.0, 1:3 + mit IV, down0.2	0.79	1.91	0.34	0.48
F19-10PP, mit I, down1.0, 1:3 + mit IV, down0.2	0.66	1.64	0.10	0.17
F19-5PP, mit I, down1.0, 1:3 + mit IV, down0.2	0.62	1.57	0.04	0.09

Table 7.5 Maximum and minimum volume-averaged salt concentration of Miraflores Lake and Gatun Lake; revised 3-lift locks with 3 wsb's (F) per lift, minimum water supply, 15, 10 and 5 PP-vessels a day, water control scenarios 13, 14, 15 – 18, 19, 25

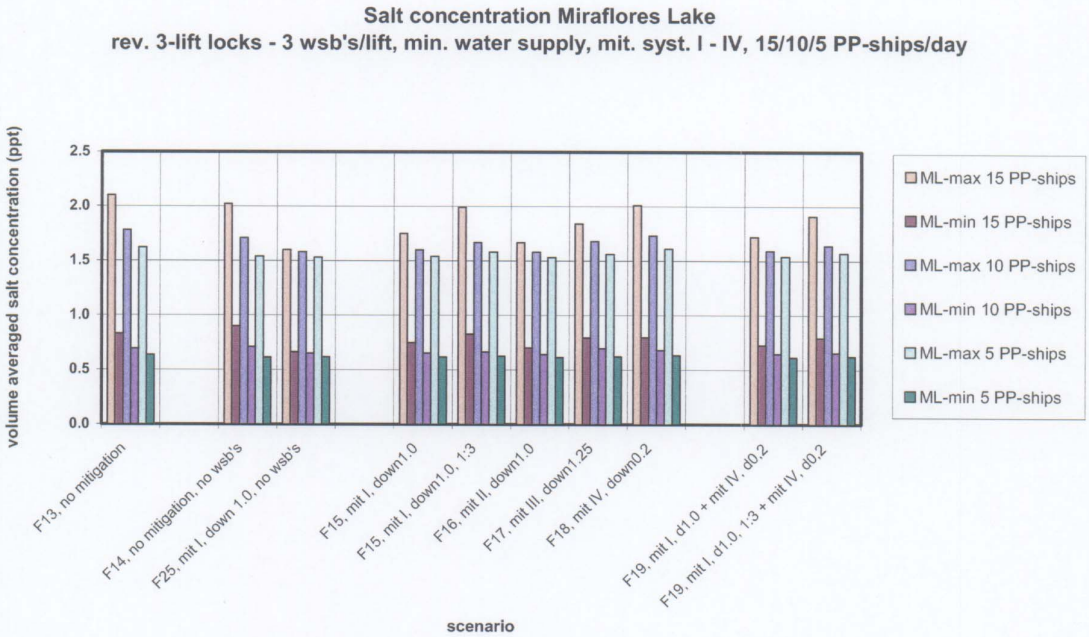


Figure 7.6a **Miraflores Lake: volume-averaged salt concentration (in ppt), maximum and minimum values, revised 3-lift locks with 3 wsb's per lift (F), 15, 10 and 5 PP-vessels/day, minimum water supply, water control scenarios 13, 14, 15 – 18, 19, 25**

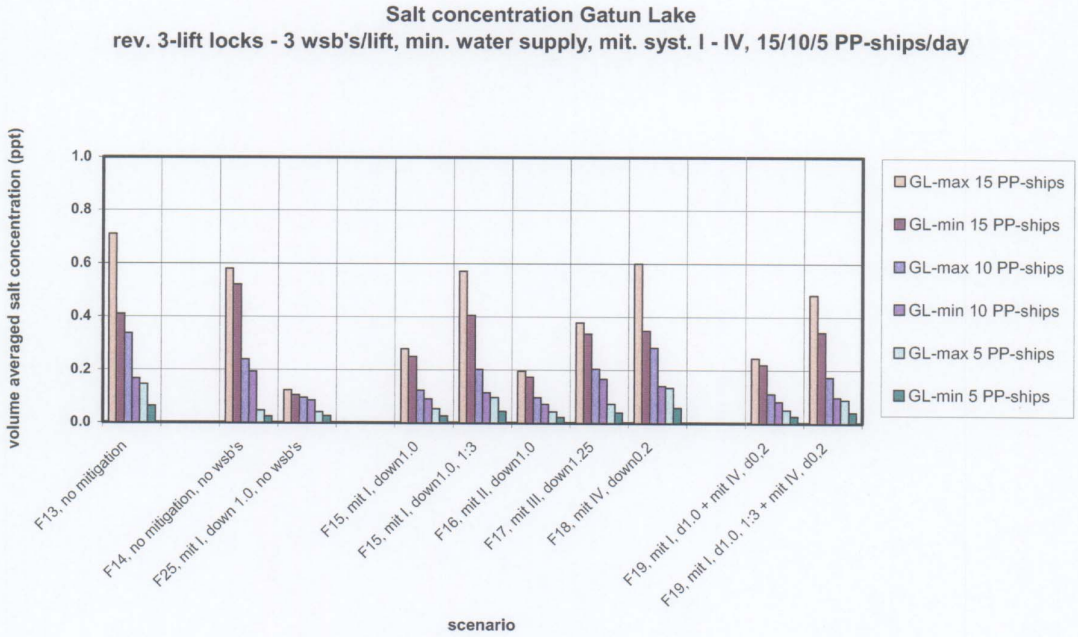


Figure 7.6b **Gatun Lake: volume-averaged salt concentration (in ppt), maximum and minimum values, revised 3-lift locks with 3 wsb's per lift (F), 15, 10 and 5 PP-vessels/day, minimum water supply, water control scenarios 13, 14, 15 – 18, 19, 25**

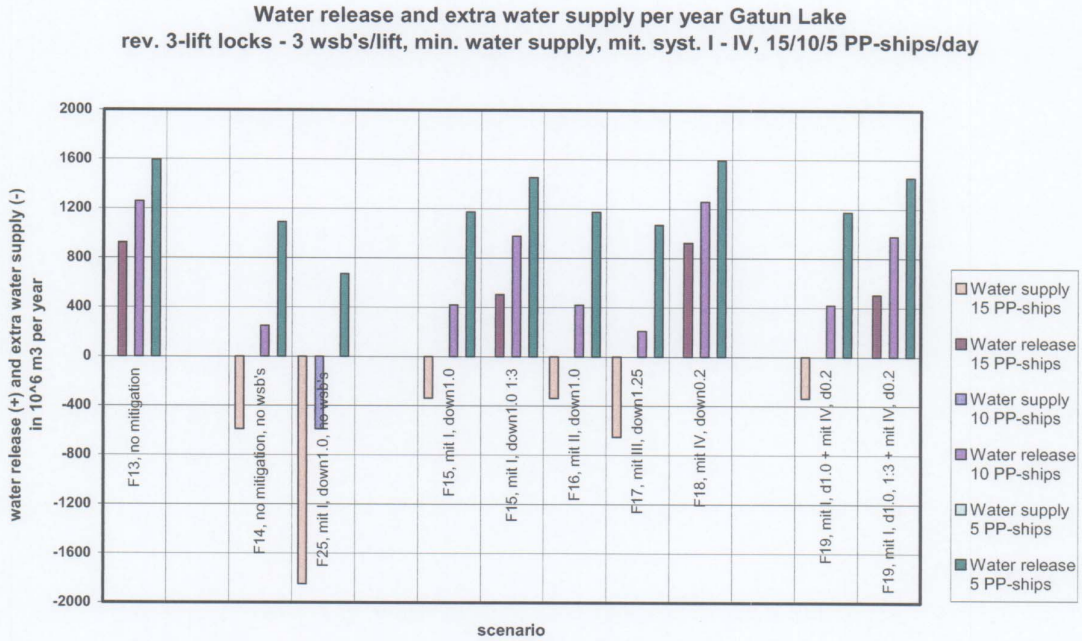


Figure 7.6c **Gatun Lake: water releases and extra water supplies in 10^6 m^3 per year, revised 3-lift locks with 3 wsb's per lift (F), 15, 10 and 5 PP-vessels/day, minimum water supply, water control scenarios 13, 14, 15 – 18, 19, 25**

Real hydraulic conditions 1992-2001; minimum water supply; solely operation of mitigation system I; 15, 10 and 5 PP-ships/day

Simulations have been executed for the revised 3-lift locks with 2 and 3 wsb's per lift, for hydraulic conditions as occurred in the period 1992 – 2001. However, because of the extra water losses caused by the new locks and mitigation system I, water releases are reduced throughout the year and extra water is supplied, if needed. Consequently, the water level variation of Gatun Lake throughout the year deviates from the real water level variation in the 1992 – 2001 period (but the mean value of the water level in a year is kept the same). In next Figures 7.7a/b the real water level variation in the period 1992 – 2001 is shown and, as an example the water level variation in case 'F15-15PP, mit I, down1.0, real cond.'.

Results of simulations for revised 3-lift locks with 2 wsb's per lift (E) and revised 3-lift locks with 3 wsb's per lift (F) are presented in Figures 7.8a/b/c and Figures 7.9a/b/c.

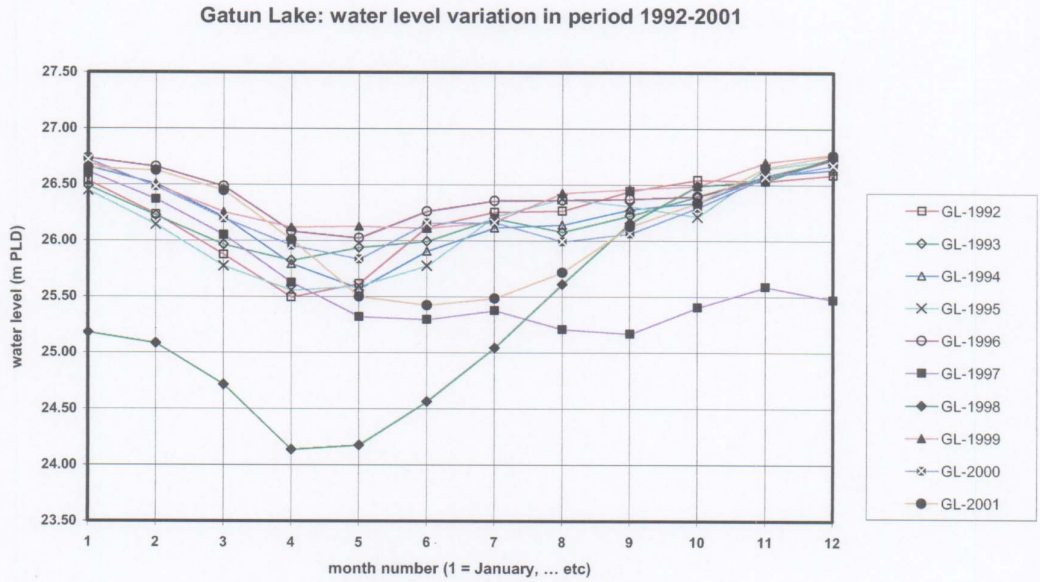


Figure 7.7a **Gatun Lake: water level variation in period 1992 - 2001**

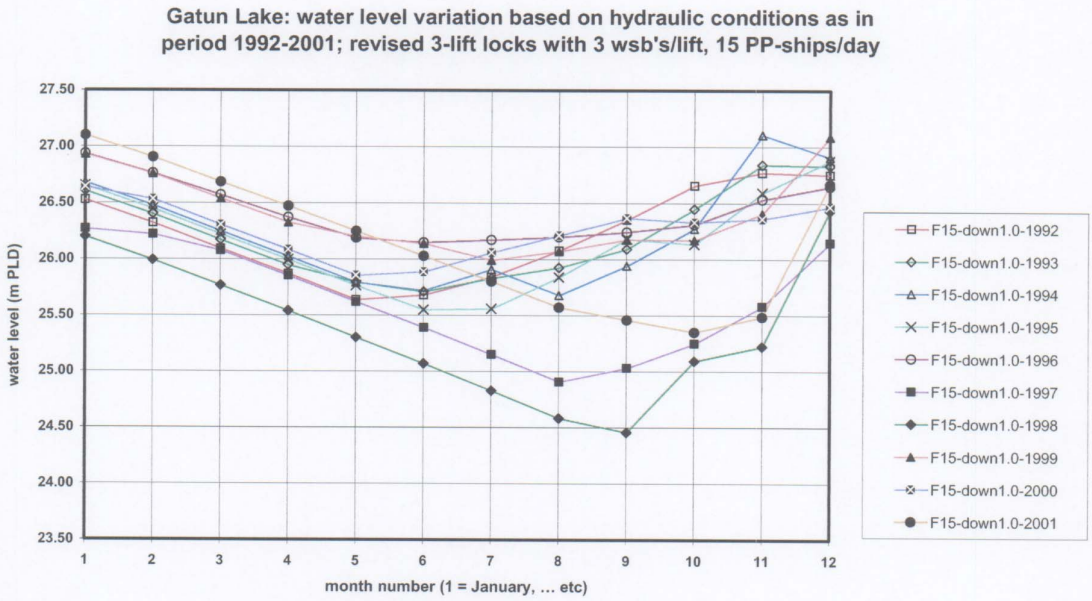


Figure 7.7b **Gatun Lake: water level variation in case 'F15-15PP, mit I, down1.0, real cond.' based on water level in period 1992 - 2001**

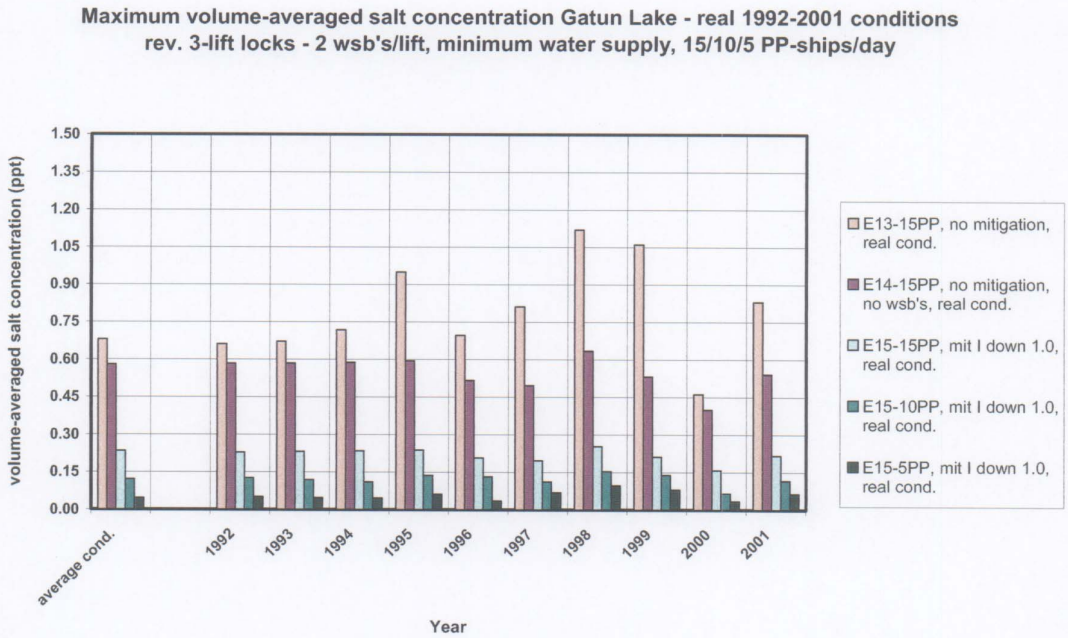


Figure 7.8a **Gatun Lake: maximum volume-averaged salt concentration (in ppt), revised 3-lift locks with 2 wsb's per lift (E), 15, 10 and 5 PP-vessels/day, real conditions, minimum water supply, water control scenarios 13, 14, 15**

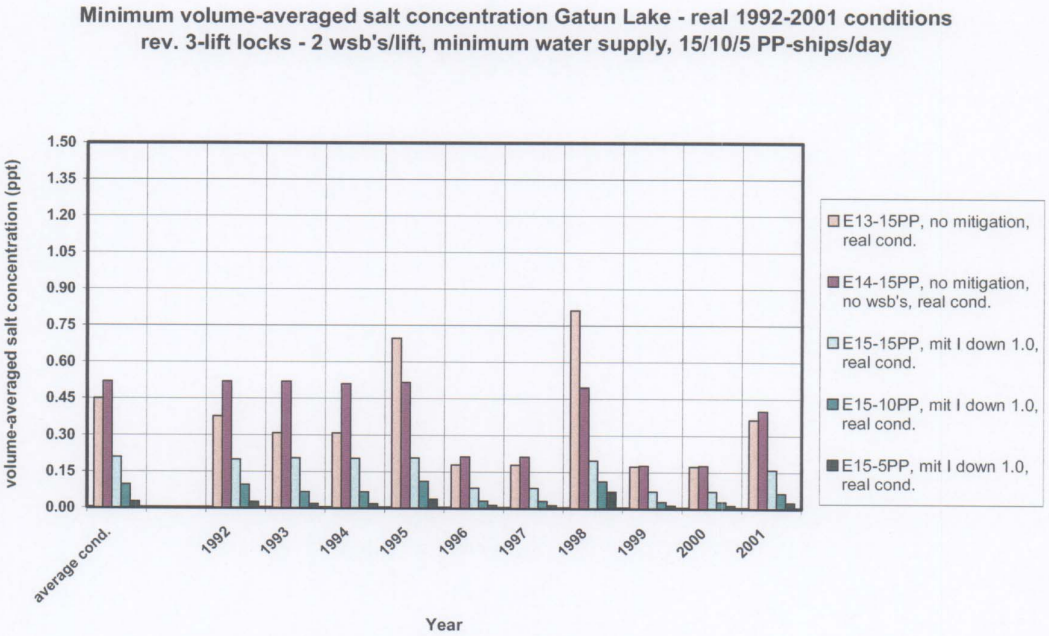


Figure 7.8b **Gatun Lake: minimum volume-averaged salt concentration (in ppt), revised 3-lift locks with 2 wsb's per lift (E), 15, 10 and 5 PP-vessels/day, real conditions, minimum water supply, water control scenarios 13, 14, 15**

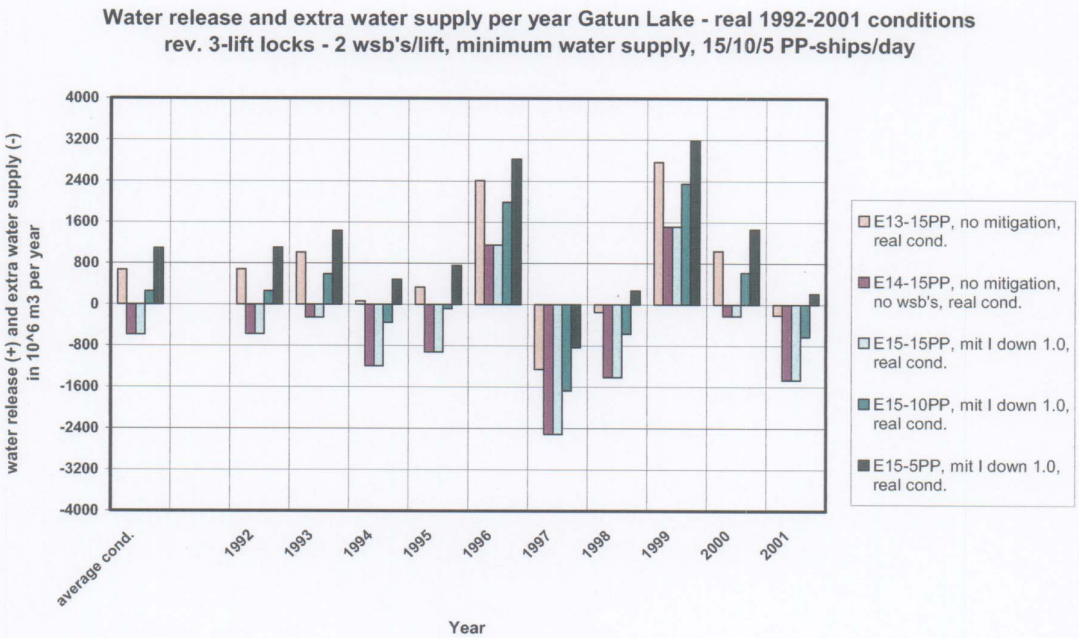


Figure 7.8c **Gatun Lake: water releases and extra water supplies in 10^6 m^3 per year, revised 3-lift locks with 2 wsb's per lift (E), 15, 10 and 5 PP-vessels/day, real conditions, minimum water supply, water control scenarios 13, 14, 15**

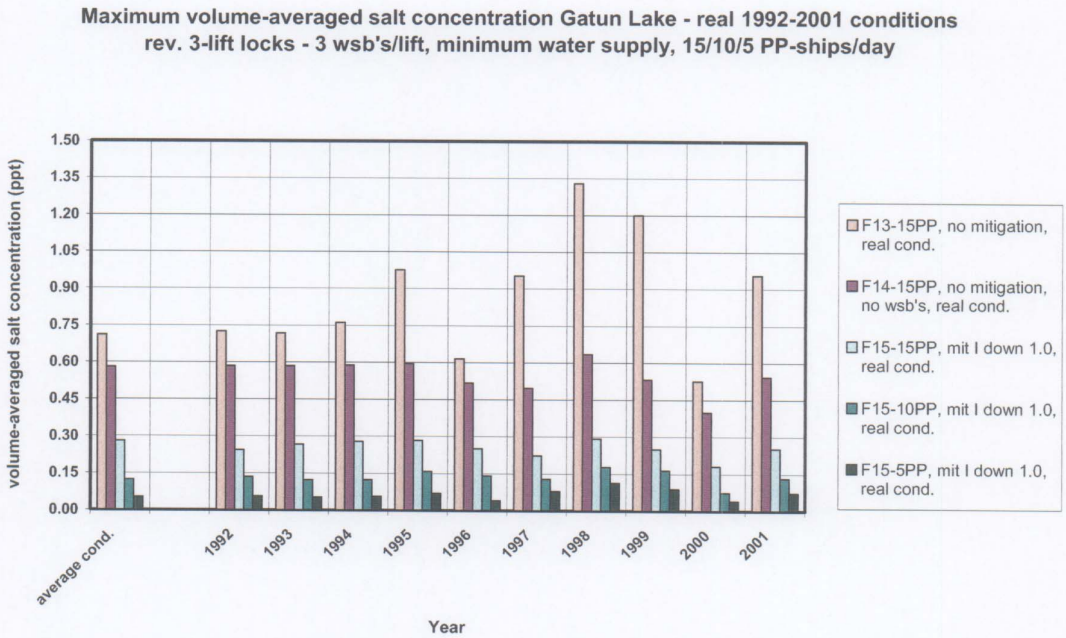


Figure 7.9a **Gatun Lake: maximum volume-averaged salt concentration (in ppt), revised 3-lift locks with 3 wsb's per lift (F), 15, 10 and 5 PP-vessels/day, real conditions, minimum water supply, water control scenarios 13, 14, 15**

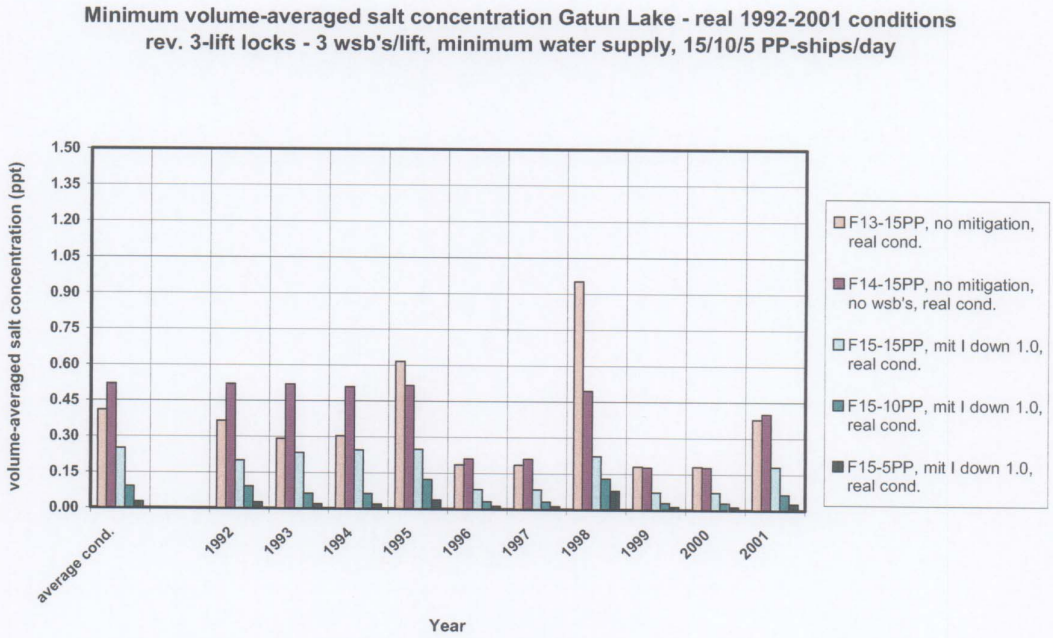


Figure 7.9b **Gatun Lake: minimum volume-averaged salt concentration (in ppt), revised 3-lift locks with 3 wsb's per lift (F), 15, 10 and 5 PP-vessels/day, real conditions, minimum water supply, water control scenarios 13, 14, 15**

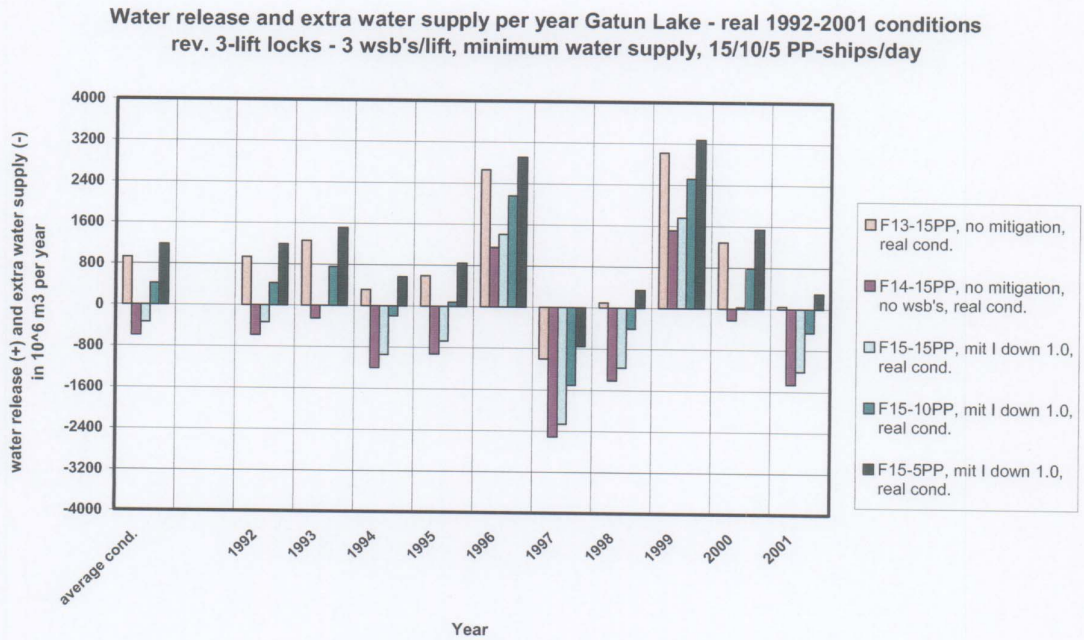


Figure 7.9c **Gatun Lake: water releases and extra water supplies in 10^6 m^3 per year, revised 3-lift locks with 3 wsb's per lift (F), 15, 10 and 5 PP-vessels/day, real conditions, minimum water supply, water control scenarios 13, 14, 15**

7.1.3 Analysis and conclusions; further simulations, minimum water supply

From an analysis of the results of the further simulations next conclusions can be drawn in addition to the conclusions of the initial simulations:

Post-Panamax ship traffic intensity 15 ships/day, Figures 7.3a/b/c and Figures 7.4a/b/c:

- The effect of mitigation system I has been studied for revised 3-lift locks without water saving basins; the mitigation system has been applied after downlockage of each ship (cases E25 and F25; note that F25 is equal to E25). As is shown, application of mitigation system I reduces the volume-averaged salt concentration of Gatun Lake considerably (compare E25 with E14 or F25 with F14 = E14), but the reduction is at the cost of a high extra fresh water supply. The reduction of the volume-averaged salt concentration of Miraflores Lake is less markedly.
- When mitigation system I is applied to revised 3-lift locks with 2 or 3 wsb's per lift (after each downlockage, see case 'E15, mit I, down1.0' or case 'F15, mit I, down1.0') a smaller reduction of the salt concentration is obtained, but since water is saved in the operation of the locks less extra fresh water is needed.
- A less intensive use of mitigation system I (operation of the mitigation system each second or third downlockage) reduces the extra fresh water need, but this is at the cost of a lesser effectiveness of the mitigation system (see cases 'E15, mit I, down1.0, 1:2', 'E15, mit I, down1.0, 1:3', 'F15, mit I, down1.0, 1:2' and 'F15, mit I, down1.0, 1:3').

- A comparison between revised 3-lift locks without wsb's, 2 wsb's/lift and 3 wsb's/lift, including the effect of mitigation system I, is made in Section 7.3.
- Combination of mitigation system IV (pneumatic barrier) with mitigation system I results in an extra reduction of the volume-averaged salt concentration of Gatun Lake with about 15% (compared to solely application of mitigation system I). The volume-averaged salt concentration of Miraflores Lake is reduced with about 4%. The water losses and thus the extra water supplies to Gatun Lake remain the same, since mitigation system IV does not cause a water loss. Compare cases E19 with corresponding cases E15, and cases F19 with corresponding cases F15.
- The salt water intrusion of revised 3-lift locks with 3 wsb's/lift and mitigation systems I and IV (operated at each downlockage) is almost equivalent to the salt water intrusion of revised 3-lift locks with 2 wsb's/lift and solely operation of mitigation system I (after each downlockage); the lockage loss of the 3-lift locks with 3 wsb's/lift is 40% of the 'normal' water loss (see Figure 3.2) instead of 50% for the 3-lift locks with 2 wsb's/lift, so that less extra fresh water has to be supplied to Gatun Lake.
- The effect of a 5 ft greater water depth in the lock chambers (5 ft lower floor level in view of 10 ft ship keel clearance instead of 5 ft clearance) on salt water intrusion is only small. Compare cases $E^{+}13$, $E^{+}14$, and $E^{+}15$ with corresponding cases E13, E14 and E15, and cases $F^{+}13$, $F^{+}14$, and $F^{+}15$ with corresponding cases F13, F14 and F15.

Post-Panamax ship traffic intensity 15, 10 and 5 ships/day, Figures 7.5a/b/c and Figures 7.6a/b/c:

- As may be expected, the salt water intrusion and thus the volume-averaged salt concentration of Gatun Lake and to a lesser extent Miraflores Lake increase with the Post-Panamax ship traffic intensity. Also the water losses and thus the need for extra water supplies to Gatun Lake increase with the ship traffic intensity. The relationship between the number of ship transfers and the salt concentration is non-linear.
- When water saving basins are applied in combination with mitigation systems I, II or III, ship traffic intensities of 5 and 10 Post-Panamax ships/day do not yet call for extra water supplies to Gatun Lake; neither does mitigation system IV for ship traffic intensities of 5, 10 and 15 Post-Panamax ships/day.

Real hydraulic conditions 1992-2001, Post-Panamax ship traffic intensity 15, 10 and 5 ships/day, Figures 7.8a/b/c and Figures 7.9a/b/c:

- The hydraulic conditions vary from year to year. When the conditions of the period 1992 – 2001 are taken as starting point for simulations instead of averaged conditions, the variation of the volume-averaged salt concentration of Gatun Lake is stronger. The variation of the maximum value of the concentration compared to this quantity at average conditions is in the range 1.7 – 0.7 in case 'E13-15PP, no mitigation, real cond.', and in the range 1.9 – 0.7 in case 'F13-15PP, no mitigation, real cond.'. When no water saving basins are applied, case 'E14-15PP, no mitigation, no wsb's, real cond.', the variation is in the range 1.1 – 0.7 (note F14 = E14). This smaller variation is caused by the fact that a larger quantity of extra water is supplied to Gatun Lake, which has a damping effect on the salt concentration variation.
- As a result of operation of mitigation system I more fresh water is needed. This has a similar effect on the variation of the salt concentration as case E14 (no wsb's). It means that the more Post-Panamax ships pass the canal, the more fresh water has to be supplied to the lake (in particular in dry years), and the lesser the variation of the salt

concentration under real conditions compared to average conditions. For example: the variation of the maximum value of the concentration is in the range 1.0 – 0.7 in case 'F15-15PP, mit I, down1.0, real cond.' (15 PP-ships/day) and in the range 2.1 – 0.7 in case 'F15-5PP, mit I, down1.0, real cond.' (5 PP-ships/day).

- It is questionable however, whether in dry years like 1997 sufficient extra fresh water is available. If not, the vessel draft has to be reduced or even shipping in the new lane has to be stopped, since the water level of Gatun Lake can not be maintained above the lower limit level for a safe shipping. When shipping continues at a reduced draft the salt water intrusion may be less since the ship-bound exchange of water is reduced, but the effect of the salt water intrusion may be stronger because of the smaller volume of the lake.

7.2 Further simulations, free water supply

7.2.1 Set up of further simulations, free water supply

The programme of simulations is shown in Tables 6.12a/b/c (solely operation of mitigation system I, II, III or IV). In all these simulations the supply of extra fresh water to Gatun Lake is free (the supply of extra fresh water is *not* minimized; extra water is supplied when needed; starting point is that sufficient extra fresh water is available). The present representative, averaged water level variation throughout the year is maintained; this water level varies between the adopted limits PLD +25.0 m (+82.0 ft) and PLD + 27.13 m (+89.0 ft).

In all simulations a maximum effectiveness of the mitigation system is prescribed (see Section 6.3.1 for water use and exchange coefficients). Mitigation systems are only operated at downlockage of each ship, not at uplockage. All simulations are executed for a 5-year period (the period 2056-2060 has been selected, similar as in earlier studies).

The ship traffic intensity is 15, 10 or 5 Post-Panamax vessels a day in the new shipping lane and 18 vessels a day in both west shipping lane and east shipping lane (see Table 6.1).

Tidal fluctuations and salt concentrations of seaside tailbays are in conformation with Section 5.2.

The water level of Miraflores Lake is kept constant at PLD +16.58 m (PLD +54.4 ft). The water releases of Miraflores Lake are shown in Figure 5.2 and Table 5.3.

The water level of Gatun Lake varies throughout the year; the present representative, averaged water level variation is maintained. In water control scenarios 3, 4 and 21 – 24 the water releases / extra water supplies of Gatun Lake vary as a function of time and are dependent on the number of Post-Panamax ship transits in the new shipping lane, the number of water saving basins and the mode of operation of the mitigation system. As an example Figures 7.10a/b present the water level variation and water releases / extra water supplies throughout the year of Gatun Lake for configuration E (revised 3-lift locks with 2 wsb's per lift) and for *15 Post-Panamax vessels per day.*

Figures 7.11a/b present the same quantities for configuration F (revised 3-lift locks with 3 wsb's per lift) and for *15 Post-Panamax vessels per day*. Note that the water level variation of Gatun Lake is similar as for configuration E.

Similar charts as presented for 15 Post-Panamax vessels per day can be made for 10 and 5 Post-Panamax vessels per day (they are not taken up in this report). In the discussion of results the totally released and supplied water quantities per year are shown.

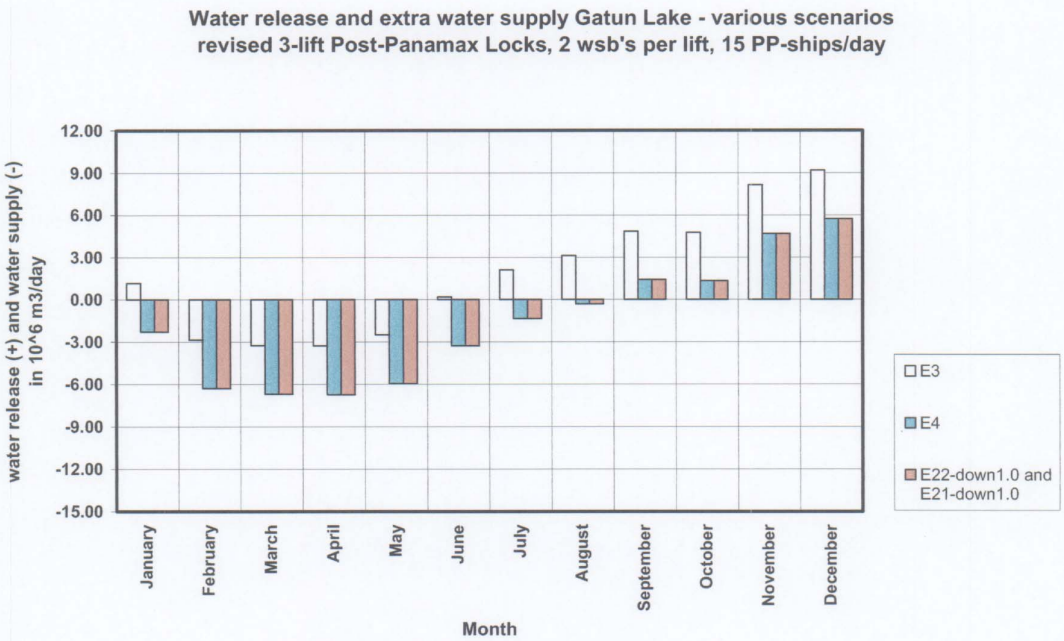


Figure 7.10a **Gatun Lake: daily water releases and extra water supplies in 10^6 m^3 per day, revised 3-lift locks with 2 wsb's per lift (E), 15 PP-vessels/day, free water supply**

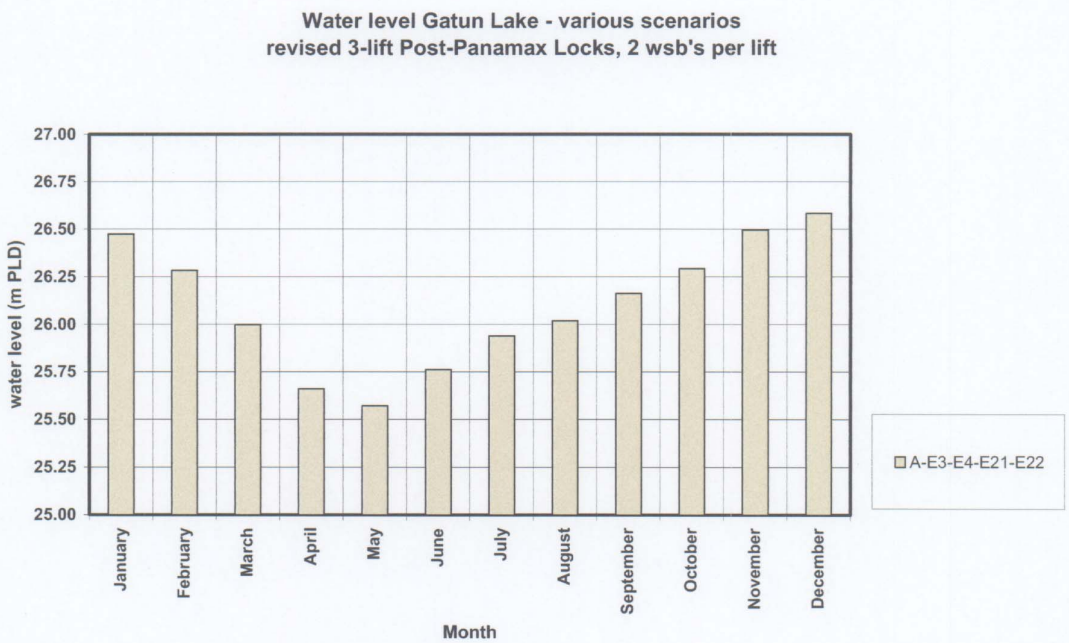


Figure 7.10b **Gatun Lake: water level variation in m PLD, revised 3-lift locks with 2 wsb's per lift (E), free water supply**

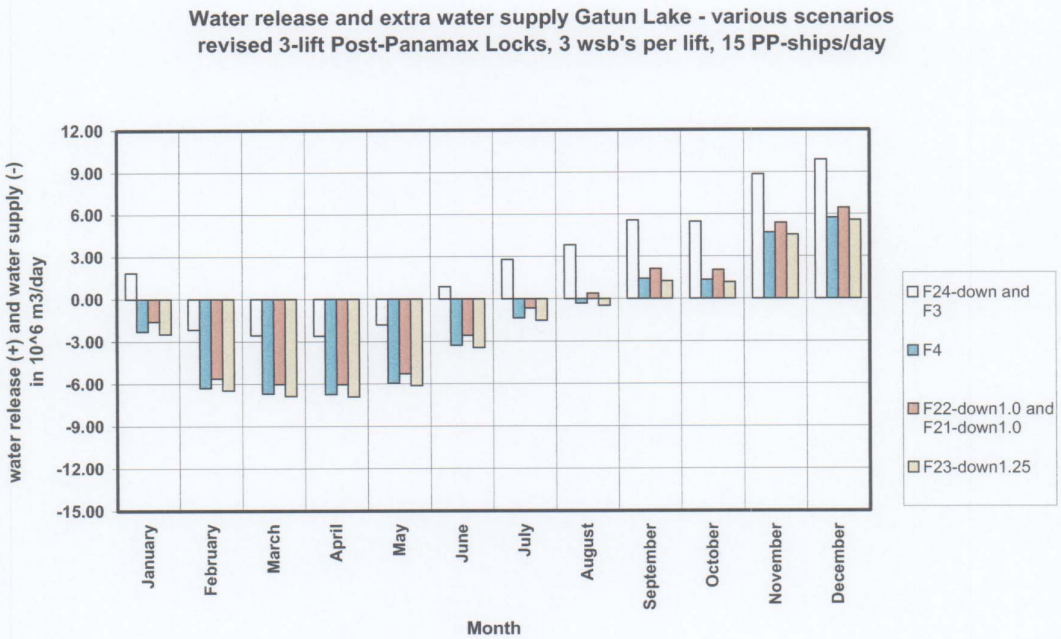


Figure 7.11a **Gatun Lake: daily water releases and extra water supplies in 10^6 m^3 per day, revised 3-lift locks with 3 wsb's per lift (F), 15 PP-vessels/day, free water supply**

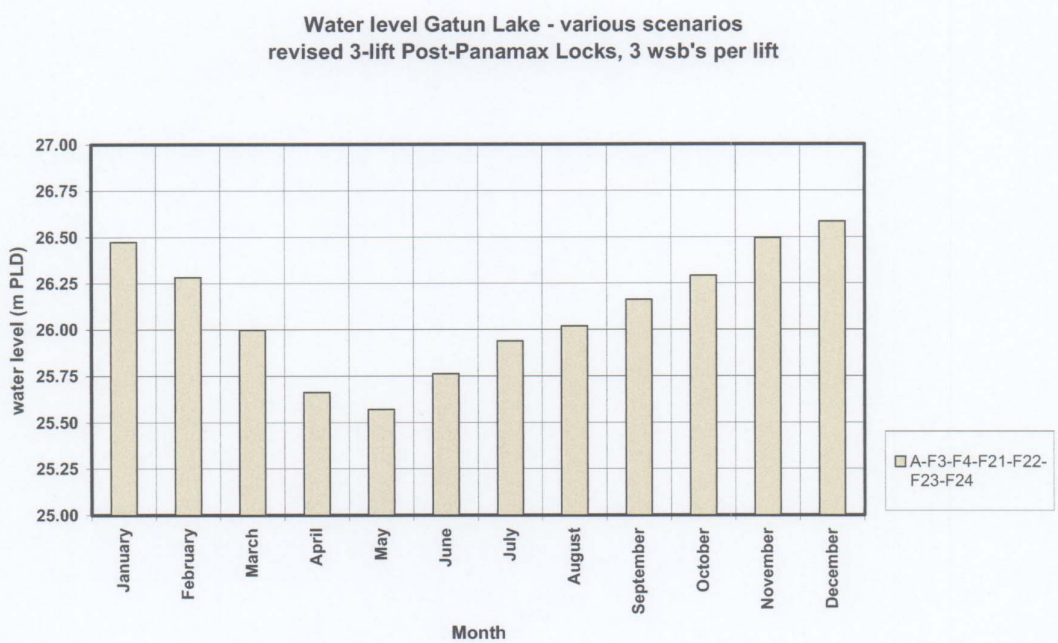


Figure 7.11b **Gatun Lake: water level variation in m PLD, revised 3-lift locks with 3 wsb's per lift (F), free water supply**

7.2.2 Results of further simulations, free water supply

The results of the simulations are presented as maximum and minimum salt concentration values (volume-averaged) of Gatun Lake and Miraflores Lake. The values found in the last year of the considered five-year period are presented in tables and graphs, together with the corresponding total water release and extra water supply per year.

Results of simulations for revised 3-lift locks with 2 wsb's per lift (E) are presented in Table 7.6 and Figures 7.12a/b/c, results of simulations for revised 3-lift locks with 3 wsb's per lift (F) are presented in Table 7.7 and Figures 7.13a/b/c.

Case / water control scenario	*Volume-averaged salt concentration (ppt) Miraflores Lake*		*Volume-averaged salt concentration (ppt) Gatun Lake*	
	minimum	*maximum*	*minimum*	*maximum*
Revised 3-lift locks – 2 wsb's/lift				
E3-15PP, no mitigation	0.76	1.97	0.28	0.62
E3-10PP, no mitigation	0.67	1.71	0.12	0.29
E3-5PP, no mitigation	0.63	1.58	0.05	0.12
E4-15PP, no mitigation, no wsb's	0.76	1.84	0.27	0.43
E4-10PP, no mitigation, no wsb's	0.65	1.63	0.09	0.18
E4-5PP, no mitigation, no wsb's	0.61	1.53	0.02	0.05
E21-15PP, mit I, down1.0	0.66	1.63	0.11	0.17
E21-10PP, mit I, down1.0	0.63	1.56	0.05	0.09
E21-5PP, mit I, down1.0	0.61	1.53	0.02	0.05
E22-15PP, mit II, down1.0	0.65	1.59	0.08	0.12
E22-10PP, mit II, down1.0	0.62	1.55	0.04	0.07
E22-5PP, mit II, down1.0	0.61	1.52	0.02	0.04

Table 7.6 Maximum and minimum volume-averaged salt concentration of Miraflores Lake and Gatun Lake; revised 3-lift locks with 2 wsb's (E) per lift, free water supply, 15, 10 and 5 PP-vessels a day, water control scenarios 3, 4, 21 – 22

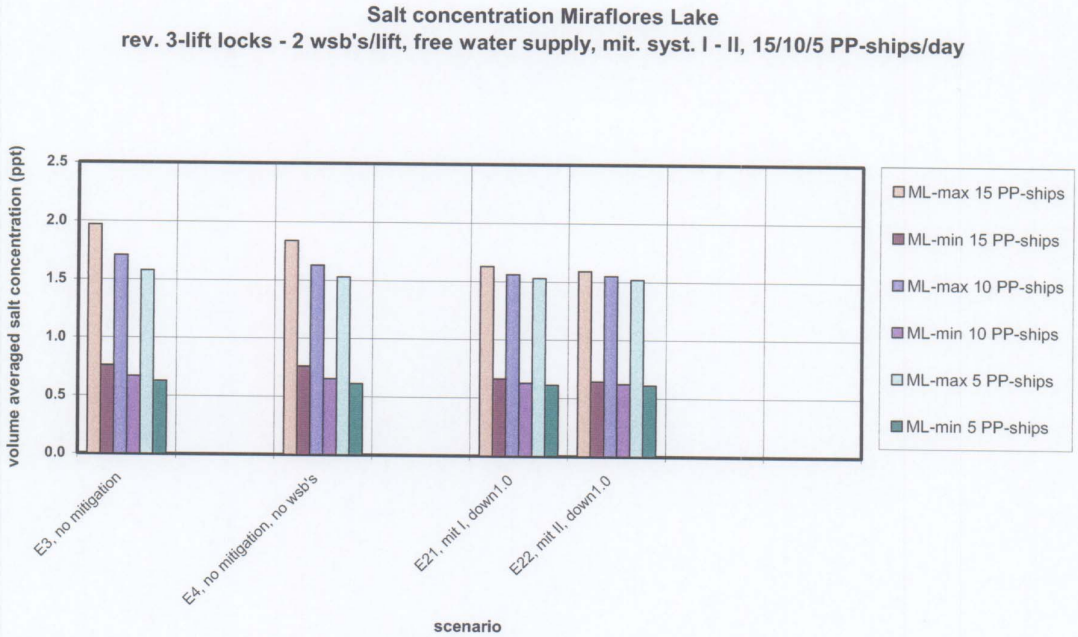


Figure 7.12a **Miraflores Lake: volume-averaged salt concentration (in ppt), maximum and minimum values, revised 3-lift locks with 2 wsb's per lift (E), 15, 10 and 5 PP-vessels/day, free water supply, water control scenarios 3, 4, 21 – 22**

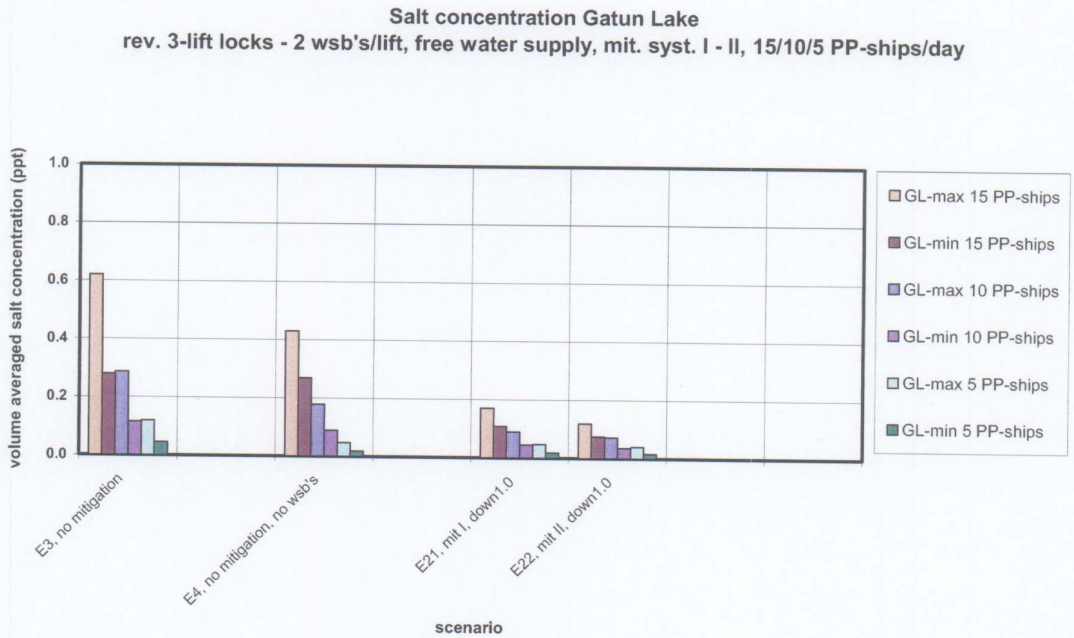


Figure 7.12b **Gatun Lake: volume-averaged salt concentration (in ppt), maximum and minimum values, revised 3-lift locks with 2 wsb's per lift (E), 15, 10 and 5 PP-vessels/day, free water supply, water control scenarios 3, 4, 21 – 22**

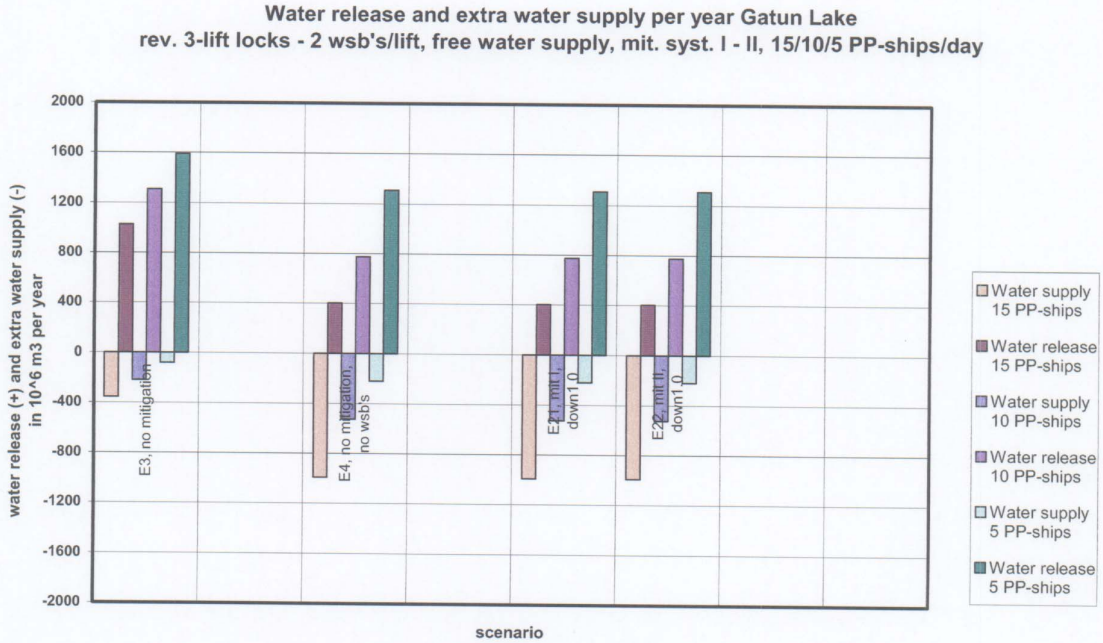


Figure 7.12c Gatun Lake: water releases and extra water supplies in 10^6 m^3 per year, revised 3-lift locks with 2 wsb's per lift (E), 15, 10 and 5 PP-vessels/day, free water supply, water control scenarios 3, 4, 21 – 22

Case / water control scenario	*Volume-averaged salt concentration (ppt) Miraflores Lake*		*Volume-averaged salt concentration (ppt) Gatun Lake*	
	minimum	*maximum*	*minimum*	*maximum*
Revised 3-lift locks – 3 wsb's/lift				
F3-15PP, no mitigation	0.77	2.02	0.29	0.69
F3-10PP, no mitigation	0.68	1.76	0.13	0.34
F3-5PP, no mitigation	0.64	1.61	0.06	0.16
F4-15PP = E4-15PP (no wsb's)	0.76	1.84	0.27	0.43
F4-10PP = E4-10PP (no wsb's)	0.65	1.63	0.09	0.18
F4-5PP = E4-5PP (no wsb's)	0.61	1.53	0.02	0.05
F21-15PP, mit I, down1.0	0.67	1.64	0.11	0.19
F21-10PP, mit I, down1.0	0.63	1.57	0.05	0.10
F21-5PP, mit I, down1.0	0.61	1.52	0.02	0.04
F22-15PP, mit II, down1.0	0.65	1.60	0.08	0.13
F22-10PP, mit II, down1.0	0.62	1.55	0.04	0.08
F22-5PP, mit II, down1.0	0.61	1.53	0.02	0.04
F23-15PP, mit III, down1.25	0.71	1.72	0.18	0.28
F23-10PP, mit III, down1.25	0.65	1.61	0.08	0.15
F23-5PP, mit III, down1.25	0.62	1.55	0.03	0.07
F24-15PP, mit IV, down0.2	0.74	1.94	0.24	0.58
F24-10PP, mit IV, down0.2	0.67	1.72	0.11	0.29
F24-5PP, mit IV, down0.2	0.63	1.60	0.05	0.14

Table 7.7 Maximum and minimum volume-averaged salt concentration of Miraflores Lake and Gatun Lake; revised 3-lift locks with 3 wsb's (F) per lift, free water supply, 15, 10 and 5 PP-vessels a day, water control scenarios 3, 4, 21 – 24

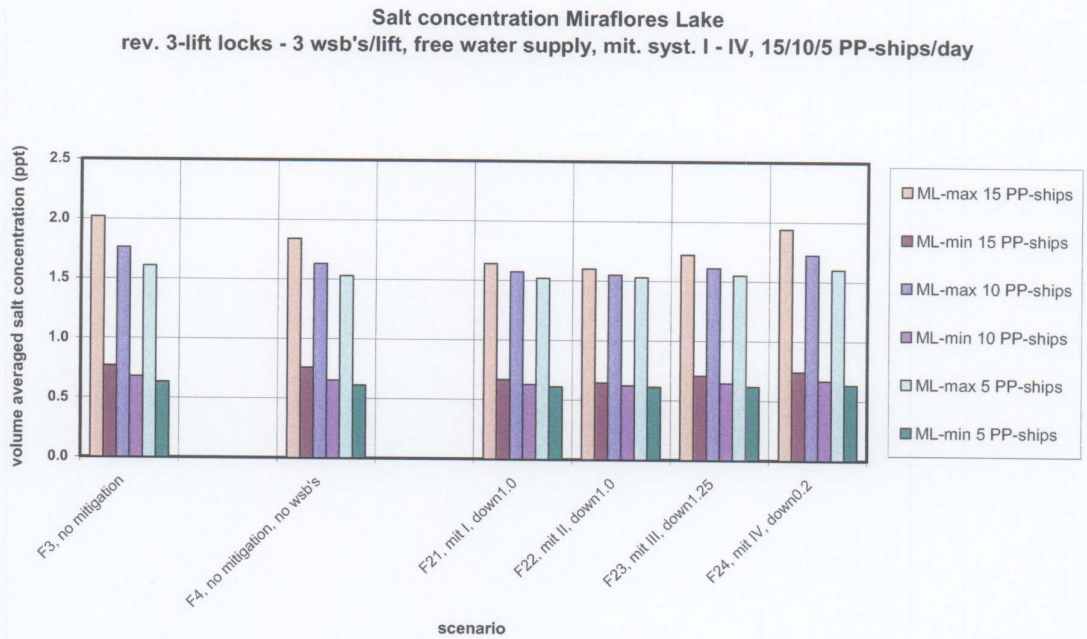


Figure 7.13a Miraflores Lake: volume-averaged salt concentration (in ppt), maximum and minimum values, revised 3-lift locks with 3 wsb's per lift (F), 15, 10 and 5 PP-vessels/day, free water supply, water control scenarios 3, 4, 21 – 24

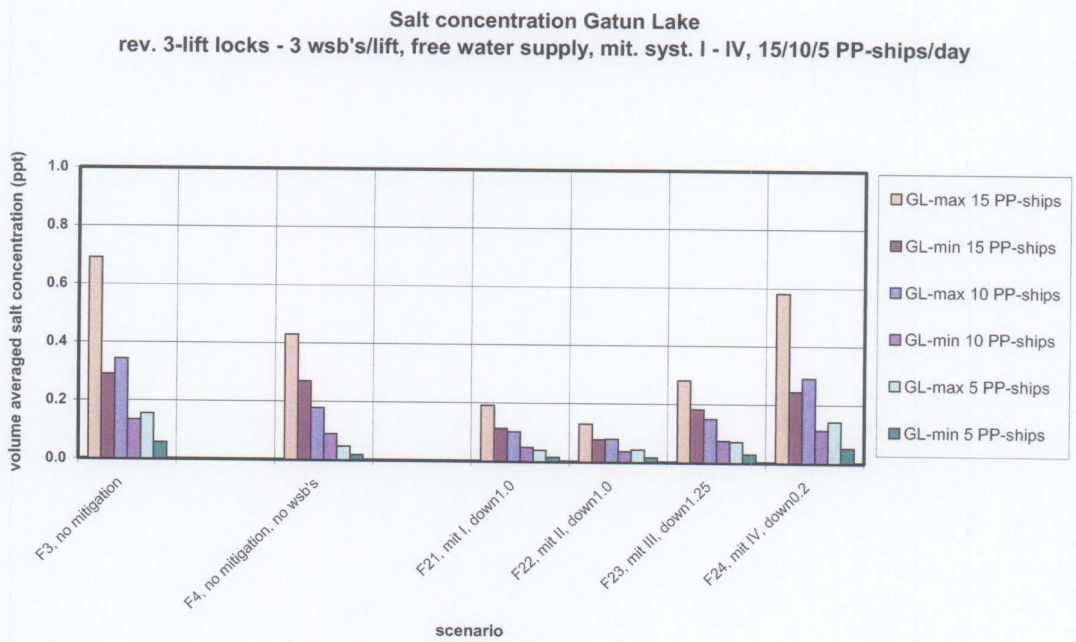


Figure 7.13b Gatun Lake: volume-averaged salt concentration (in ppt), maximum and minimum values, revised 3-lift locks with 3 wsb's per lift (F), 15, 10 and 5 PP-vessels/day, free water supply, water control scenarios 3, 4, 21 – 24

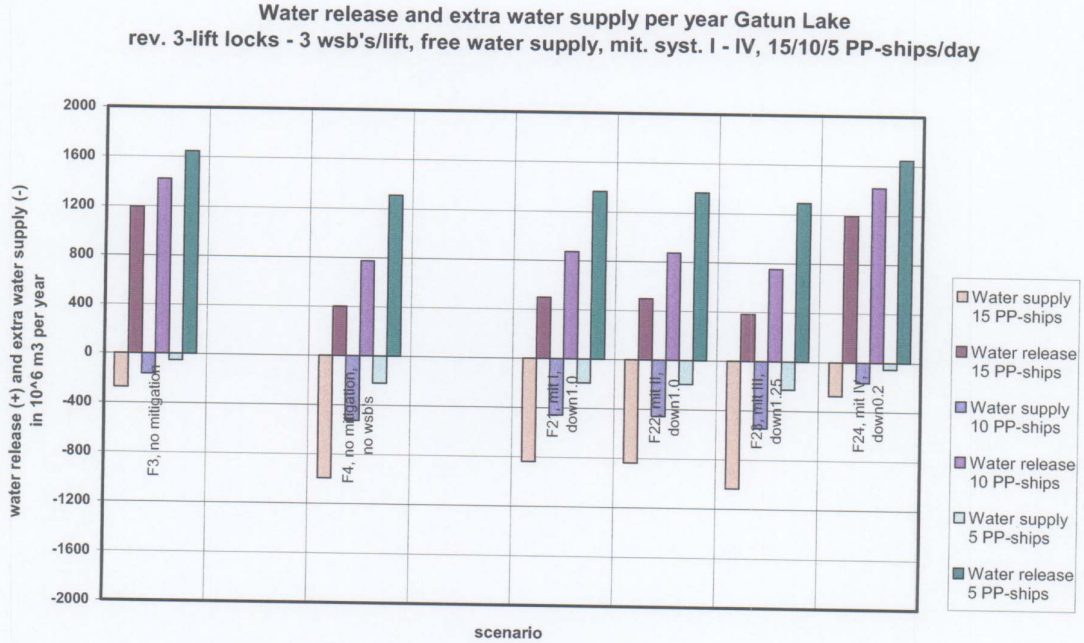


Figure 7.13c Gatun Lake: water releases and extra water supplies in 10^6 m^3 per year, revised 3-lift locks with 3 wsb's per lift (F), 15, 10 and 5 PP-vessels/day, free water supply, water control scenarios 3, 4, 21 – 24

7.2.3 Analysis and conclusions; further simulations, free water supply

From an analysis of the results of the further simulations next conclusions can be drawn in addition to the conclusions of the initial simulations:

Post-Panamax ship traffic intensity 15, 10 and 5 ships/day, Figures 7.12a/b/c and Figures 7.13a/b/c

- Water control scenarios in which the supply of fresh water to Gatun Lake is free (sufficient water available throughout the year) ask for a supply of fresh water in the dry season, while simultaneously water is released in the wet season.
- As a result of this more intensive flushing, volume-averaged salt concentrations of Gatun Lake are less than in the case of minimum water supply scenarios (as in the previous section). For example compare case 'F15-15PP, mit I, down1.0' with case 'F21-15PP, mit I, down1.0': salt concentration range 0.28 – 0.25 ppt versus 0.19 – 0.11 ppt in the latter case. However this is at the cost of a higher fresh water supply: 337.10^6 m^3 per year versus 835.10^6 m^3 per year.
- In general, effects of mitigation systems and effects of Post-Panamax ship traffic intensities are similar as in the case of minimum water supply scenarios.

7.3 General conclusions revised 3-lift locks and mitigation systems

7.3.1 Mutual comparison of results

In this section we first summarize general conclusions for all four selected and studied mitigation systems I – IV.
Then we compare into more detail the results of simulations for revised 3-lift locks without wsb's, with 2 wsb's/lift and with 3 wsb's/lift, for 15 Post-Panamax vessels per day. The preferred mitigation system I (stepwise flushing of locks, 'dummy lockage') is applied at downlockage operations, but we analyse also the salt water intrusion when no mitigation system is active. In addition, we compare the effects of the two main water control scenarios for Gatun Lake: minimum extra water supply and free extra water supply.
Finally, we analyse other aspects: ship traffic intensity, combined use of mitigation systems I and IV, effect of real hydraulic conditions, and effect of greater keel clearance. The analysis is focused on the volume-averaged salt concentration of the lakes (see also Section 8.1) and on water releases / extra water supplies of Gatun Lake.

Mitigation systems I - IV:

- In the present study four different salt-intrusion mitigation systems have been selected for modeling in SWINLOCKS and analysis of the effectiveness. The salt water intrusion and the effect of mitigation systems I – IV thereupon has been simulated for revised 3-lift locks without wsb's, with 2 wsb's/lift and with 3 wsb's/lift.
- Without mitigation system the *revised* 3-lift Post-Panamax locks with smaller dimensions than the original 3-lift locks (earlier CPP design) cause a lesser salt water load. The reduction of the volume-averaged salt concentration of Gatun Lake is 20% - 25% (15 Post-Panamax vessels/day). The net yearly supply of water to Gatun Lake (= extra water supply – water release) is also considerably smaller.
- All four studied mitigation systems reduce the salt load on Gatun Lake, and to a lesser extent on Miraflores Lake (through Pedro Miguel locks). The effect of the mitigation systems is somewhat better when mitigation systems are combined with the revised 3-lift locks with 2 wsb's per lift (configuration E) than combined with the revised 3-lift locks with 3 wsb's per lift (configuration F). This is caused by a better 'flushing' of the lock chambers in the case of 2 wsb's per lift (greater lockage loss, systems I and II), but also the greater extra fresh water supply to Gatun Lake or the lesser water release at Gatun Dam plays a role in the salt balance of the lake.
- From the viewpoint of salt water intrusion mitigation, mitigation system II (flushing of middle and upper lock chamber) is the best option, immediately followed by mitigation system I (stepwise flushing of all three lock chambers). Mitigation system III (salt pit at upstream side of upper lock) has a somewhat smaller effect than earlier expected (Chapter 3), but the effectiveness can be improved when the salt pit is made deeper than a depth of 17.0 m as was adopted for the present simulations. Mitigation system IV (pneumatic barrier at the entrance to both the lower lock chamber and the upper lock chamber) has a relatively small effect, but has the advantage of a zero water loss.
- When the mitigation systems are applied both at downlockage and at uplockage of ships the effect of the mitigation systems is somewhat better than when operation of the

mitigation systems is limited to downlockage of ships only. However, this is at the cost of a twice as high water loss.

The above conclusions apply to mitigation systems which are operated at a maximum effectiveness, which means that a maximum quantity of water is used in the operation of the mitigation system; consequently the water loss caused by operation of the mitigation systems is relatively high (apart from mitigation system IV, pneumatic barrier, that is operated without a loss of water). Mitigation systems I, II and III can also be operated using a smaller quantity of water, but this reduces the effectiveness. This mode of operation is not studied.

Mitigation system I:
Most salt water intrusion simulations have been executed for mitigation system I. Mitigation system I does not require extra investments for the revised 3-lift locks. The system can be deployed when needed and has a high effectiveness when operated after downlockage of each ship. For that reason it is the preferred system of ACP, possibly in combination with mitigation system IV. Results of simulations for a ship traffic intensity of 15 Post-Panamax vessels per day are presented in Table 7.8 and Figures 7.14a/b and Figures 7.15a/b. The mitigation system is only operated after downlockage of ships.

Case / water control scenario	*Volume-averaged salt concentration (ppt) Miraflores Lake*		*Volume-averaged salt concentration (ppt) Gatun Lake*		*Water release and extra water supply Gatun Lake (10^6 m^3/year)*	
	minimum	*maximum*	*minimum*	*maximum*	*release*	*supply*
Existing situation						
A	0.64	1.42	0.010	0.027	1929	-
Future situation, revised 3-lift locks, minimum water supply, 15 PP-ships/day						
E14-15PP, no mitigation, no wsb's	0.90	2.02	0.52	0.58	0	589
E13-15PP, no mitigation, 2 wsb's/lift	0.85	2.08	0.45	0.68	670	0
F13-15PP, no mitigation, 3 wsb's/lift	0.83	2.10	0.41	0.71	922	0
E25-15PP, mit I, down1.0, no wsb's	0.67	1.60	0.11	0.12	0	1848
E15-15PP, mit I, down1.0, 2 wsb's/lift	0.72	1.71	0.21	0.24	0	589
F15-15PP, mit I, down1.0, 3 wsb's/lift	0.75	1.75	0.25	0.28	0	337
E15-15PP, mit I, down1.0, 2 wsb's/lift	0.72	1.71	0.21	0.24	0	589
E15-15PP, mit I, down1.0, 1:2, 2 wsb's/lift	0.89	2.01	0.50	0.56	40	0
E15-15PP, mit I, down1.0, 1:3, 2 wsb's/lift	0.87	2.01	0.47	0.58	251	0
F15-15PP, mit I, down1.0, 3 wsb's/lift	0.75	1.75	0.25	0.28	0	337
F15-15PP, mit I, down1.0, 1:2, 3 wsb's/lift	0.84	1.96	0.42	0.53	292	0
F15-15PP, mit I, down1.0, 1:3, 3 wsb's/lift	0.83	1.99	0.41	0.57	503	0
Future situation, revised 3-lift locks, free water supply, 15 PP-ships/day						
E4-15PP, no mitigation, no wsb's	0.76	1.84	0.27	0.43	402	992
E3-15PP, no mitigation, 2 wsb's/lift	0.76	1.97	0.28	0.62	1027	357
F3-15PP, no mitigation, 3 wsb's/lift	0.77	2.02	0.29	0.69	1196	274
E21-15PP, mit I, down1.0, 2 wsb's/lift	0.66	1.63	0.11	0.17	402	992
F21-15PP, mit I, down1.0, 3 wsb's/lift	0.67	1.64	0.11	0.19	498	835

Table 7.8 Comparison revised 3-lift locks – no wsb's, 2 wsb's/lift, 3 wsb's/lift – mitigation system I, 15 PP-vessels/day

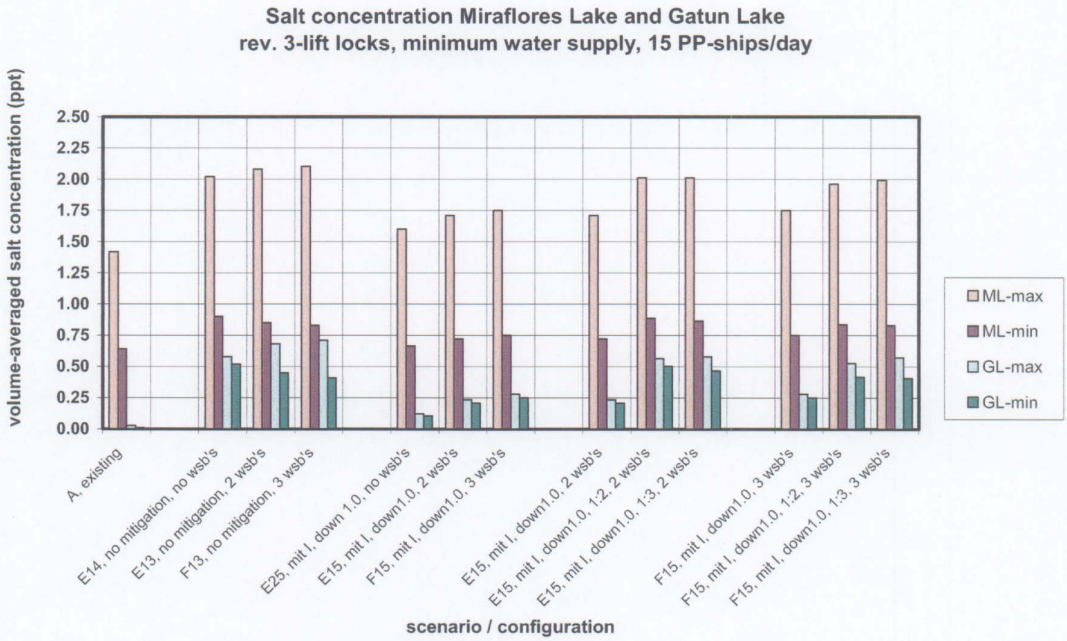


Figure 7.14a Miraflores`Lake and Gatun Lake: volume-averaged salt concentration (in ppt), maximum and minimum values, revised 3-lift locks, 15 PP-vessels/day, minimum water supply

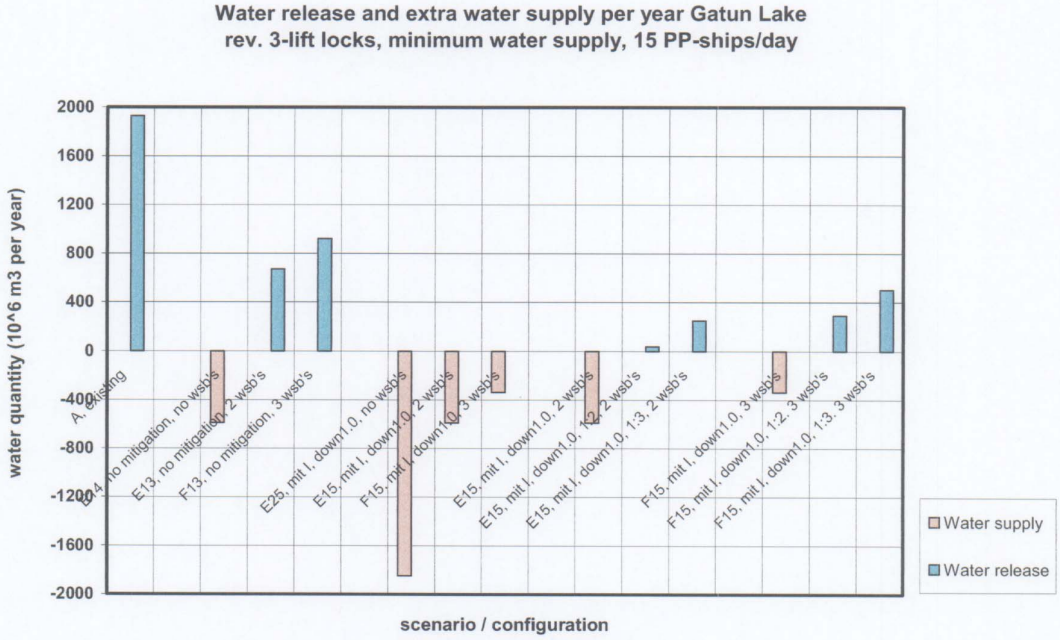


Figure 7.14b Gatun Lake: water releases and extra water supplies in 10^6 m^3 per year, revised 3-lift locks, 15 PP-vessels/day, minimum water supply

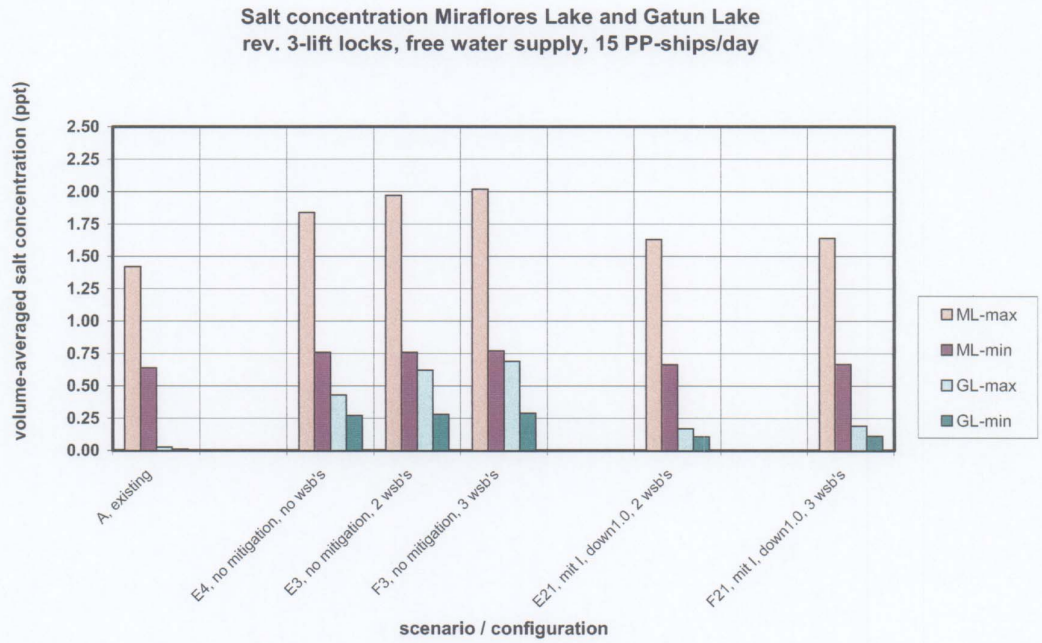


Figure 7.15a Miraflores`Lake and Gatun Lake: volume-averaged salt concentration (in ppt), maximum and minimum values, revised 3-lift locks, 15 PP-vessels/day, free water supply

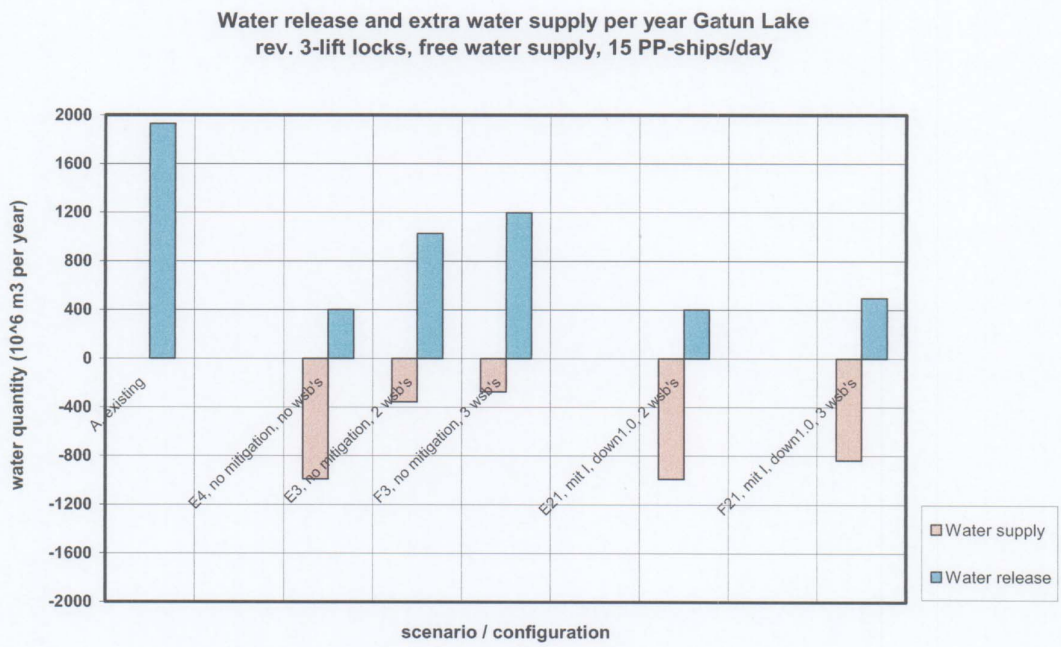


Figure 7.15b Gatun Lake: water releases and extra water supplies in 10^6 m^3 per year, revised 3-lift locks, 15 PP-vessels/day, free water supply

From these results for a ship traffic intensity of 15 PP-ships/day we conclude:

- When no mitigation system is applied and revised 3-lift locks are not provided with water saving basins, an extra supply of water from new water resources to Gatun Lake is necessary. With 2 wsb's/lift or 3 wsb's/lift, no mitigation, there is a net surplus of water throughout the year, so that water is available for hydropower generation, but there is also a lesser 'flushing' of lock chambers, causing a greater salt water intrusion and higher salt concentration levels of the lakes.
- The water control scenario 'free water supply' requires always a supply of extra water, also when wsb's are in operation, but in the wet season water is released. In the water control scenario 'minimum water supply' the available water is better utilized, which leads to a minimum supply of extra water to Gatun Lake (but the sum of water release and extra water supply per year is the same in both scenarios).
- The lockage loss is reduced with 50% and 60% respectively when 2 wsb's/lift or 3 wsb's/lift are applied (no mitigation system active). The lesser the lockage loss, the lesser the supply of extra water to Gatun Lake and / or the greater the release of water at Gatun Dam, and the stronger the salt concentration variation of Gatun Lake throughout the year, see next table. The supply of extra water has thus a damping effect on the salt concentration variation throughout the year. (Note: the relative lockage loss for each ship transfer is 100%, when the Post-Panamax Locks have no wsb's.)

Simulation	*extra water supply*	*no of wsb's per lift*	*relative lockage loss of PP-locks*	*Gatun Lake salt concentration (ppt, volume-averaged)*		
				range	*variation*	*mean*
E14	minimum	0	100%	0.52 – 0.58	0.06	0.55
E13	minimum	2	50%	0.45 – 0.68	0.23	0.56
F13	minimum	3	40%	0.41 – 0.71	0.30	0.56
E4	free	0	100%	0.27 – 0.43	0.16	0.35
E3	free	2	50%	0.28 – 0.62	0.34	0.45
F3	free	3	40%	0.29 – 0.69	0.40	0.49

- The mean volume-averaged salt concentration of Gatun Lake (mean of maximum and minimum in a year) is not reverse proportional to the Post-Panamax lockage losses (and thus the number of wsb's), see above table, since also the extra water supplies, the water releases at Gatun Dam and the shipping in the existing locks play a role in the water balance and salt balance of Gatun Lake.
- The water control scenario 'minimum water supply' is the better option from the view point of conservation of water, but is less favourable in view of salt concentration levels, which are higher, while also less water is available for hydropower generation. Compare results of E14-E13-F13 with E4-E3-F3 in above table.
- The water control scenario 'minimum water supply' causes a lesser variation of the salt concentration of Gatun Lake than the scenario 'free water supply', mainly because minimum salt concentration values, which occur at the end of the wet season, remain high. Compare results of E14-E13-F13 with E4-E3-F3 in above table.
- When mitigation system I is applied at downlockage (Post-Panamax Locks) the salt water load on Gatun Lake and thus the volume-averaged salt concentration is considerably reduced, see next table. The reduction of the mean salt concentration is between 50% and 80%, dependent on the number of wsb's and the water control scenario applied. It is however, remarkable that the effect of mitigation system I strongly reduces,

when the mitigation system is only used after each second (1:2) or third (1:3) ship downlockage (studied for water control scenario 'minimum water supply', but this effect will most probably also occur at water control scenario 'free water supply'). The reduction of the effectiveness when the system is only applied each 2nd or 3rd downlockage operation, is most probably caused by the fact that higher salt concentrations can build up in the upper lock chamber in the semi-convoy mode of operation. But also the different water balance of Gatun Lake when the mitigation system is less intensive used (less water supply, greater water release at Gatun Dam, different distribution of water over Gatun Dam and Gatun locks) plays a role.

Simulation	*extra water supply*	*no of wsb's per lift*	*Gatun Lake mean vol-aver. salt conc. (ppt) no mitigation*	*Gatun Lake: reduction of mean salt concentration mit. I compared to no mitigation (%)*		
				mit I, down1.0, 1:1	*mit I, down1.0, 1:2*	*mit I, down1.0, 1:3*
E14 – E25	minimum	0	0.55	79%	-	-
E13 – E15	minimum	2	0.56	61%	6%	7%
F13 – F15	minimum	3	0.56	53%	16%	13%
E4	free	0	0.35	-	-	-
E3 – E21	free	2	0.45	69%	-	-
F3 – F21	free	3	0.49	69%	-	-

Next table shows the corresponding relative water loss per ship transfer caused by operation of the Post-Panamax locks and mitigation system I.

Simulation	*extra water supply*	*no of wsb's per lift*	*relative lockage loss of PP-locks each ship transfer no mitigation*	*relative lockage loss of PP-locks and mitigation system I, for each ship transfer*		
				mit I, down1.0, 1:1	*mit I, down1.0, 1:2*	*mit I, down1.0, 1:3*
E14 – E25	minimum	0	100%	150%	-	-
E13 – E15	minimum	2	50%	100%	125%	67%
F13 – F15	minimum	3	40%	90%	65%	57%
E4	free	0	100%	-	-	-
E3 – E21	free	2	50%	100%	-	-
F3 – F21	free	3	40%	90%	-	-

- Generally, the indirect effect of the Post-Panamax locks, which by-pass Miraflores Lake, on the salt concentration of Miraflores Lake is relatively small, see Figure 7.14a and Figure 7.15a. Extra salt water intrudes through Pedro Miguel Locks; the salt load varies with the salt concentration of Gatun Lake and varies thus with the configuration of Post-Panamax Locks, application of a mitigation system, and the water control scenario of Gatun Lake.

We now discuss other aspects:

Effect of Post-Panamax ship traffic intensity:

- As may be expected the salt water intrusion increases with the ship traffic intensity. Detailed results of simulations are presented in Section 7.1.2. In next table the volume-averaged mean salt concentration of Gatun Lake is shown for 15, 10 and 5 PP-ships/day

(mean of maximum and minimum in a year). No mitigation, mitigation system I and combination of mitigation systems I and IV are compared. As is shown, the relationship between volume-averaged salt concentration and the number of ship transfers is non linear, since also the water releases / water supplies play a role, as well as the shipping in the existing lanes.

Simulation	*extra water supply*	*no of wsb's per lift*	*mitigation system*	*Gatun Lake: mean salt concentration at various PP-traffic intensities*		
				15 PP/day	*10 PP/day*	*5 PP/day*
E14	minimum	0	no mit.	0.55	0.22	0.04
E13	minimum	2	no mit.	0.57	0.22	0.08
F13	minimum	3	no mit.	0.56	0.25	0.10
E25	minimum	0	mit I, down1.0	0.11	0.09	0.03
E15	minimum	2	mit I, down1.0	0.22	0.11	0.04
F15	minimum	3	mit I, down1.0	0.27	0.11	0.04
E19	minimum	2	mit I, down1.0 + mitIV, d0.2	0.19	0.10	0.04
F19	minimum	3	mit I, down1.0 + mitIV, d0.2	0.23	0.10	0.04
E4	free	0	no mit.	0.35	0.13	0.03
E3	free	2	no mit.	0.45	0.20	0.08
F3	free	3	no mit.	0.49	0.24	0.11
E21	free	2	mit I, down1.0	0.14	0.07	0.03
F21	free	3	mit I, down1.0	0.15	0.07	0.03

Next table shows the corresponding extra water supply and water release per year:

Simulation	*extra water supply*	*no of wsb's per lift*	*mitigation system*	*Gatun Lake: extra water supply / water release in 10^6 m^3 per year, various PP-traffic intensities*					
				15 PP/day		*10 PP/day*		*5 PP/day*	
				supply	*release*	*supply*	*release*	*supply*	*release*
E14	minimum	0	no mit.	-589	0	0	250	0	1090
E13	minimum	2	no mit.	0	670	0	1090	0	1510
F13	minimum	3	no mit.	0	922	0	1258	0	1593
E25	minimum	0	mit I, down1.0	-1848	0	-589	0	0	670
E15	minimum	2	mit I, down1.0	-589	0	0	250	0	1090
F15	minimum	3	mit I, down1.0	-337	0	0	418	0	1174
E19	minimum	2	mit I, down1.0 + mitIV, d0.2	-589	0	0	250	0	1090
F19	minimum	3	mit I, down1.0 + mitIV, d0.2	-337	0	0	418	0	1174
E4	free	0	no mit.	-992	402	-524	774	-219	1309
E3	free	2	no mit.	-357	1027	-219	1309	-81	1590
F3	free	3	no mit.	-274	1196	-164	1421	-54	1647
E21	free	2	mit I, down1.0	-992	402	-524	774	-219	1309
F21	free	3	mit I, down1.0	-835	498	-455	873	-191	1365

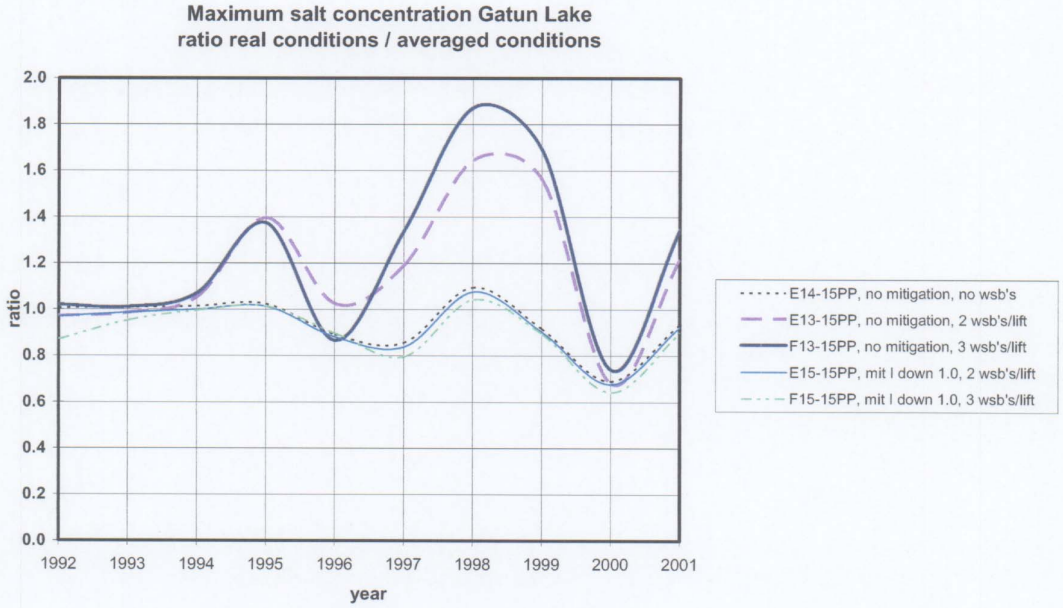
- Initially, up to a ship traffic intensity of about 5 PP-ships/day, the effect of operation of the Post-Panamax Locks on the volume-averaged salt concentration of Gatun Lake is still relatively small; in this initial period there is time to monitor the salt water intrusion and to decide on an appropriate use of the mitigation system.
- In the initial period there is no need to supply extra water to Gatun Lake, provided that water control scenario 'minimum water supply' is applied.

Combined use of mitigation systems I and IV:

- Combined use of mitigation systems I and IV may reduce the volume-averaged salt concentration of Gatun Lake with about 15% compared to solely use of mitigation system I. It should be noted however, that no experimental data is available for pneumatic barriers which are installed in water with such a great depth as at the Panama Canal. The functioning of pneumatic barriers in deep water needs to be checked.
- When the salt concentration of Gatun Lake is considered, revised 3-lift-locks with 2 wsb's/lift and mitigation system I (operated at downlockage) are more or less equivalent to revised 3-lift locks with 3 wsbs/lift and the combination of mitigation systems I and IV (operated at downlockage), see results in red in above tables. Some water can thus be saved by applying 3 wsb's instead of 2 wsb's/lift, while the resulting extra salt water intrusion is combated by a pneumatic barrier that is installed at the entrance to upper lock chamber and lower lock chamber.

Effect of real hydraulic conditions

- When the real hydraulic conditions of the period 1992-2001 are taken as starting point for simulations instead of averaged conditions, the variation of the volume-averaged salt concentration of Gatun Lake is stronger. This is shown in next figure, where the ratio of the *maximum* volume-averaged salt concentration at real conditions and the *maximum* volume-averaged salt concentration at averaged conditions has been plotted for a few cases. From this figure it appears: the more extra fresh water is supplied to Gatun Lake (E14, E15, F15) the lesser the ratio varies about 1. Clearly, the supply of extra water has a damping effect on the salt concentration variation. This effect is studied for water control scenario 'minimum water supply'. A similar effect may be expected for water control scenario 'free water supply'.
- The simulations in which real hydraulic conditions of the period 1992 – 2001 have been taken as starting point indicate that the variation from year to year of the salt concentration of Gatun Lake may be twice as high as computed for averaged hydraulic conditions.



Effect of greater keel clearance:

- The effect of a 1.52 m (5 ft) greater water depth in the lock chambers of the revised 3-lift locks on the salt water intrusion is relatively small (a 1.52 m lower floor level in view of a ship keel clearance of 3.05 m (10 ft) instead of 1.52 m (5 ft)). The greater depth has no effect on lockage losses, losses caused by mitigation systems, extra water supplies to Gatun Lake and water releases at Gatun Dam. When 3.05 m (10 ft) keel clearance is required for safe shipping, the results of the salt intrusion simulations presented in this report for a keel clearance of 1.52 m (5 ft) in the lock chambers of the revised 3-lift locks, can approximately be applied.

7.3.2 Concluding remarks / recommendations

When sufficient water from new water resources can be made available, the best option from the view point of salt water intrusion mitigation is to build Post-Panamax shipping locks without water saving basins. Stepwise flushing of all lock chambers (mitigation system I) should at least be done after each downlockage operation. Extra water should be supplied to Gatun Lake to immediately compensate the losses caused by operation of the new locks and the mitigation system (free water supply). In that case the intrusion of salt water is most effective combated and the present quantities of water remain available for hydropower generation at Gatun Dam.

However, it is questionable whether an abundant quantity of extra water can be made available or is acceptable. It is therefore that ACP wishes to minimize the water losses caused by operation of Post-Panamax locks and mitigation systems, but it is clear that with a growing Post-Panamax ship traffic intensity the need of supplying extra water to Gatun Lake increases. ACP plans to control the water releases at Gatun Dam in such a way that the supply of extra water throughout the year is minimum. This will generally lead to a higher salt concentration level of Gatun Lake than with a free supply of extra water.

Water control scenarios that are focused on a minimum supply of extra water to Gatun Lake ask for an active and careful planning of the water releases at Gatun Dam. This may put stronger demands on the operation of power station and spillways of Gatun Dam. Moreover, since a considerably smaller quantity of water is available at Gatun Dam for the generation of electrical power, a search for additional sources of energy may be necessary.
The concept of a minimum extra water supply to Gatun Lake requires that water at Gatun Dam is only released when the water level threatens to exceed the upper limit level of Gatun Lake. When the spill capacity of Gatun Dam is sufficient to instantaneously discharge the water caused by intensive showers in the water shed area, the water level at which the release of water shall start, can be chosen close to the upper limit level of the lake.

A minimum loss of water is obtained when the Post-Panamax locks are provided with water saving basins and the lock chambers are optimally used (e.g. lockage of two ships at a time, when possible). Mitigation systems cause a considerable additional loss of water. Since the intrusion of salt water at uplockage of ships is much smaller than at downlockage, the mitigation systems should preferably only be operated at downlockage. This reduces the water losses of the mitigation system with a factor 2.
From the viewpoint of water conservation the option of 3 wsb's per lift is better than the option of 2 wsb's/lift, but the extra saving of water in the case of 3 wsb's/lift has to be considered in relation to the total loss of water caused by operation of locks *and* mitigation systems, and in relation to the somewhat higher salt water load. The higher salt water load in the case of 3 wsb's/lift can be combated with a pneumatic barrier (mitigation system IV) at the entrance to lower lock chamber and upper lock chamber.

We advise to choose the option of 3 wsb's/lift in combination with mitigation system I (stepwise flushing of all lock chambers) and to make provisions in the design of the locks, that enable an easy construction of additional pneumatic barriers (mitigation system IV) after the locks have been realised, if needed. It should be noted however, that pneumatic barriers are most effective when the open time of the gates at the entrance to the lock chambers is minimized. This implies that the gates are only shortly opened to pass a ship, but as a result water level differences across the gates will occur, which are caused by the tide variation (in particular at the Pacific side). These water level differences can be prevented, if needed, when the valves of the culvert system between the tailbay and the lower lock chamber are kept open (this causes also an additional salt water intrusion, but it is a better option than leaving the gates open). In conclusion, the present operation of the existing locks, that permits an early opening of the gates, can not be maintained, when pneumatic barriers are applied.

It is advised to operate mitigation system I after each downlockage operation, since the simulations indicate that the effectiveness strongly reduces when the mitigation system is only used each second or third downlockage. As a consequence, when the relay-mode of operation or a similar time saving mode is applied in ship locking, a part of the saved time is needed for mitigation operations between two subsequent lockages. The capacity of the new lane will thus be effected. It is therefore advised to study the most efficient way of handling the ships in the locks and operating mitigation system I. When delays are not acceptable, mitigation system III (salt collecting pit) is the best alternative.

Initially, when the Post-Panamax shipping intensity is still low, there is time to evaluate the salt water intrusion in the real situation and to decide on the most optimal use of mitigation system I, possibly in combination with mitigation system IV. To that purpose an efficient salt water intrusion monitoring system should be installed at both sides of the canal.
It is advised to check the proper functioning of pneumatic barriers (mitigation system IV) prior to the decision of installation, since data on application in deep water, like the Panama Canal, do not exist.

8 Further studies on salt water intrusion

8.1 Considerations about the use of SWINLOCKS

The simulation model SWINLOCKS has been set up for the purpose of predicting the salt water load on Gatun Lake and Miraflores Lake after the new, third shipping lane of the Panama Canal has been realized and new, bigger Post-Panamax Locks have been constructed and have come into operation. The simulation model offers the possibility to compare the salt intrusion effects of various designs of Post-Panamax Locks, with or without water saving basins, with or without salt intrusion mitigation systems, for various water control scenarios of Gatun Lake, and for different Post-Panamax ship traffic intensities, and to compare the possible future situation with the existing situation. It is thus a tool for decision makers to get insight in the possible environmental effects of the future Post-Panamax Locks, both in terms of salt water intrusion and additional fresh water needs.

The simulation model is not aimed, and also not capable, to predict the time dependent dispersion of salt water in Miraflores Lake, Gaillard Cut and Gatun Lake. To that purpose a full three-dimensional (3d) flow model is required, that is also capable to compute the flows driven by density-differences. The salt water load caused by the operation of existing and Post-Panamax Locks (including the effects of systems aimed to mitigate the salt water intrusion), may serve as input for such a 3d-model.

The model SWINLOCKS consists of a series of mutually connected basins. Base variables are the water volume and the volume-averaged salt concentration of the various basins. It is recalled that real density flows are not computed, only the transfer of (salt) water from one basin to another is calculated. Yet, with the help of salt exchange coefficients the salt load of the shipping locks on the lakes can correctly be calculated, as well as the effects of water losses caused by operation of the locks and mitigation systems. Water supplies and water releases of the lakes are prescribed as a function of time. This makes that the water balance and the salt balance of the lakes can be computed, provided that also the outflow of salt water through the outlets at Gatun Dam and Miraflores Dam is adequately described in the simulation model.

The set of exchange coefficients which is used in the SWINLOCKS simulations, was validated for the existing locks on the basis of site measurements (executed in wet and dry season in locks and lakes, see Report A for reference). Results of detailed measurements in the locks and results of Delft3D computations were used to select values for individual exchange coefficients, also for the new Post-Panamax locks and related components.

The effect of water releases on the salt concentration of the lake (Gatun Lake or Miraflores Lake) is computed with the help of next salt balance equation:

$$c_{lake2} = \frac{(V_{lake1} \cdot c_{lake1}) - (e_x \cdot Q \cdot c_{lake1})}{V_{lake2}}$$

where

e_x = exchange coefficient (-); no outflow of salt water when $e_x = 0$

Q = outflow discharge (m^3/s)

V_{lake} = water volume of lake (m^3)

The equation is such defined that when a value 1 is selected for the outflow exchange coefficient, the salt concentration of the spilled water is the same as the volume-averaged salt concentration of the lake. The choice of $e_x = 1$ is, however, not realistic. In Miraflores Lake a short-cut flow is likely between Miraflores Locks and the water outlets at Miraflores Dam; this flow may be sustained by the overall flow pattern in the lake, that at present causes a net water transport in southern direction (Miraflores Locks and the outlets in Miraflores Dam draw water from the lake). Though higher salt concentrations have been measured near the bed of the deeper shipping channel towards Pedro Miguel Locks, indicating the existence of a density flow away from Miraflores Locks, it is reasonable to assume that the intruded salt water will not equally spread over the full lake area, but will have some preference to concentrate in the southern part of the lake, near the outlets in Miraflores Dam. The salt concentration of the spilled water at Miraflores Dam will thus generally be higher than the average salt concentration of the full lake, which leads to a value for the outflow exchange coefficient > 1.

The water volume of Gatun Lake is about 220 times greater than the water volume of Miraflores Lake. The prevailing flow direction at present is towards the northern area near Gatun Dam and Gatun Locks, in particular in the wet season, when large quantities of water are spilled. Salt water may intrude through Pedro Miguel Locks and Gaillard Cut in the south and Gatun Locks in the north. It is most likely that the intruded salt water propagates along the bed of the deeper shipping channel and follows the deeper parts (old Chagres River) towards the outlets in Gatun Dam. The present salt concentration levels in Gatun Lake are very low and below 0.1 ppt (= lower limit of CTD sensors used during our site surveys), also in the area near Gatun Dam. Though, despite we could not measure different salinity values, we expect that the salt concentration in the area near Gatun Dam is higher than the average salt concentration of the full lake.

The expectation of a concentration of water with higher salinity in the areas near the outlets at Gatun Dam and Miraflores Dam is tested in validation runs. In final validation runs we have used next exchange coefficients for water releases at Gatun Dam and Miraflores Dam:

Outlet	*Exchange coefficient*
Miraflores Spillway	1.5
Miraflores Cooling Water Offtake	1.5
Gatun Spillway	7.5
Gatun Power Station	7.5

These coefficients together with the coherent set of lock exchange coefficients for Atlantic locks and Pacific locks appeared to predict the volume-averaged salt concentration levels in Miraflores Lake and seasonal variations as were measured in wet and dry season (2001 – 2002); a very low volume-averaged salt concentration level was predicted for Gatun Lake, similar as in the existing situation. See also Report A for a further explanation.

Equal salt exchange coefficients for water releases at Gatun Dam and Miraflores Dam have been applied in numerical simulations for the future situation with Post-Panamax Locks (all variants). We decided to do so for next reasons:

- Most probably, the overall flow patterns in Miraflores Lake will not importantly change, since the new locks bypass Miraflores Lake, but some extra salt water will intrude the lake through Pedro Miguel Locks. Because of the dominant flow pattern we expect, that the tendency remains that the intruded salt water concentrates stronger in the southern area.
- The resultant flows in Gatun Lake will still be in northern direction towards the area near Gatun Dam and Gatun Locks. Simultaneously, more water will flow through Gaillard Cut to feed the new Pacific locks. Though in the north the distribution of outflowing water over Gatun Dam and Gatun Locks will be different (this depends also on the extra quantity of water that is supplied to the lake), the salt water that intrudes through the Atlantic locks will still have preference to remain in the deeper northern areas of the lake. The extra salt water that intrudes through the Pacific locks may proceed in northern direction along the deepened shipping channel in Gaillard Cut, but this is uncertain because of the stronger flow in southern direction.
- A better founded choice of the outflow exchange coefficients can only be made after extensive 2d and 3d flow computations for the lakes; in particular the 3d computations, if feasible, require huge modeling and computational efforts (it may therefore be advisable to limit these computations to relevant parts of the lakes).
- When equal exchange coefficients are applied for the existing situation and the future situation, a more straight forward comparison is possible between the various designs of Post-Panamax Locks and the effects of mitigation systems and water control scenarios.

The strength of the simulation model SWINLOCKS is thus that it enables a mutual comparison of the effects of various Post-Panamax Locks designs, rather than an accurate prediction of the future salt concentration levels of Gatun Lake.

8.2 Salt dispersion studies Gatun Lake

Since the simulation model SWINLOCKS is not able to compute the time-dependent dispersion of salt water in the lakes, the computed volume-averaged salt concentrations do not provide a picture of salt water concentrations in the lakes. It is however most likely that strong variation of the salt concentration will occur in Gatun Lake and Gaillard Cut. The intruded salt water propagates along the bed of the shipping channels and follows the deeper parts of the lake (for example the gully of the old Chagres River). It may than concentrate in the deeper area near the outlets in Gatun Dam or remain in the deepened part of the shipping channel in Gaillard Cut. Full 3-dimensional density flow computations may give insight in the salt dispersion processes of the lake.

The computations with the 3d flow model should be done for a sufficient long period of time, taking into account the seasonal variations of precipitation, lake water levels, water supplies and water releases, time dependent salt water loads through the shipping locks and the developments in ship traffic intensities. The effects of sailing ships (effects caused by screw race and return currents, in particular relevant in Gaillard Cut) and wind should be

taking into account. It is doubtful however, whether these very complicated computations are fully feasible; in any case it requires huge modeling and computational efforts.
Therefore, more schematized 2d flow computations (depth averaged) should be done to study the overall flow patterns in Gatun Lake and Gaillard Cut without the effects of density differences, followed by schematized 3d flow computations for relevant parts of the lakes, for example Gaillard Cut or the northern area of Gatun Lake, which include the local density flows. This computational approach is more attractive and also more within reach of the present possibilities.
The schematized computations will give insight in the highly important local salt water flows, including the flows towards and near the outlets of Gatun Dam, and may also give a reliable indication of the salinity levels in the neighbourhood of for example the drinking water inlet in Gailllard Cut near Paraiso. The 3d flow computations can be done using the salt water loads computed with the salt water intrusion simulation model SWINLOCKS, as input. The 2d and 3d flow computations require the modeling of the bathymetry of Gatun Lake and Gaillard Cut in the areas of interest. Boundaries of the modeled areas and the boundary conditions have carefully to be selected.

ACP is advised to investigate the possibilities of 2d and (local) 3d flow computations for the selected configuration of Post-Panamax Locks, including a salt intrusion mitigation system. These computations will provide a better insight into the salt dispersion processes. As a result, the value of salt exchange coefficients used in SWINLOCKS simulations, in particular the coefficients used in water releases at Gatun Dam, can better be assessed. When it appears that the presently applied coefficients are not optimally suited to predict the salt water load and the release of salt water, it is advised to repeat some selected SWINLOCKS simulations with adapted coefficients.

8.3 Studies on salt water intrusion in final design stage of Post-Panamax Locks

Though with the help of the SWINLOCKS simulations a comparison of lock designs on the subject of salt water intrusion and water losses can be made, and a selection of the most suited lock design is possible, there is still a need for further studies on the salt water intrusion in the final design stage of the selected Post-Panamax Locks. These studies will focus on the process of salt water intrusion through the locks and on the functioning of the proposed mitigation systems, but also other (related) aspects need a further study. All aspects should be studied in their mutual connection.

Important study subjects are:

- The filling and emptying system of the locks (operation of the culverts, operation of the water saving basins, flow capacity of the system, filling and emptying times, control of the fill and emptying process in view of a well distributed inflow and outflow of water, inertia effects in culverts possibly causing an overshoot in the lock chamber, siltation in culverts, air entrainment in culverts, possible cavitation phenomena, dynamic forces on valves).
- (Density) flow phenomena in the lock chambers during levelling up or down, mixing processes, internal wave phenomena, translatory wave phenomena.
- (Dynamic) forces on lock gates and on the ship due to flows, waves and density differences, hawser forces of the ship.

- (Density) flow phenomena and wave phenomena in the lock chambers, forebays and tailbays when lock gates are opened, effects of moving ships.
- Functioning of selected mitigation systems.
- Manoeuvring of approaching ships.

The studies on the salt water intrusion shall in particular be focused on density flow phenomena and mixing processes in the lock chambers, forebays and tailbays of the final design of the locks, including water saving basins and mitigation systems. Mitigation systems I and II require a check of the phenomena which occur at a stepwise transfer of water from lock chamber to lock chamber without opening the gates of the locks; mitigation system III (salt collecting pit) requires a check of the inflow process of salt water and the subsequent discharge of water from the salt collecting pit; the functioning of mitigation system IV (pneumatic barrier) has to be checked for deep water as at the Panama Canal. For all four mitigation systems it applies that the choice of coefficients used in SWINLOCKS simulations has to be founded by a further experimental study in the final design stage of the Post-Panamax Locks.

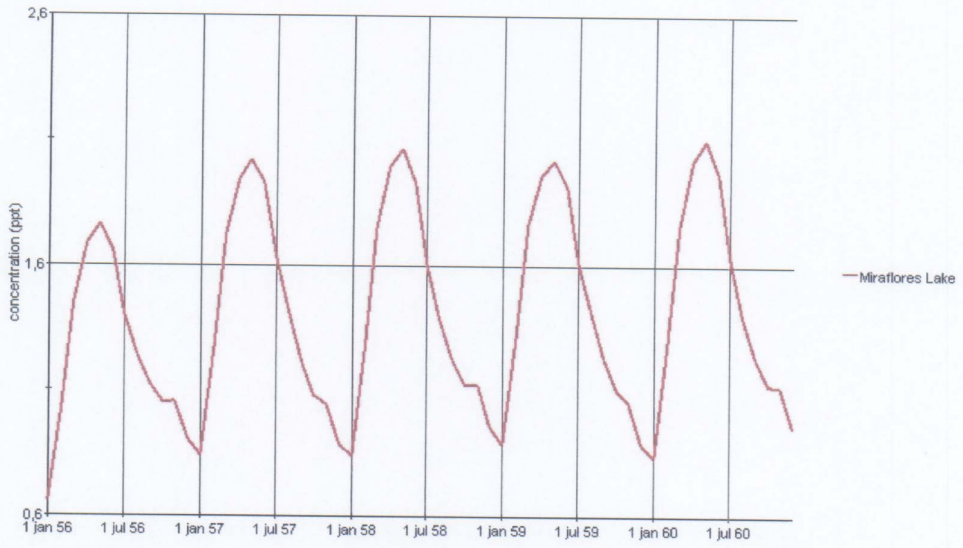
Scale modeling is advised in combination with numerical modeling. The tests in scale models are needed to study the physical processes and to sustain the detailing of the design, while mathematical models can be used to study overall processes and long term water quality effects. The scale models should preferably comprise a tailbay – lock configuration, a lock – lock configuration and a lock – forebay configuration, including the related water saving basins and mitigation system elements.

Strongly related to the operation of Post-Panamax Locks and the combat of salt water intrusion into Gatun Lake is the availability of extra fresh water from new water resources. It is advised to thoroughly study the future water control of Gatun Lake, taking into account the natural variations of the precipitation in the watershed area, the growing need of water for operation of the existing and Post-Panamax locks, including mitigation systems, the growing need of fresh water for households and industry, the need of water for electrical power generation, and considering also the demands made by a preservation of a sound aquatic environment. This requires an integrated water basin management approach.

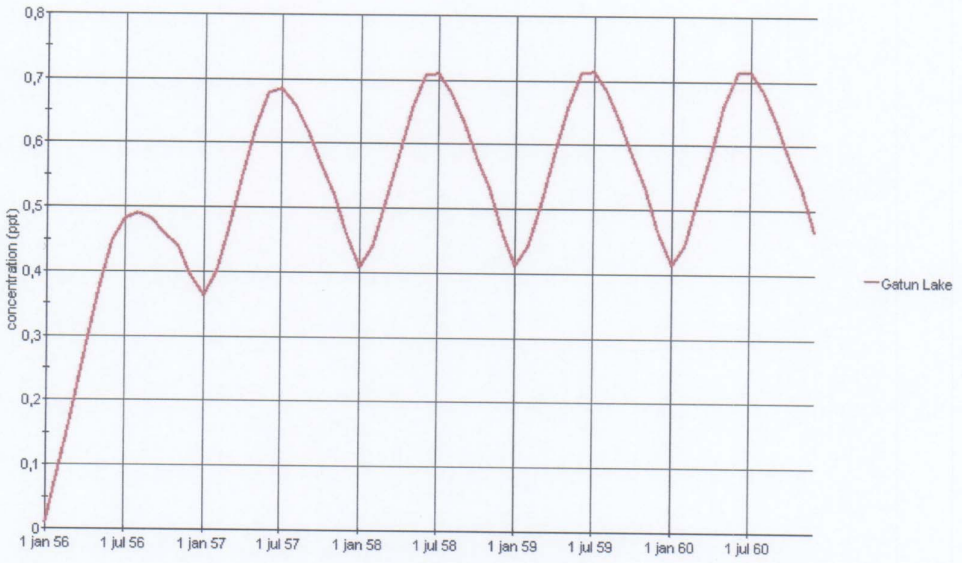
When a minimum supply of extra fresh water is opted for, the water of Gatun Lake has to be maintained in the wet season at an as high as possible level. In such a water control method water is only released from the lake when the water level threatens to exceed the upper limit level. When the spill capacity of Gatun Dam is sufficient to instantaneously discharge floods caused by intensive showers in the water shed area, the water level at which the release of water shall start, can be chosen close to the upper limit level of the lake. This has to be studied more in detail, also in relation to the use of water for electrical power generation at Gatun Dam, and in relation to possible additional fresh water reservoirs in the future.

Annex A

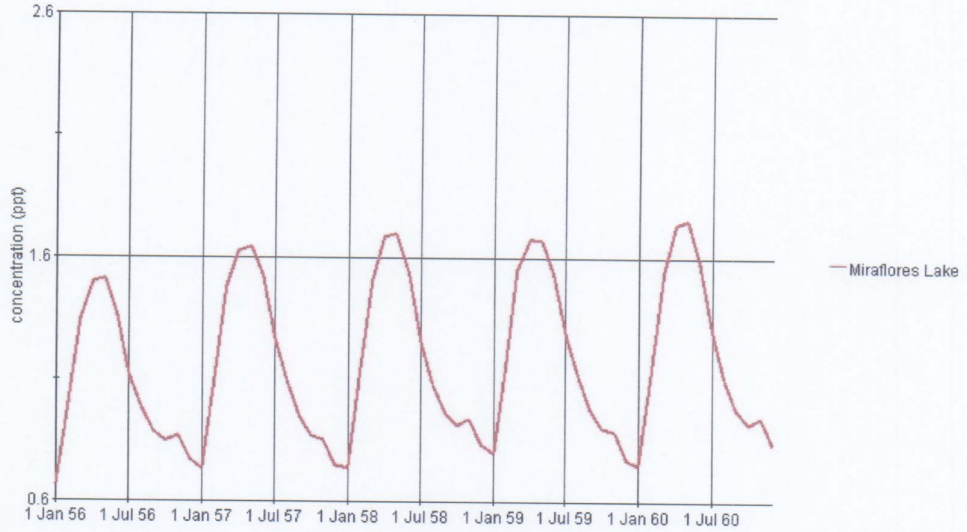
Selected figures
initial SWINLOCKS simulations



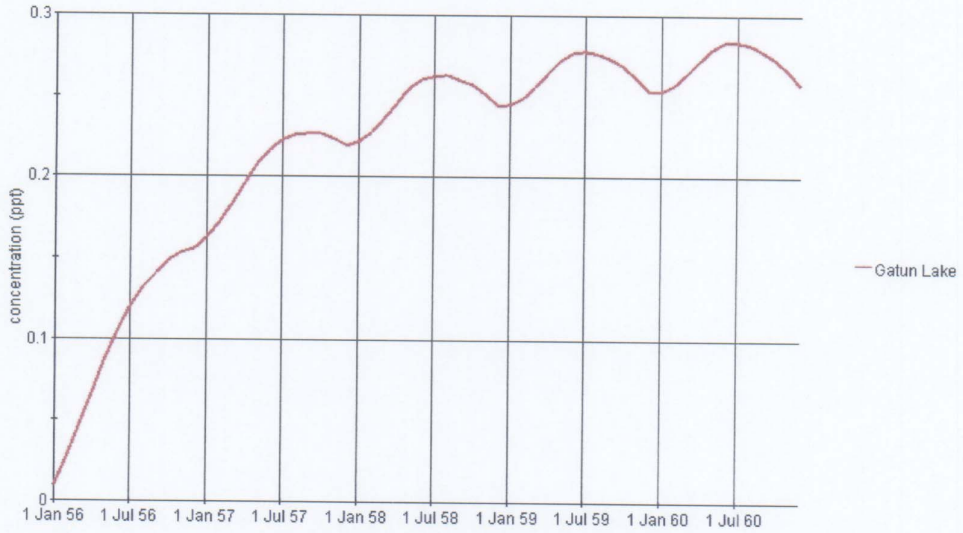
Case F13-15PP.
Volume-averaged salt concentration of Miraflores Lake (output interval: month)



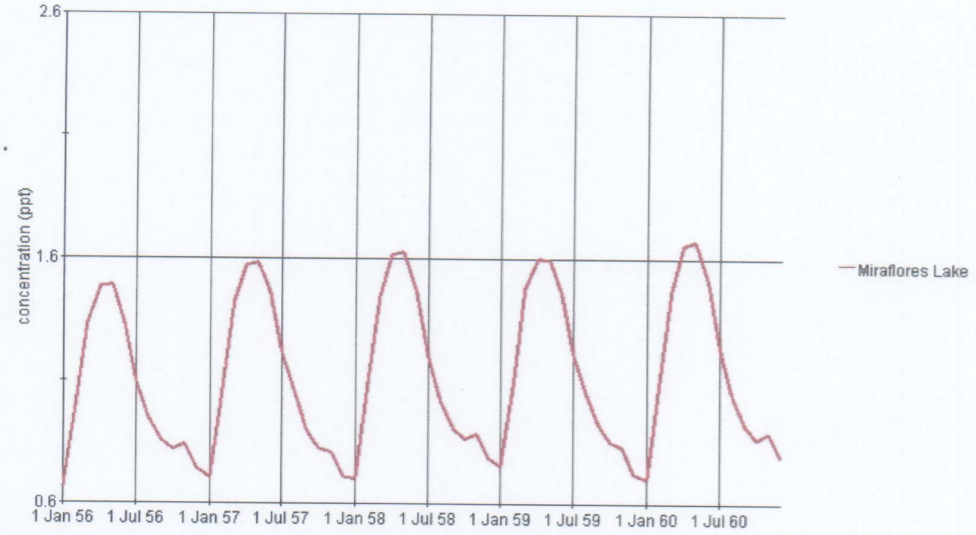
Case F13-15PP.
Volume-averaged salt concentration of Gatun Lake (output interval: month)



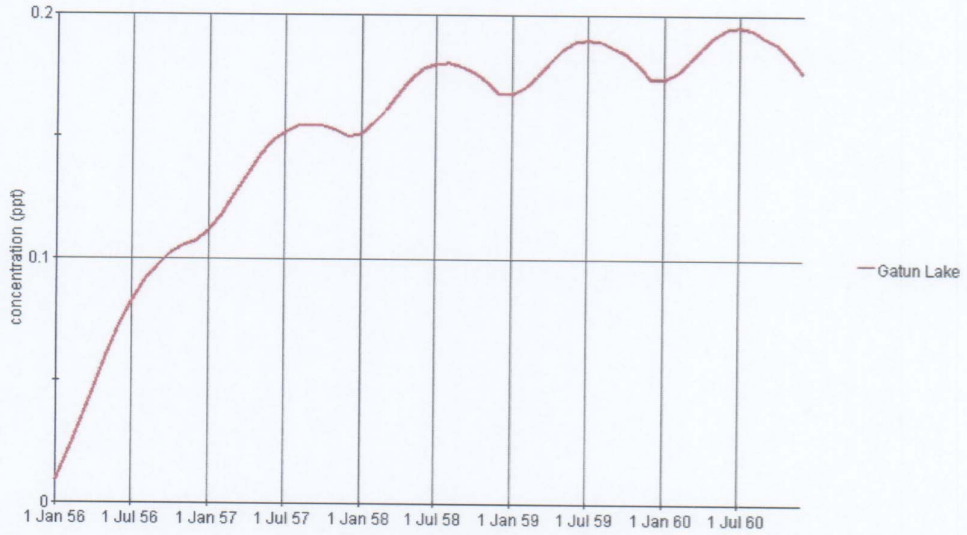
Case F15-15PP, mit I, down1.0.
Volume-averaged salt concentration of Miraflores Lake (output interval: month)



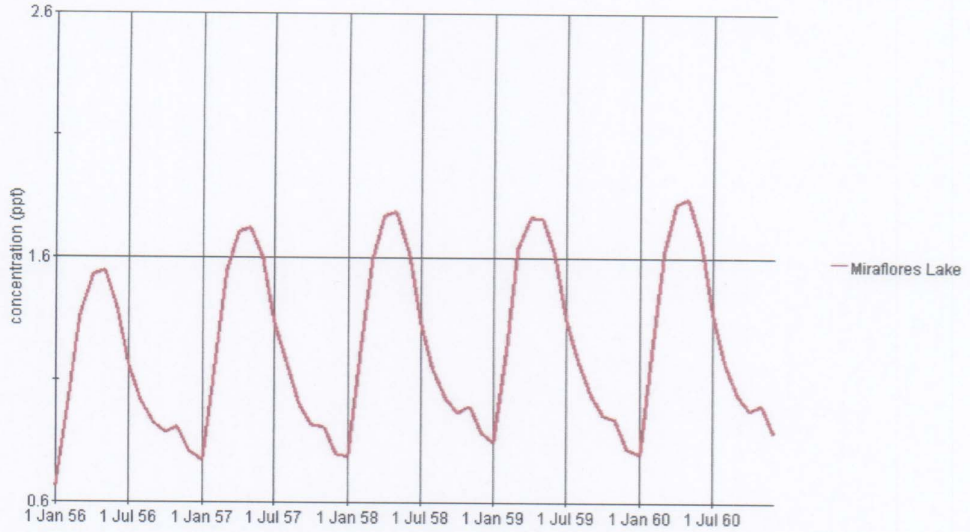
Case F15-15PP, mit I, down1.0.
Volume-averaged salt concentration of Gatun Lake (output interval: month)



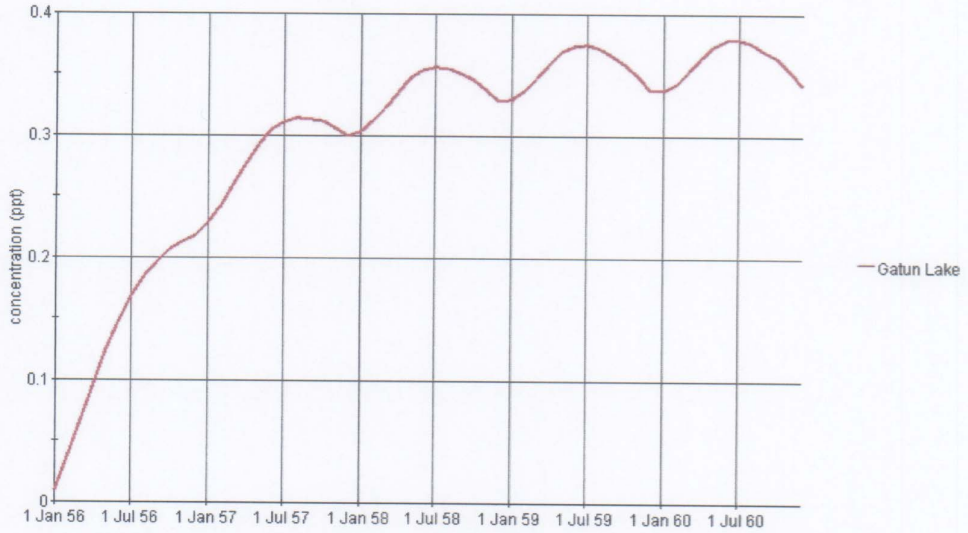
Case F16-15PP, mit II, down1.0
Volume-averaged salt concentration of Miraflores Lake (output interval: month)



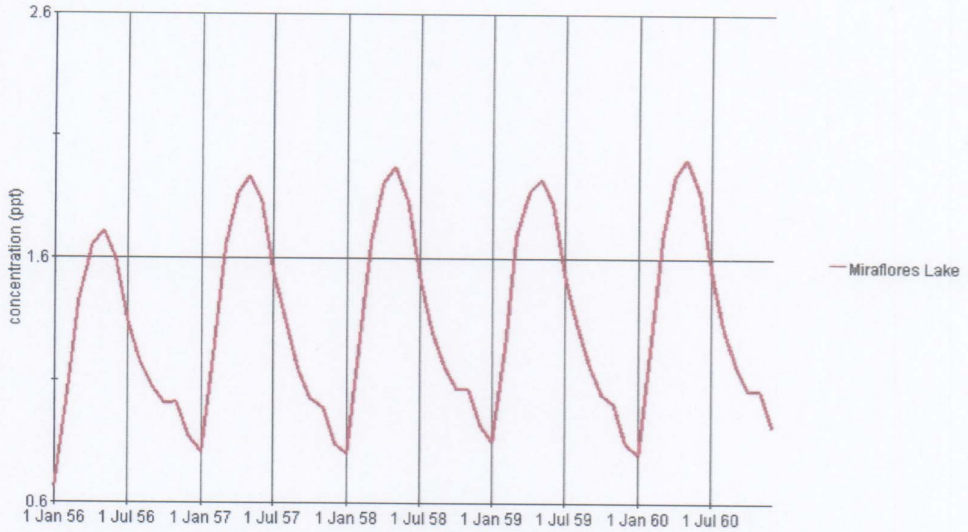
Case F16-15PP, mit II, down1.0
Volume-averaged salt concentration of Gatun Lake (output interval: month)



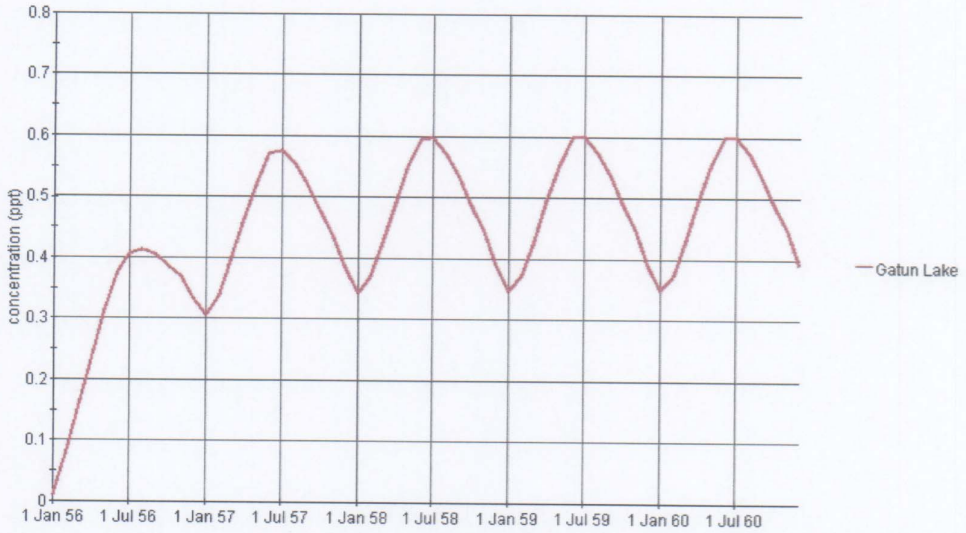
Case F17-15PP, mit III, down1.25
Volume-averaged salt concentration of Miraflores Lake (output interval: month)



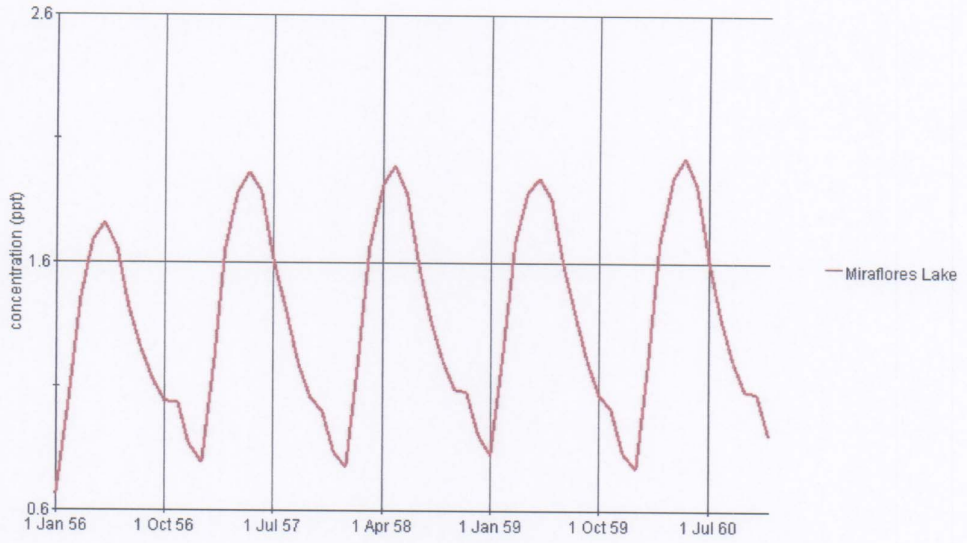
Case F17-15PP, mit III, down1.25
Volume-averaged salt concentration of Gatun Lake (output interval: month)



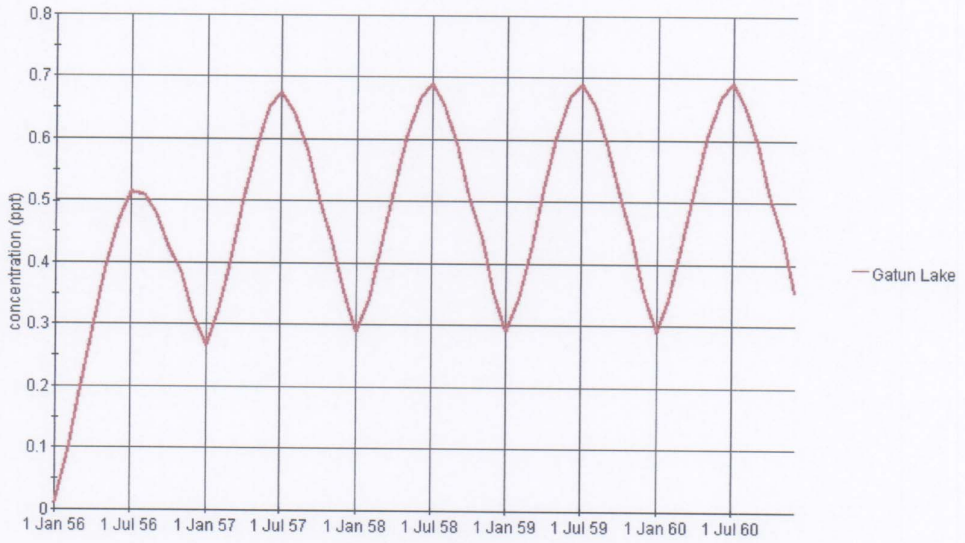
Case F18-15PP, mit IV, down0.2
Volume-averaged salt concentration of Miraflores Lake (output interval: month)



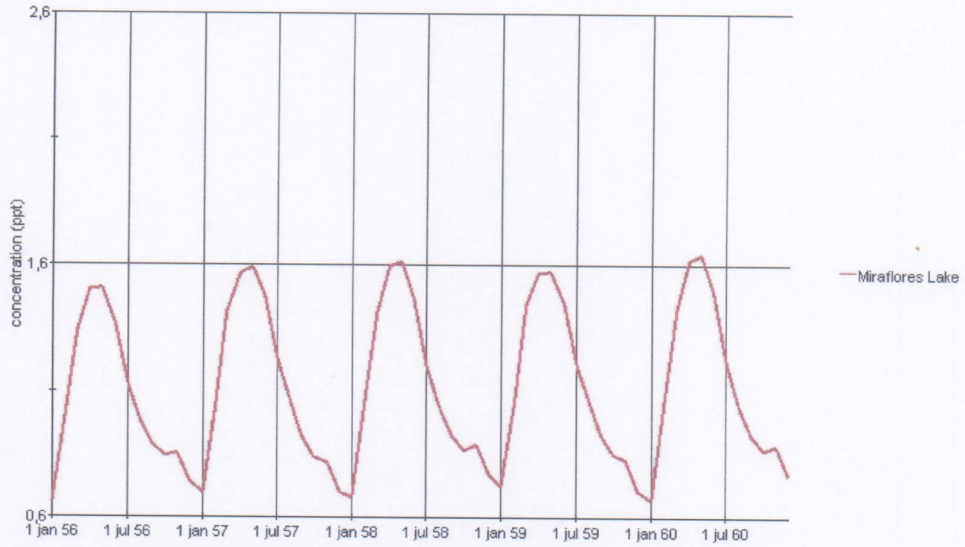
Case F18-15PP, mit IV, down0.2
Volume-averaged salt concentration of Gatun Lake (output interval: month)



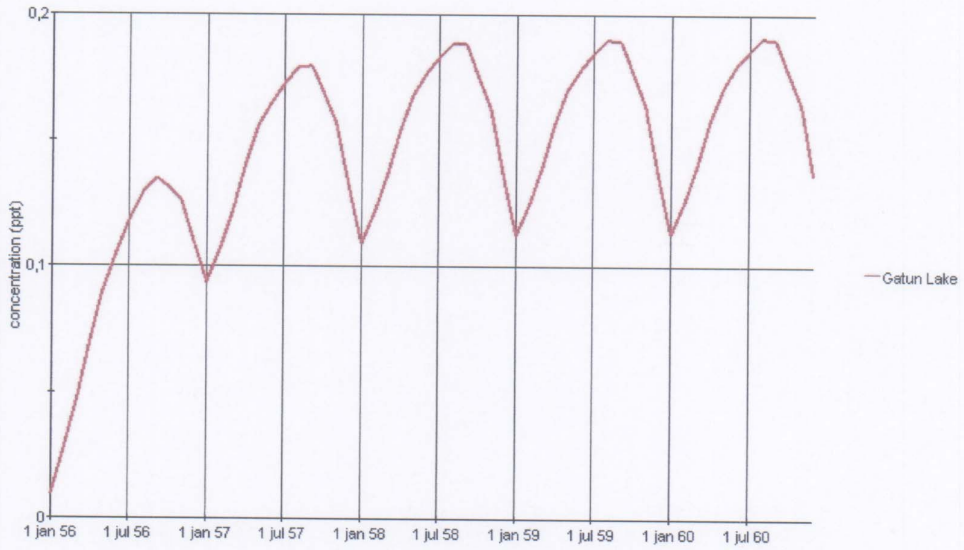
Case F3-15PP
Volume-averaged salt concentration of Miraflores Lake (output interval: month)



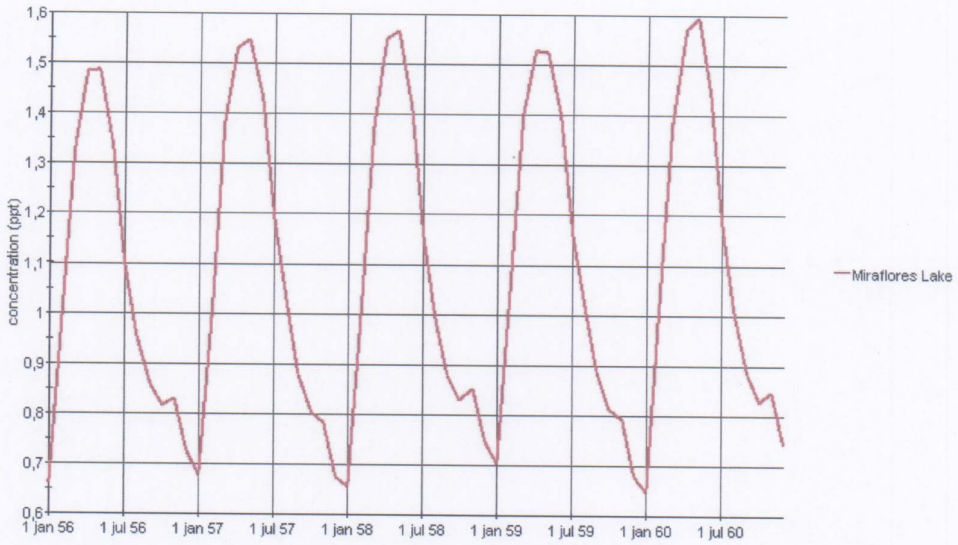
Case F3-15PP
Volume-averaged salt concentration of Gatun Lake (output interval: month)



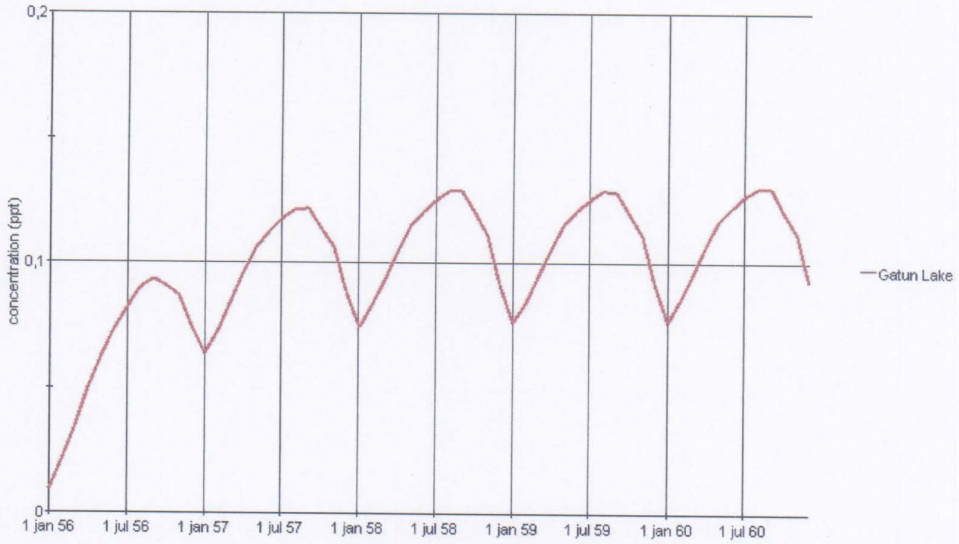
Case F21-15PP, mit I, down1.0
Volume-averaged salt concentration of Miraflores Lake (output interval: month)



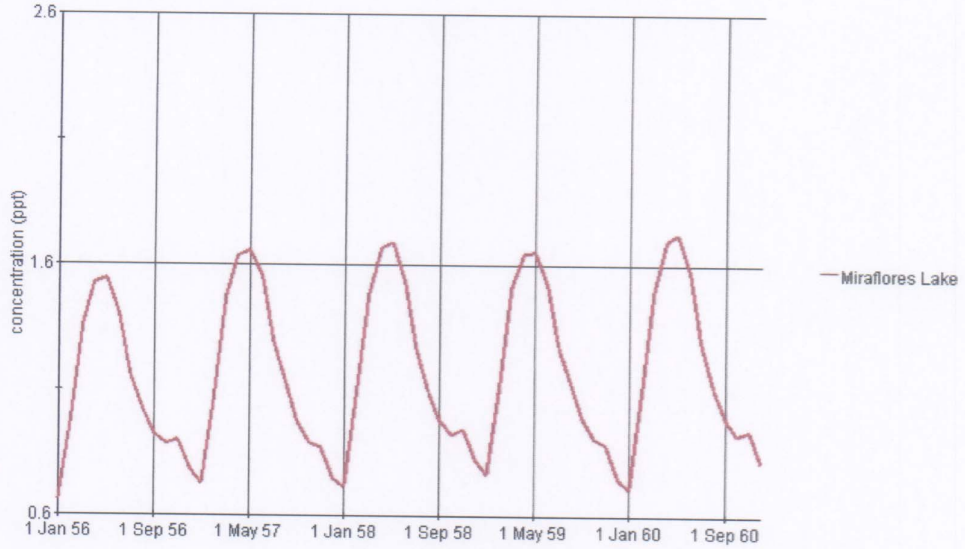
Case F21-15PP, mit I, down1.0
Volume-averaged salt concentration of Gatun Lake (output interval: month)



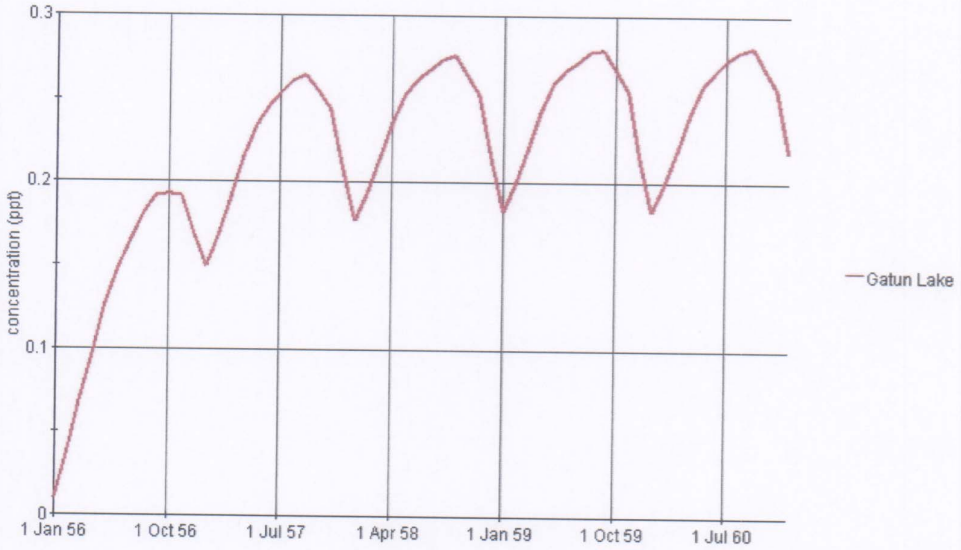
Case F22-15PP, mit II, down1.0
Volume-averaged salt concentration of Miraflores Lake (output interval: month)



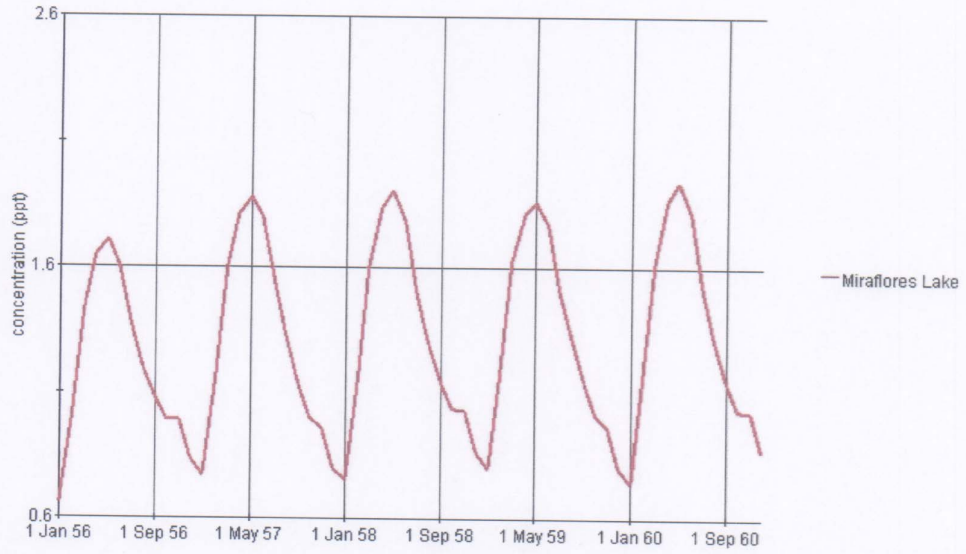
Case F22-15PP, mit I, down1.0
Volume-averaged salt concentration of Gatun Lake (output interval: month)



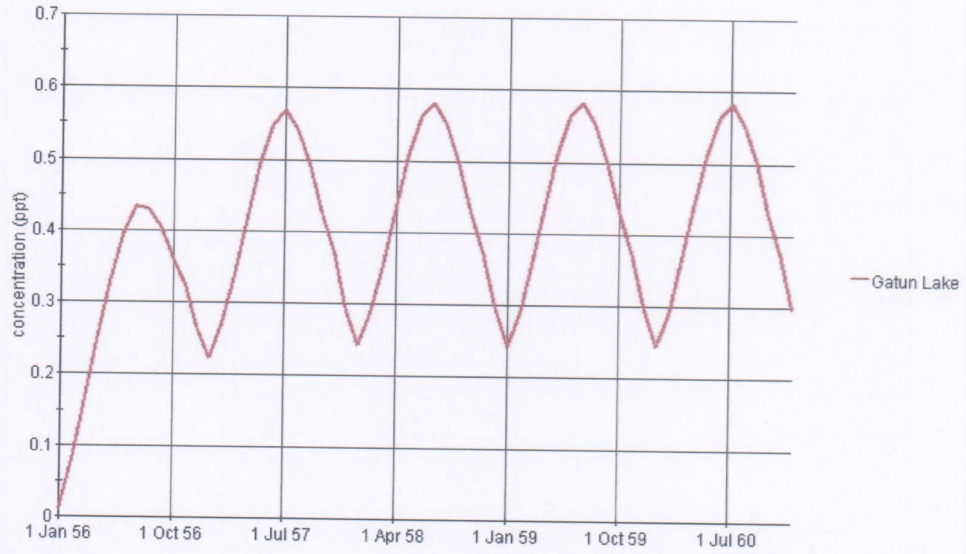
Case F23-15PP, mit III, down1.25
Volume-averaged salt concentration of Miraflores Lake (output interval: month)



Case F23-15PP, mit III, down1.25
Volume-averaged salt concentration of Gatun Lake (output interval: month)



Case F24-15PP, mit IV, down0.2
Volume-averaged salt concentration of Miraflores Lake (output interval: month)



Case F24-15PP, mit IV, down0.2
Volume-averaged salt concentration of Gatun Lake (output interval: month)

Annex B

Effect of mitigation system 1 (dummy lockage) on handling time of ships

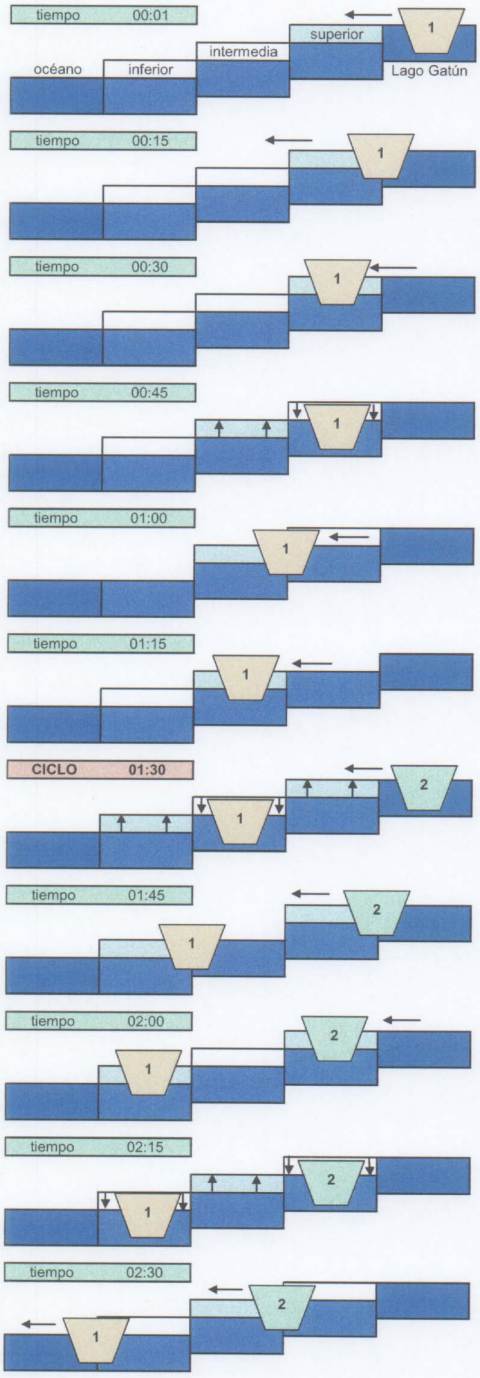
downlockage, relay mode of operation (source: ACP)

Esclusaje Post-Panamax "RELEVO" (30-15)

revisado: 16-feb-05 (Jwong)

Suposiciones: 15 minutos tiempo de llenado-vaciado de cámaras
30 minutos movimiento de buque de cámara-a-cámara

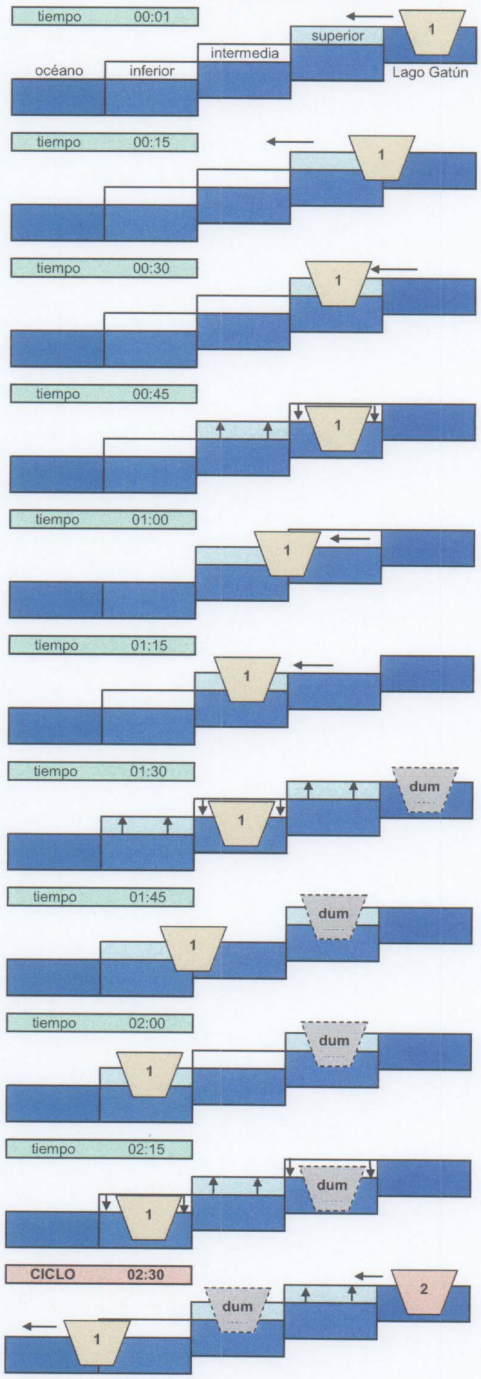
Resultados: **2:45 horas tiempo para 1 esclusaje**
1:30 horas tiempo de ciclo

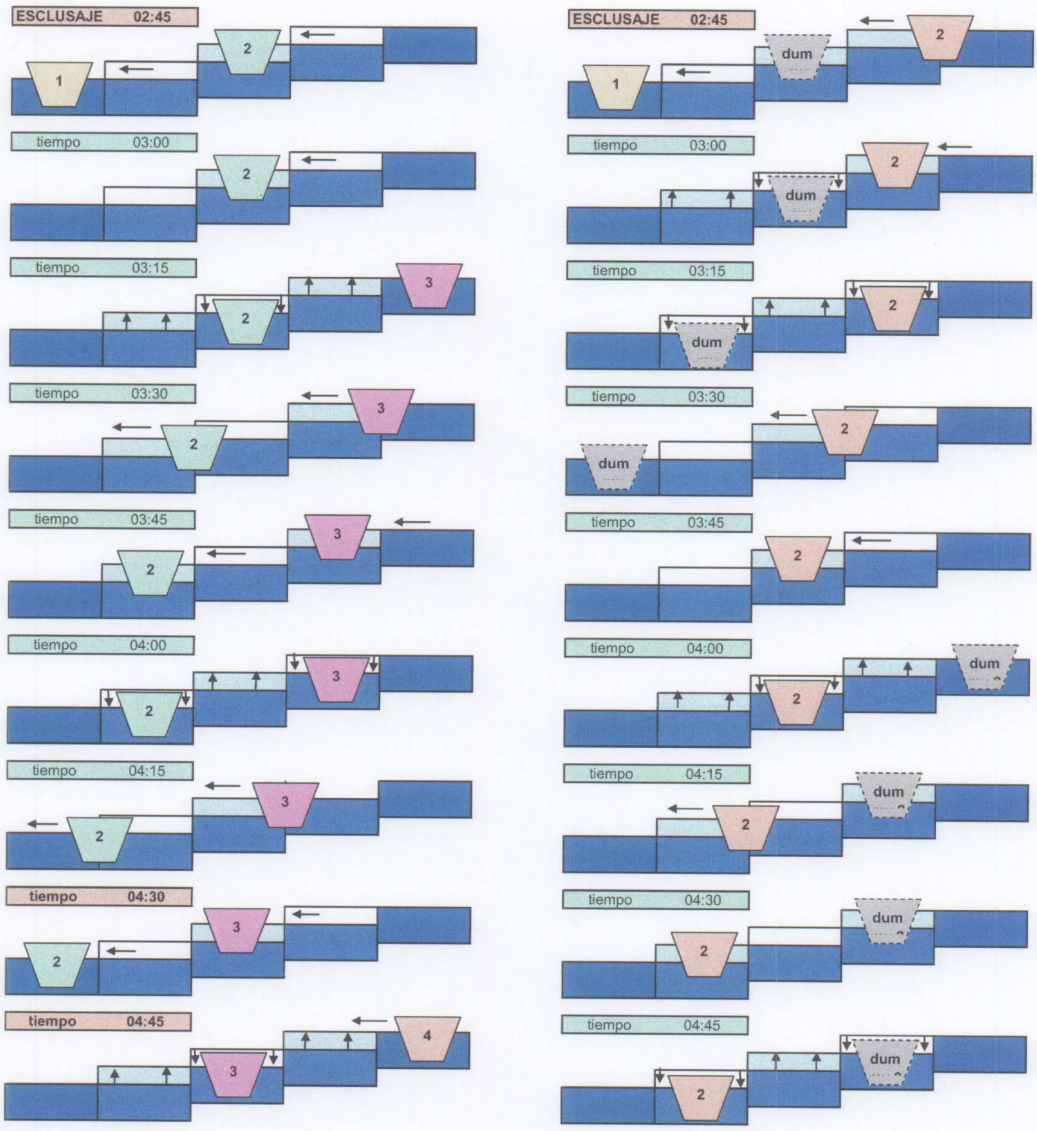


MITIGACION SISTEMA I "FLUSH" o "DUMMY" (30-15)

Suposiciones: 15 minutos tiempo de llenado-vaciado de cámaras
30 minutos movimiento de buque de cámara-a-cámara

Resultados: **2:45 horas tiempo para 1 esclusaje**
2:30 horas tiempo de ciclo (pérdida de 1 hora)




ESCLUSAJE 02:45
tiempo 03:00
tiempo 03:15
tiempo 03:30
tiempo 03:45
tiempo 04:00
tiempo 04:15
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ESCLUSAJE 02:45
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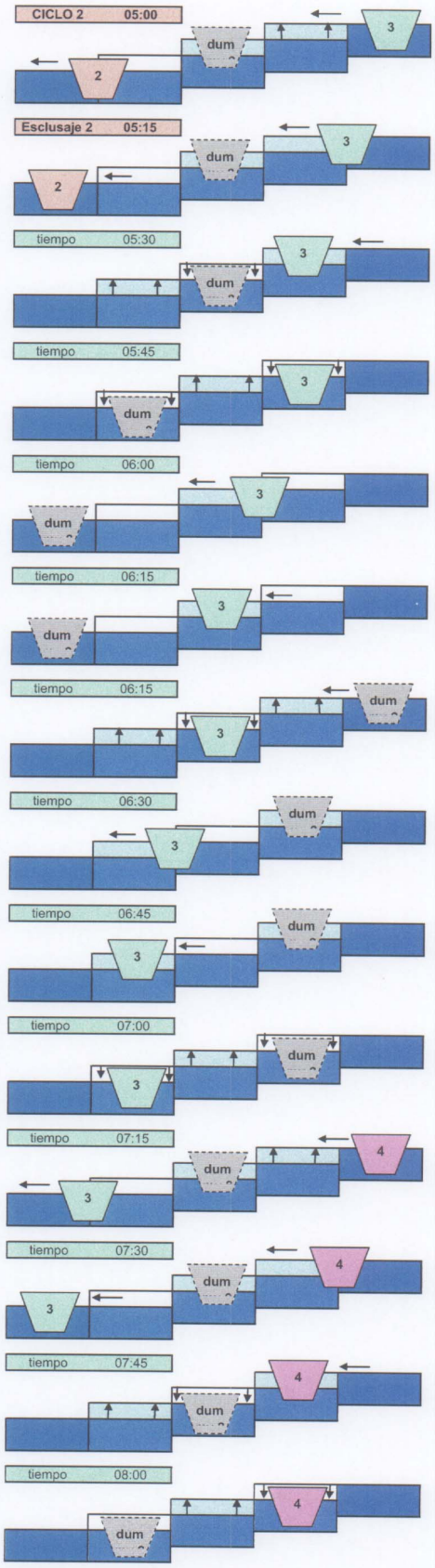
tiempo 04:45
dum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tiempo 08:00
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Filename:	Q3696ReportF.doc
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