Prepared for:

Autoridad del Canal de Panamá

Salt Water Intrusion Analysis
Panama Canal Locks

Future situation: Post-Panamax Locks

Report E

part I: Effect of water recycling at Pacific side of canal

part II: Alternative methods to mitigate salt water intrusion

April 2004

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Report E
part I: Effect of water recycling at Pacific side of canal
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Tom H.G. Jongeling

April 2004

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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 E. Part I: Effect of water recycling at Pacific side of canal, Part II: Alternative methods to mitigate salt water intrusion.

ABSTRACT:

The objective of this Consultancy is to provide services to the ACP on the subject of salt water intrusion through the locks of the Panama Canal. The services are focused on the future situation with Post-Panamax Locks in a third shipping lane and comprise:

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

The recycling system is aimed to compensate for the loss of water caused by the lock operations in the third shipping lane, and may be an alternative for the supply of fresh water to Gatun Lake from new water sources. At the same time it may cause an extra salt water load on Gatun Lake, and – indirectly – Miraflores Lake.

Three options for recycling of water are considered by ACP:

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

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

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

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

The study on mitigation measures focuses on the process of salt water intrusion, measures that can be taken to mitigate the salt water intrusion, apropriate measures for the Panama canal locks and expected efficiency.

REFERENCES: Contract No SAA-110830, signed by ACP on 3 June 2003
Modification no 1 to Contract SAA-110830, signed by ACP on 9 February 2004

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01	T.H.G. Jongeling		16 February 2004		R.J. de Jong			
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Salt Water Intrusion Analysis Panama Canal Locks
Future situation: Post-Panamax Locks

Report E, summary

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

Contents of Summary

1 Introduction

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

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

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

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

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

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

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

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

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

2 Effect of water recycling at Pacific side of canal

2.1 Background and purpose of study

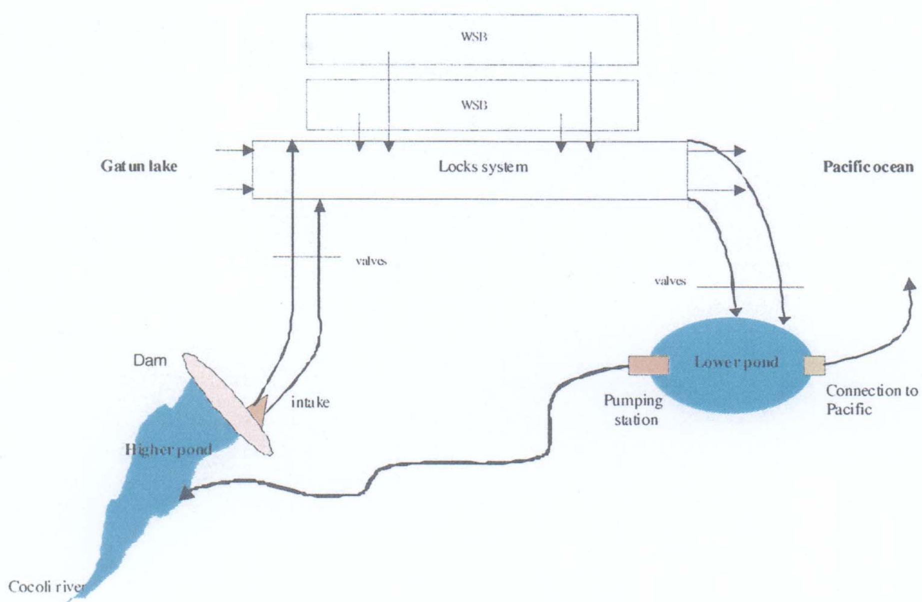
ACP is considering the installation of a water recycling system in the Post-Panamax Locks at the Pacific side of the canal. This system is aimed to compensate for the loss of water caused by the lock operations in the third shipping lane, and is used in dry periods, when there is a shortage of fresh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

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

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

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

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



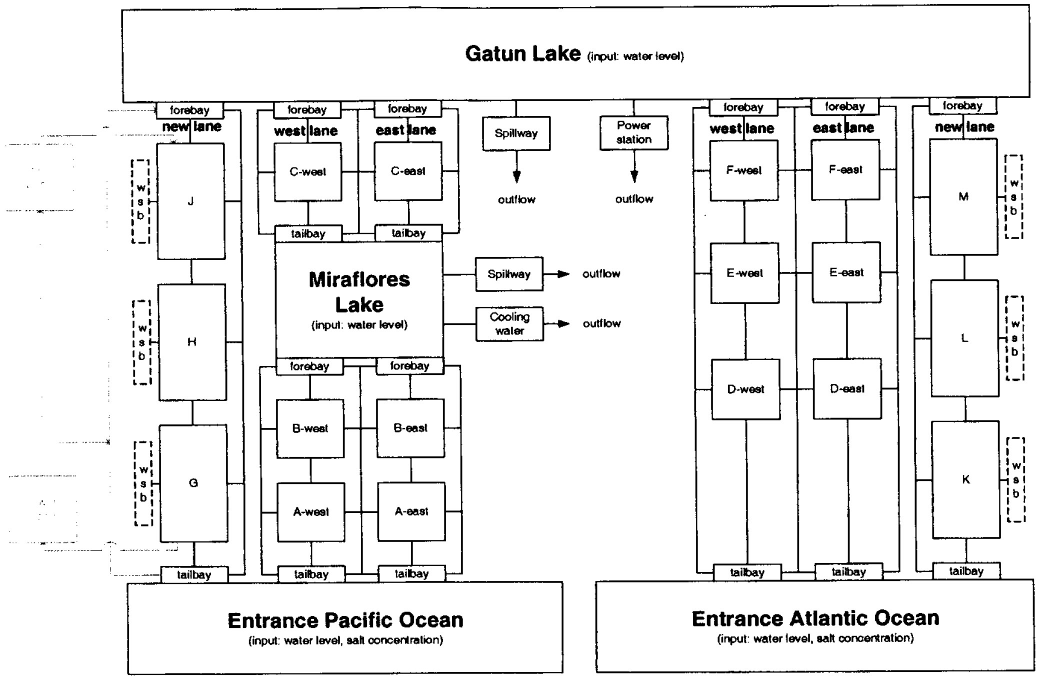
Recycling option 3: pond to pond recycling (source: Consorcio Post-Panamax)

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

2.2 Simulation model for salt water intrusion

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

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



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

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

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

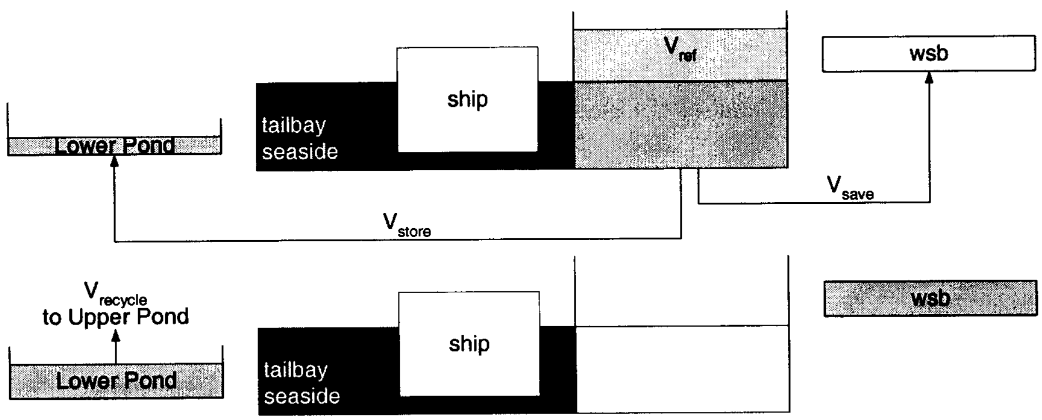
The first two steps repeat each time that a ship moves from one basin to another, the last step is executed when the full uplockage or downlockage operation at the Pacific side of the canal has been concluded (or after a turn around operation has been executed).
A set of mass conservation equations is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

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

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

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

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



Salt balance equations:

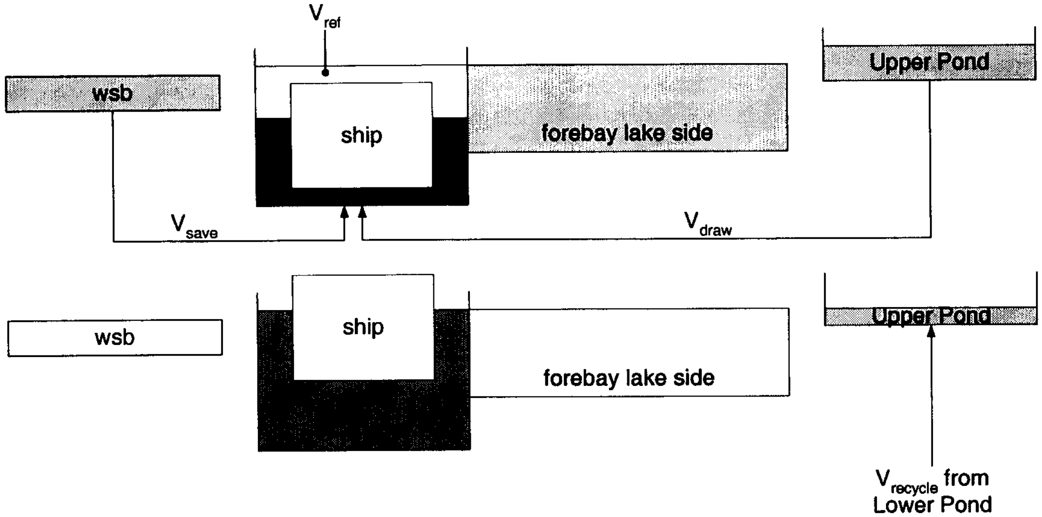
$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_{wsbfill} \cdot V_{save} \cdot c_{high1}) - (e_{LPfill} \cdot V_{store} \cdot c_{high1}) - (e_x \cdot (V_{ref} - V_{save} - V_{store}) \cdot c_{high1})}{V_{high2}}$$

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

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

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

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



Salt balance equations:

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

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

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

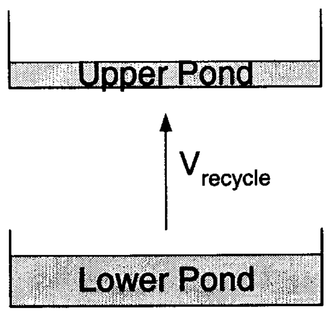
$$c_{lake2} = c_{lake1} - \frac{(V_{ref} - V_{save} - V_{draw})}{V_{lake}} \cdot c_{lake1}$$

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

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

The exchange coefficients used in step I are always positive or nil, meaning that transfer of water through the water filling and emptying system from one basin to another does not allow for a salt transfer in the opposite direction. The exchange coefficients e_x , $e_{wsbfill}$ and e_{LPfill} can be greater than 1; this indicates that the water portion that is transferred from one basin to another has a higher salt concentration than the water in the basin where it is withdrawn from. For example, water that is withdrawn from the higher lock chamber and spilled into the wsb and lower lock chamber has, generally, a higher salt concentration than the initial water in the higher lock chamber (volume averaged). This, since the water is drawn from the water body near the floor with a higher than average salt concentration. The exchange coefficients e_x , $e_{wsbfill}$ and e_{LPfill} are selected on the basis of measurements in situ, on results of Delft3D computations and on considerations regarding upper and lower limit values (see Reports A, B, C, D, E-partI for further explanations). The exchange coefficients $e_{wsbempty}$ and $e_{UPempty}$ are always set to 1 in the present study. We assume that the water in the wsb's and upper pond is fully mixed up during filling; the water that is subsequently withdrawn has thus an equal salt concentration as the water in the wsb's and upper pond prior to the withdrawal.

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



Salt balance equations:

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

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

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

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

2.3 Exchange of salt water between forebay and lake

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

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

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

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

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

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

with:

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

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

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

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

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

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

2.4 Water control scenarios Gatun Lake

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

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

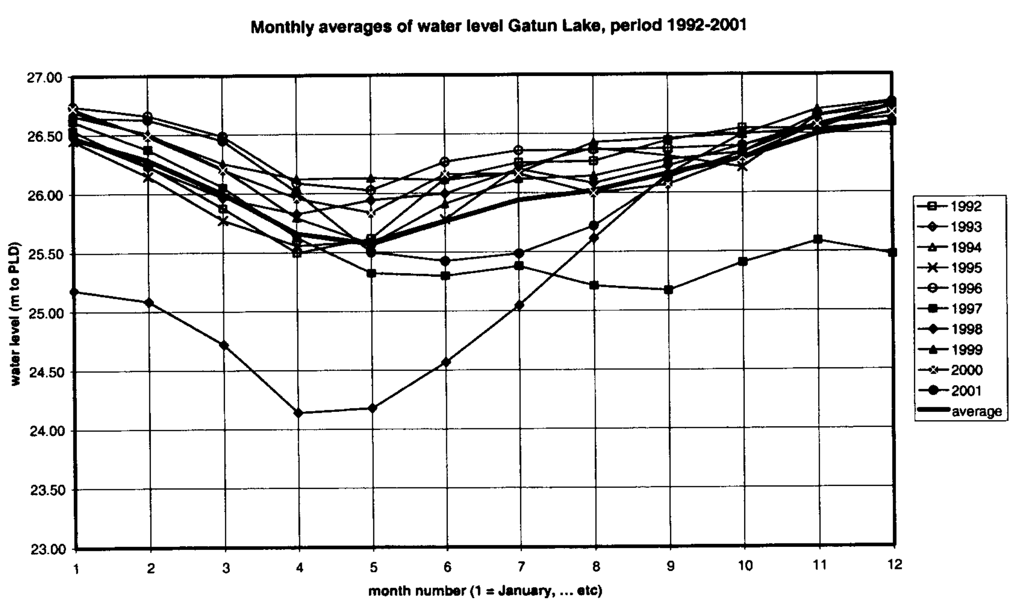
In scenarios 5, 7 and 9 (locks with wsb's) and 6, 8 and 10 (locks without wsb's) the extra water losses caused by the new locks are compensated by a lesser water release at Gatun Dam; if insufficient, in dry periods, the water lost by operation of the new locks at the Pacific side of the canal is recycled;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

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

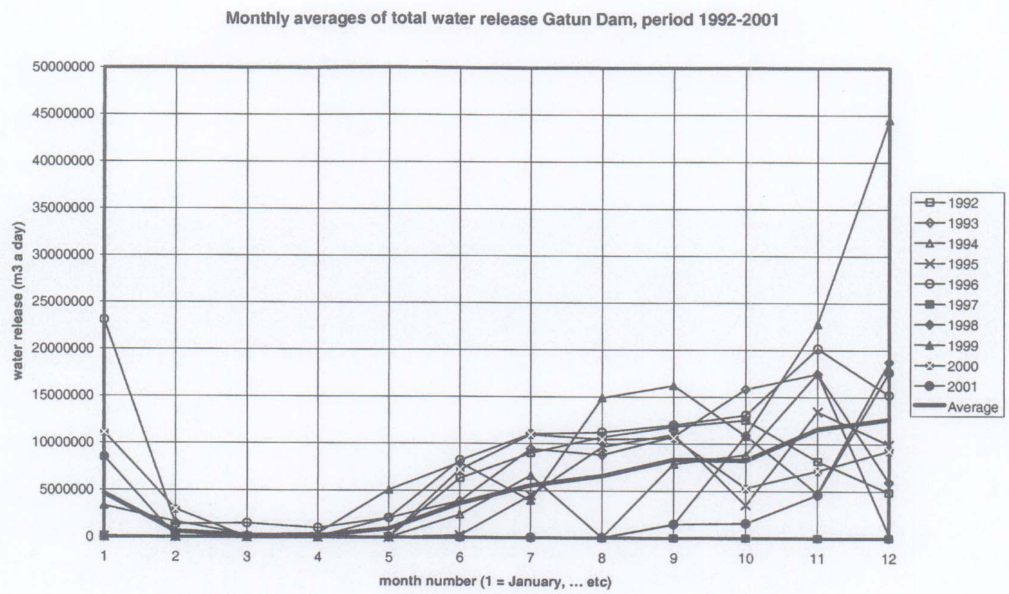
Scenario	*Description*	*3-lift locks*	*2-lift locks*	*1-lift locks*
1 baseline scenario	wsb's *no* reduction of water releases at Gatun Dam extra fresh water supply to Gatun Lake	*B1*	*C1*	*D1*
2	*no* wsb's *no* reduction of water releases at Gatun Dam extra fresh water supply to Gatun Lake	*B2*	*C2*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

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

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

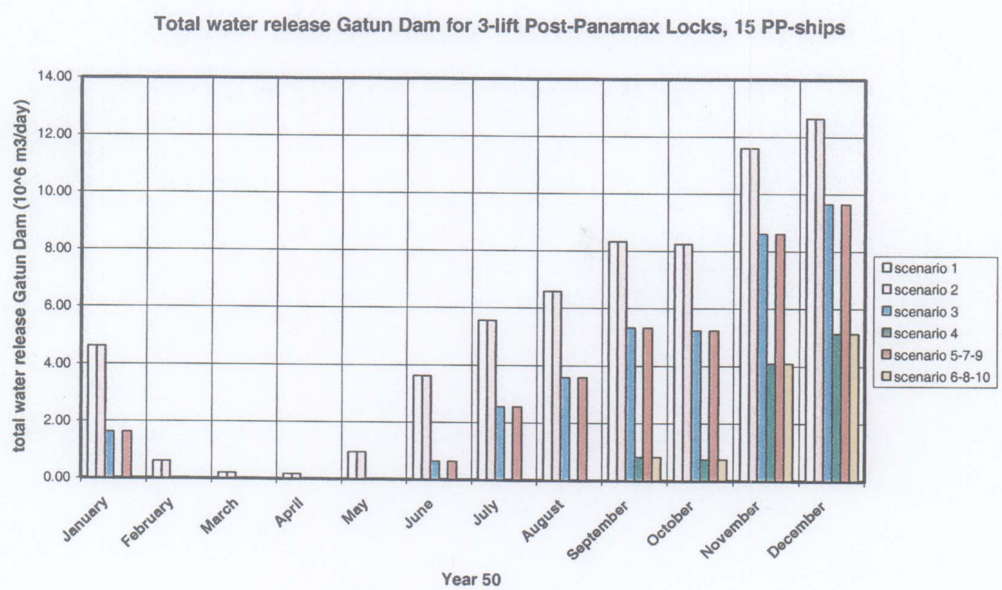


Monthly averages of water level Gatun Lake, period 1992-2001

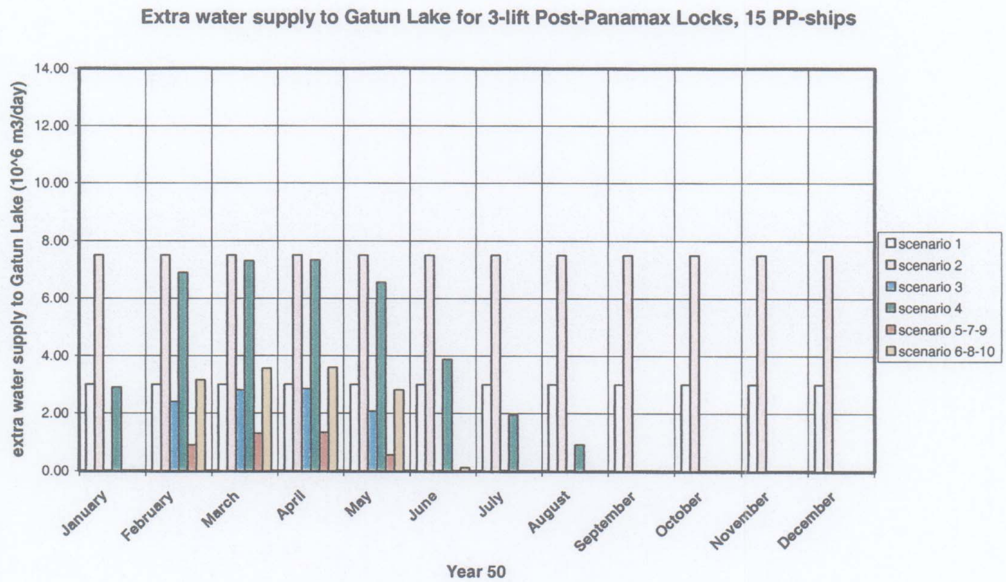


Monthly averages of water releases at Gatun Dam, period 1992-2001

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

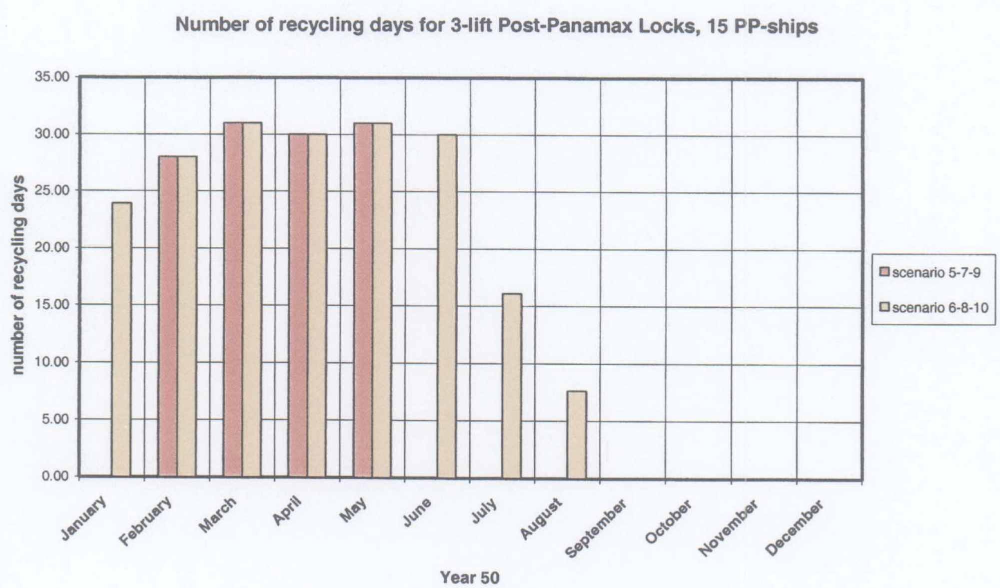


Water releases at Gatun Dam in initial simulations, 3-lift locks, 15 PP-ships/day



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

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

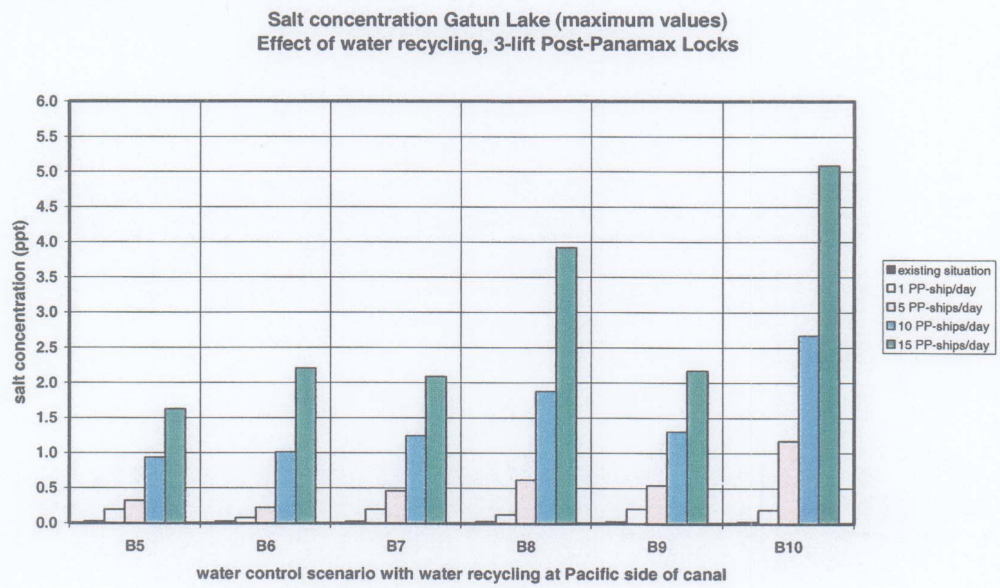


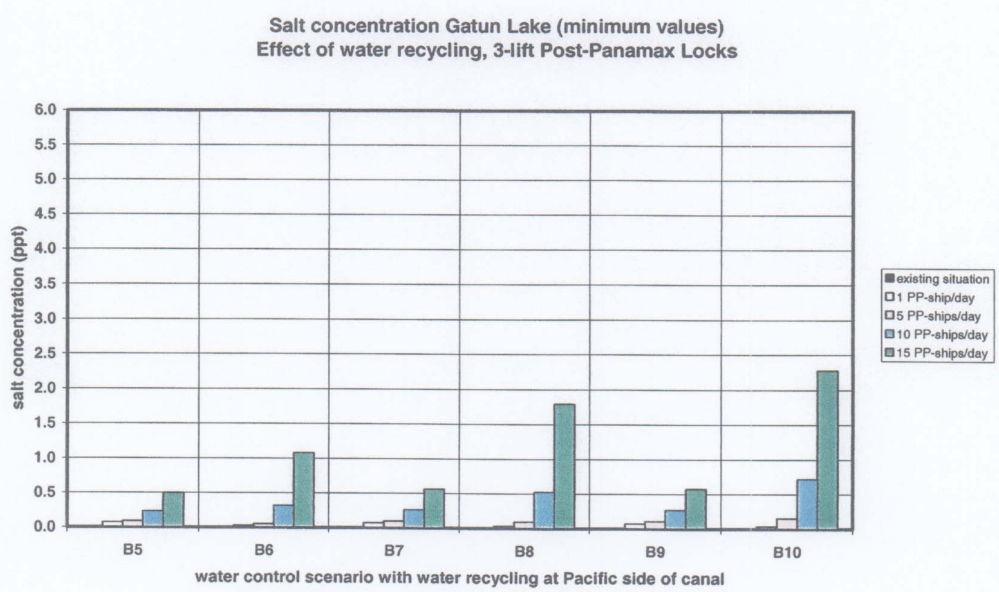
Number of recycling days in initial simulations, 3-lift locks, 15 PP-ships/day

2.5 Effect of water recycling on salt concentration levels

2.5.1 3-lift locks

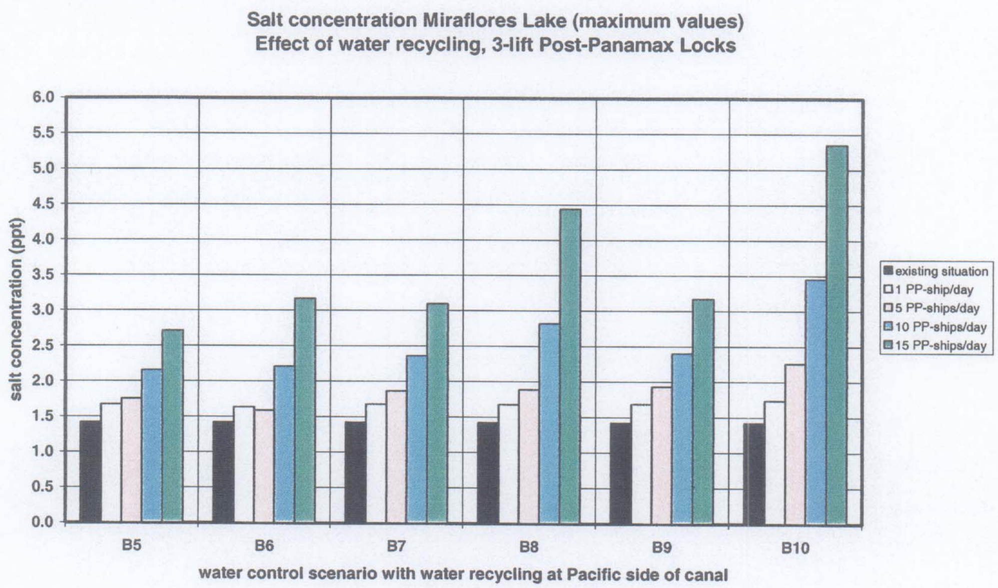
The effect of water recycling is analyzed for ship traffic intensities of 1, 5, 10 and 15 Post-Panamax ships a day in addition to the 'normal' 36 ship transfers in the existing two shipping lanes. The salt concentration levels of Gatun Lake and Miraflores Lake appear to be very sensitive to the number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

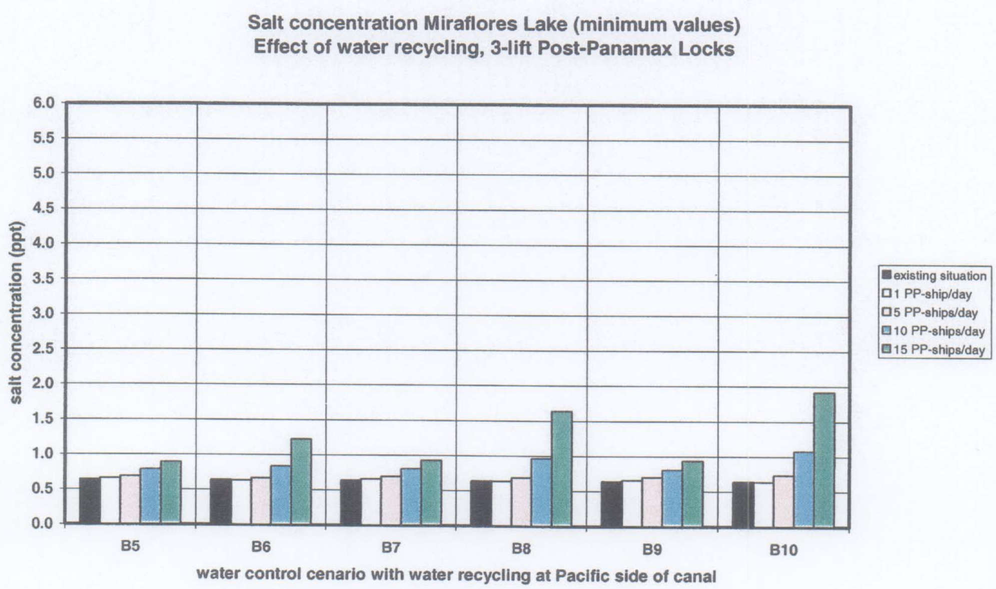




Maximum and minimum salt concentration Gatun Lake, initial simulations, 3-lift locks

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

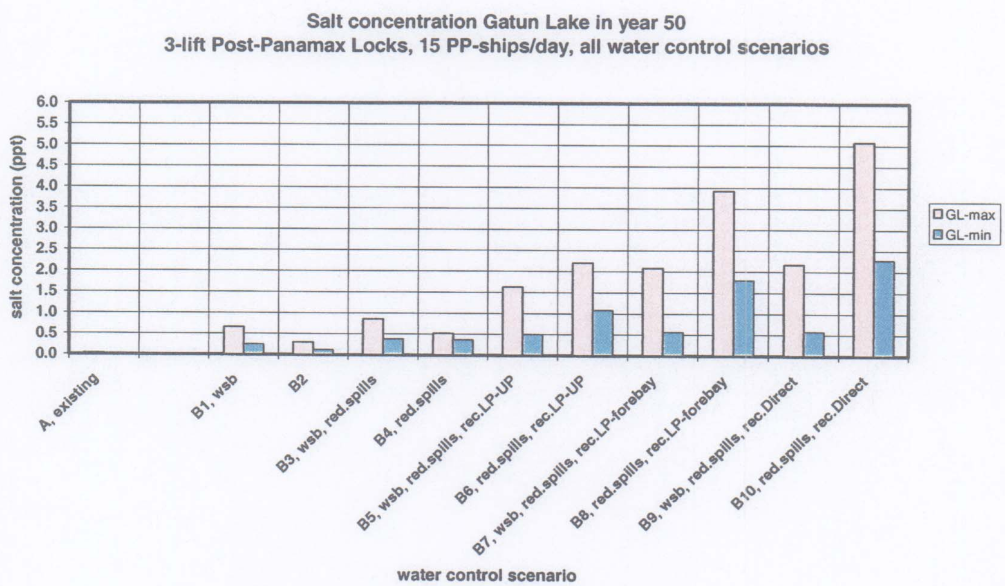




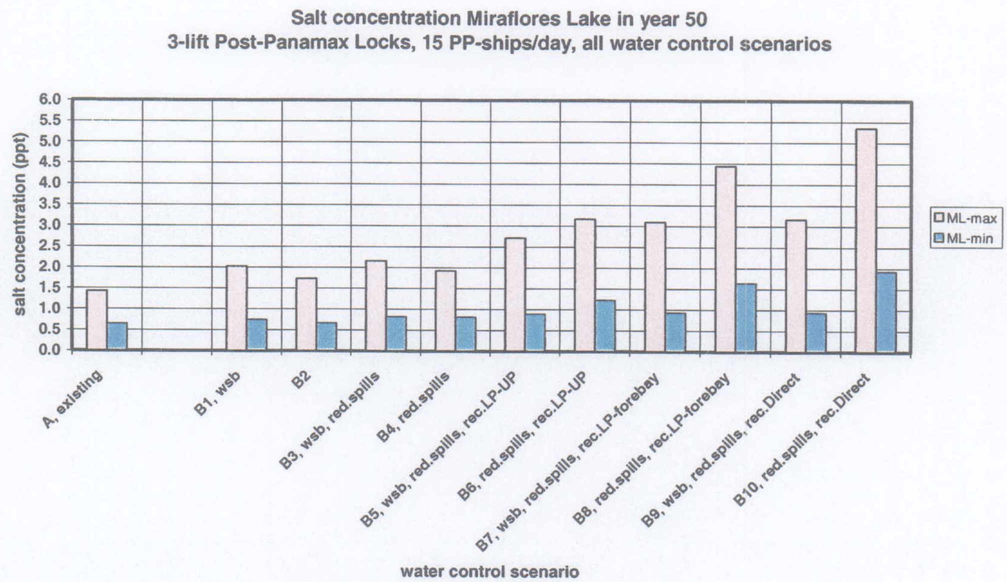
Maximum and minimum salt concentration Miraflores Lake, initial simulations, 3-lift locks

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

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

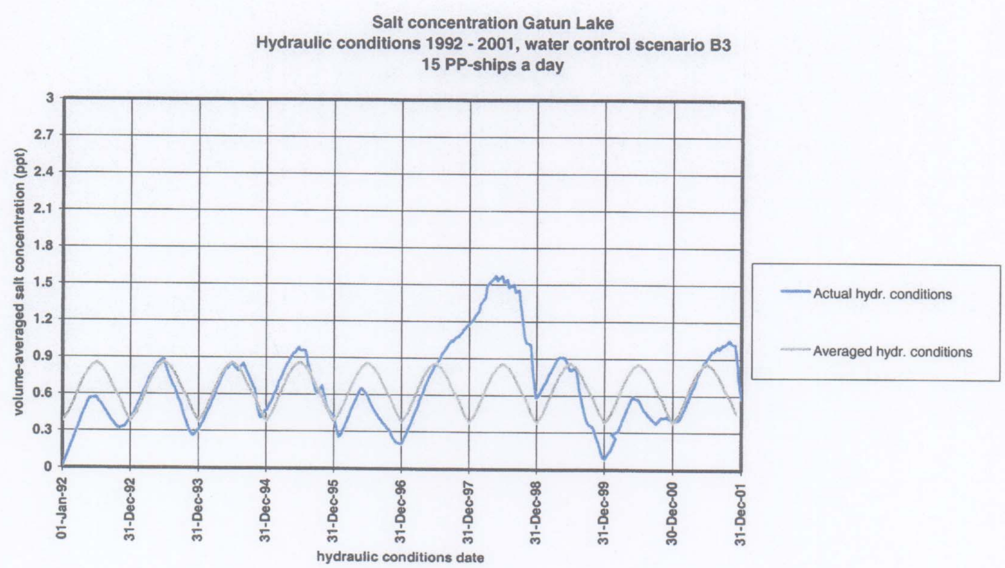


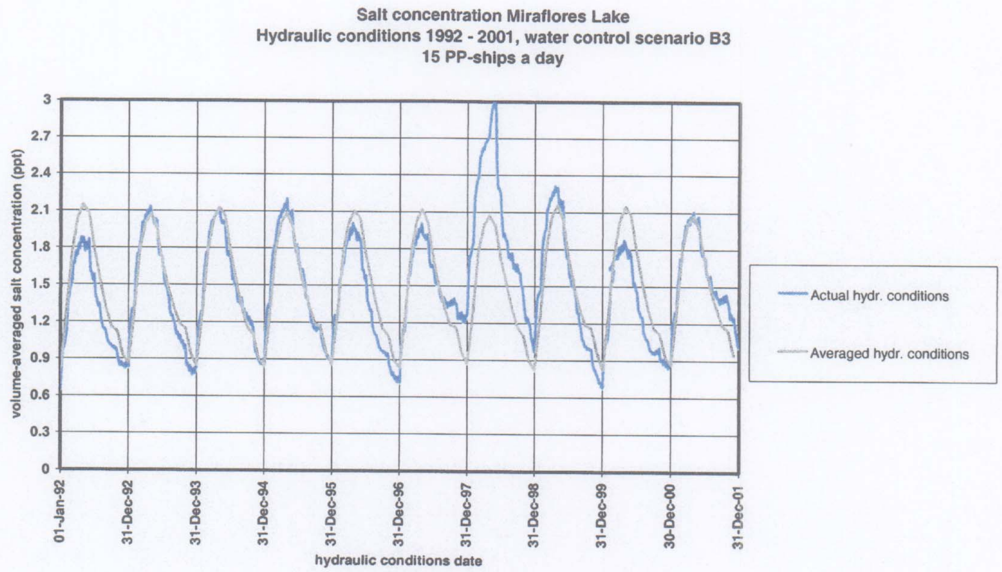
Salt concentration Gatun Lake, 3-lift locks, 15 ships a day, all scenarios



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

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

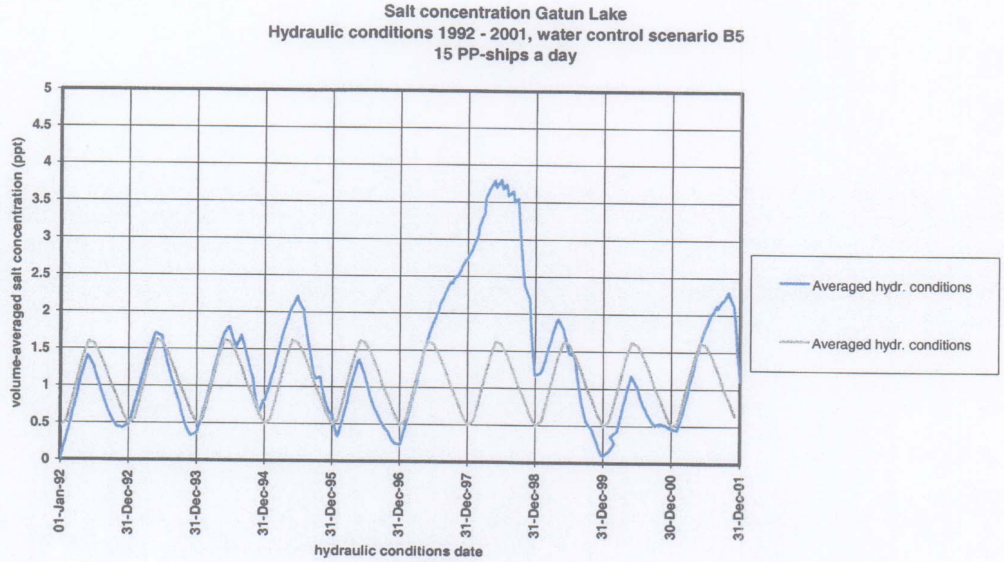


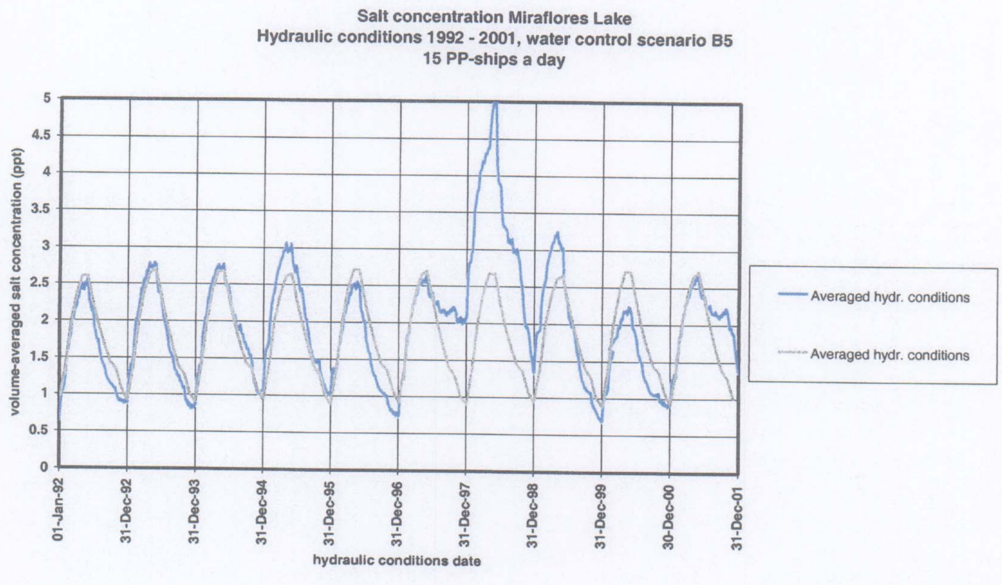


Salt concentration Gatun Lake and Miraflores Lake, 3-lift locks, 15 ships a day, scenario B3 (no recycling), actual and averaged hydraulic conditions

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

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



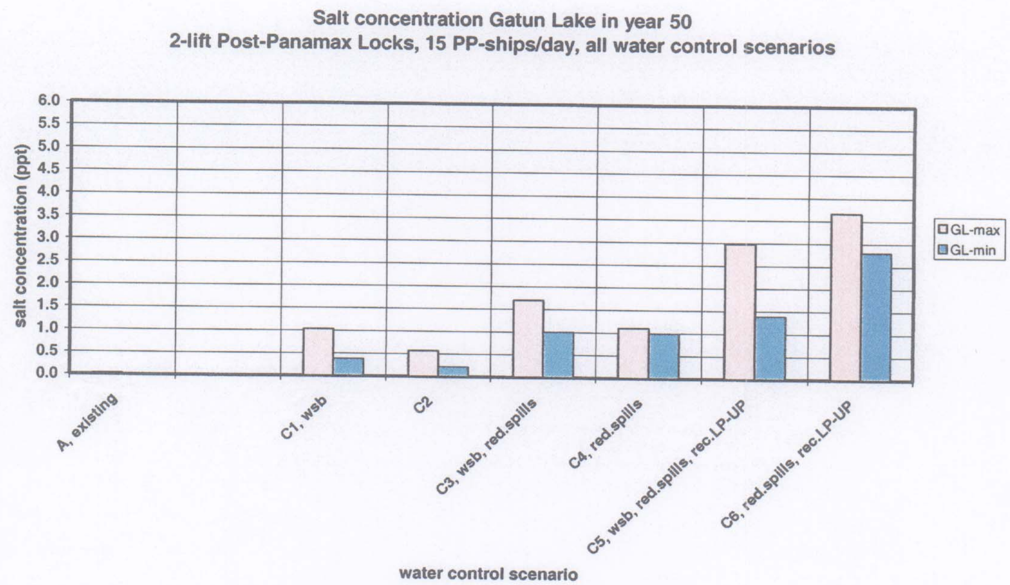


Salt concentration Gatun Lake and Miraflores Lake, 3-lift locks, 15 ships a day, scenario B5 (recycling from lower pond to upper pond), actual and averaged hydraulic conditions

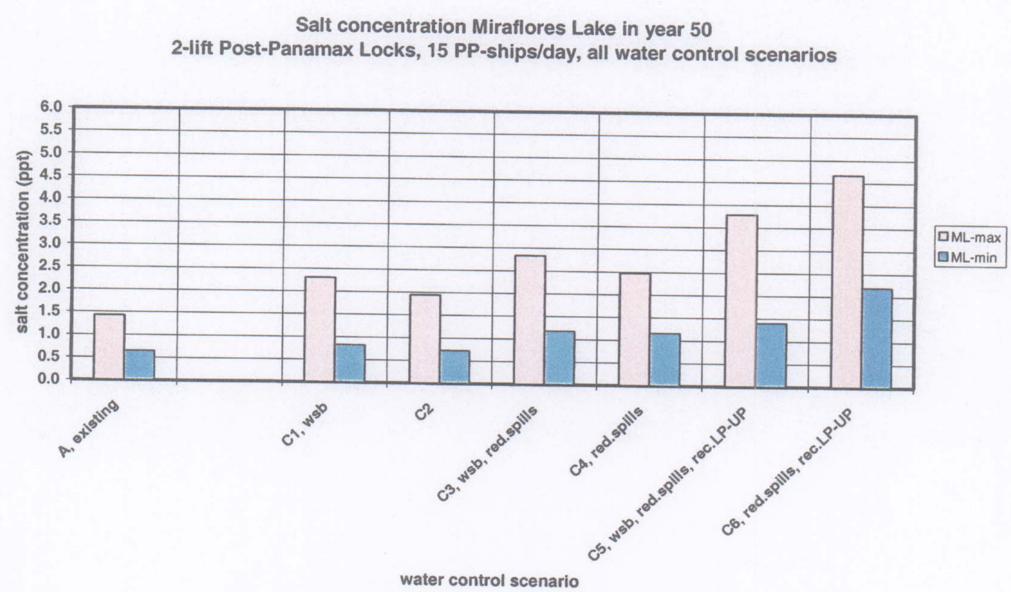
2.5.2 2-lift locks and 1-lift locks

A limited number of salt intrusion simulations have been executed for 2-lift locks and 1-lift locks applying recycling option 3 (recycling from lower storage pond to upper storage pond), see table on page 2-9. These simulations have been run with averaged hydraulic conditions of the period 1992-2001, so that the extremes in seasonal variations were filtered off. In next charts the results of these simulations (volume-averaged salt concentration of Gatun Lake and Miraflores Lake) are compared with the results of previous simulations without recycling. The comparison is done for year 50, with a ship traffic intensity of 15 Post-Panamax ships a day in the new shipping lane.

Results for 2-lift locks:

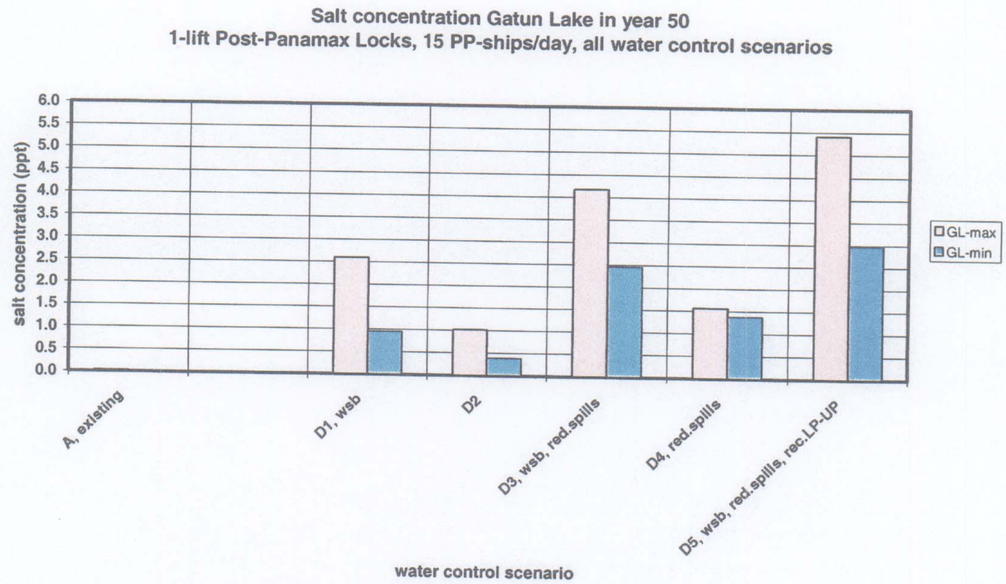


Salt concentration Gatun Lake, 2-lift locks, 15 ships a day, all scenarios

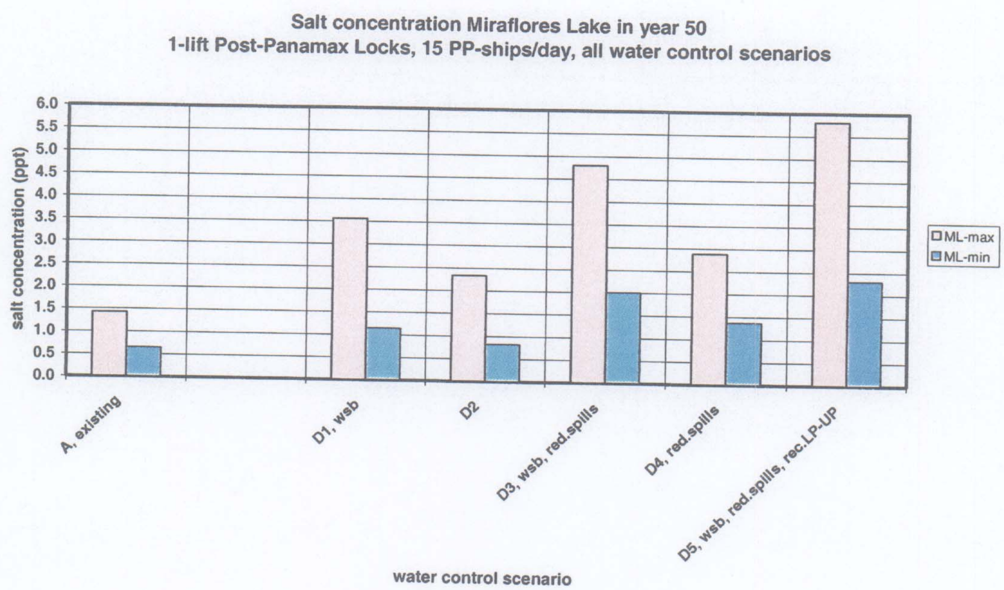


Salt concentration Miraflores Lake, 2-lift locks, 15 ships a day, all scenarios

Results for 1-lift locks:



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



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

2.6 Conclusions water recycling

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

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

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

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

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

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

3 Salt water intrusion mitigation measures

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

3.1 Process of salt water intrusion

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

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

3.2 Mitigation measures

3.2.1 Overview of measures

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

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

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

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

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

3.2.2 Feasibility and effectivity of measures

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

A1 Operational measures

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

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

Pneumatic barriers in tailbay and forebay may reduce the total salt water intrusion of Post-Panamax Locks to maximum 30% (expected upper limit). The ship-bound salt water intrusion is not prevented. The required air discharge is about 250 m^3/s (at atmospheric pressure) for a barrier in the tailbay; a second barrier in the forebay may require a twice as little air discharge; this second barrier has a lesser effect. Since pneumatic barriers have not yet been applied in water with a depth of 20 m or more, a further study into the efficiency is advisable. The pneumatic barrier has the advantage that it neither causes an additional fresh water loss, nor a delay for shipping, but small yachts can not safely pass the pneumatic barriers.

A3 Limit the exchange of salt water and fresh water between lock chamber and forebay by means of an adjsutable sill
An adjustable sill at the entrance to the forebay may reduce the salt water intrusion of Post-Panamax Locks to a maximum of 5%. The ship-bound salt water intrusion is not prevented. When the adjustable sill malfunctions there is a risk of a collision of a passing ship. The adjustable sill must therefore be designed in such a way that damage of the ship is prevented. The sill has the advantage that no extra fresh water is lost. Shipping is not delayed.

B Remove the salt water that has passed the locks:

B1 Flush the area near the locks

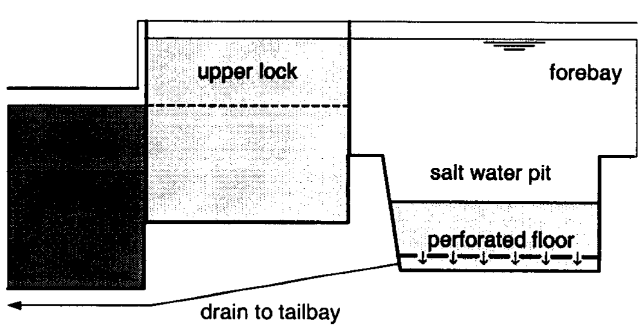
The direct flushing method may be feasible for Gaillard Cut, not for the area near Gatun Locks. An effective flushing requires the availability of a large quantity of fresh water throughout the year, which is however questionable at the Panama Canal. The efficiency of the flushing method is expected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

B2 Drain the salt tongue through a slit in the floor

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

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

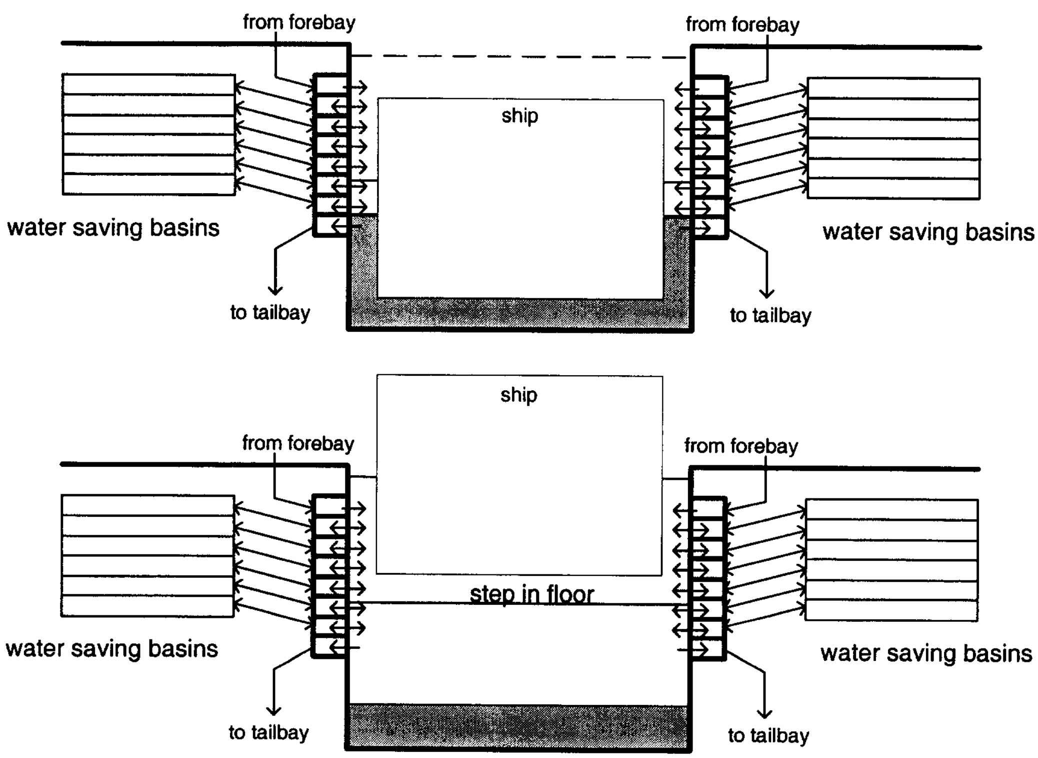
When a salt water pit is constructed at the upstream side of the locks the greater part of the salt water that intrudes the forebay can be caught and subsequently be discharged at low speed into the tailbay (expected upper limit of salt water intrusion reduction 60% - 90%). The pit should be sufficient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



Withdrawal of salt water from salt water pit with perforated floor

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

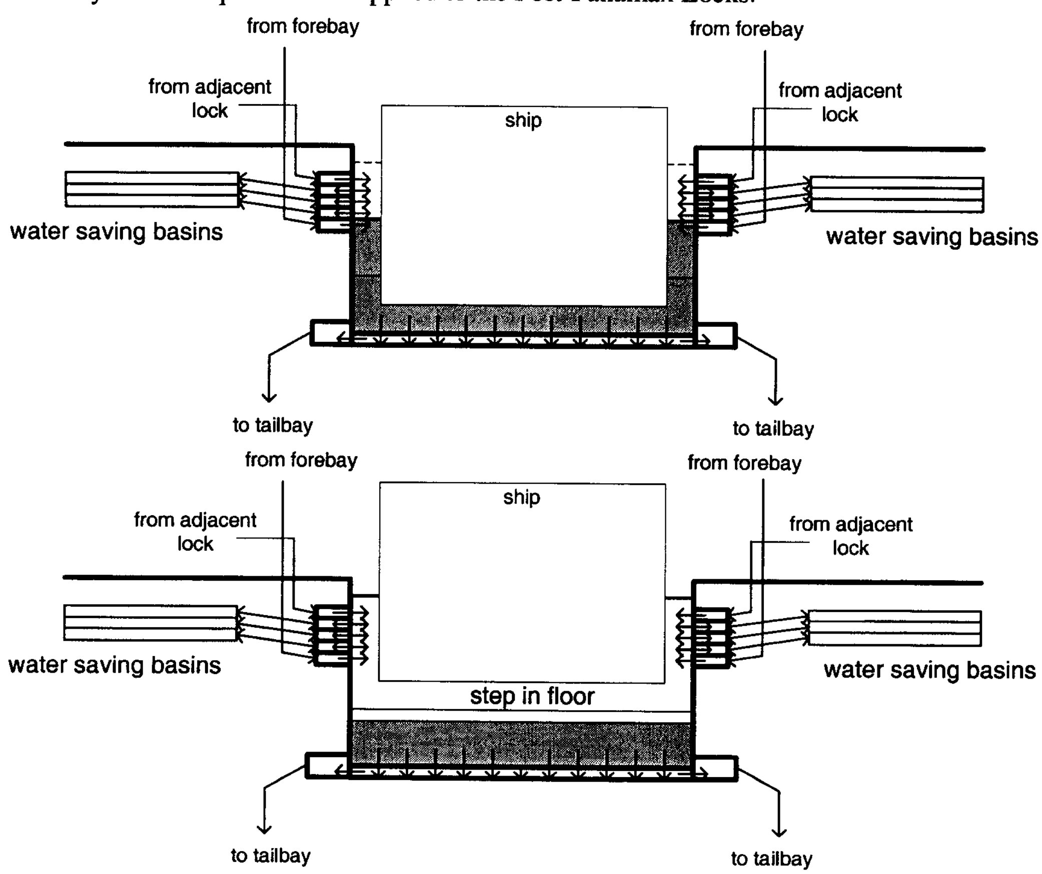
C1 Make use of the density difference between salt and fresh water and the step in the floor to prevent the migration of salt water from the lower lock chamber to higher levels
A considerable reduction of the salt water intrusion can be obtained with a system that is designed to keep the salt water in the lower lock chamber during lock operations (expected upper limit of salt water intrusion reduction 90%). The upward step in the floor at the upstream side of the lower lock chamber forms a crucial element of this system. In view of the required step height the system is best suited for a 1-lift lock configuration (with water saving basins; 1-lift locks without wsb's are not considered). Another crucial element of the system is the wall filling / emptying system with openings in both lock walls above the salt water layer in the lock chamber. By means of a careful filling and emptying, mixing of salt water and fresh water can for the greater part be prevented. In the case of a 1-lift lock configuration the salt water remains below the level of the step in the floor, which prevents an escape of salt water to the forebay, provided that the ship moves slowly without using too much it's engine. The system does not cause an additional water loss. Since lock filling and - emptying as well as ship manoeuvring have to be done very carefully, a delay of shipping is unevitable. However, the required total lockage time of the 1-lift locks may be smaller than with a normal 3-lift lock configuration or even a normal 2-lift lock configuration. In view of the large tidal range it may be necessary to install vertical lifting gates in the lower fill openings in the walls of the locks at the Pacific side. A thorough study into all relevant aspects of this system is required when applied to the Post-Panamax Locks.



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

C2 Partly remove the salt water from the lower lock chamber

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



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

3.3 Conclusions mitigation measures and recommendations

3.3.1 Conclusions

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

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

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

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

Promising, highly effective mitigation measures are:

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

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

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

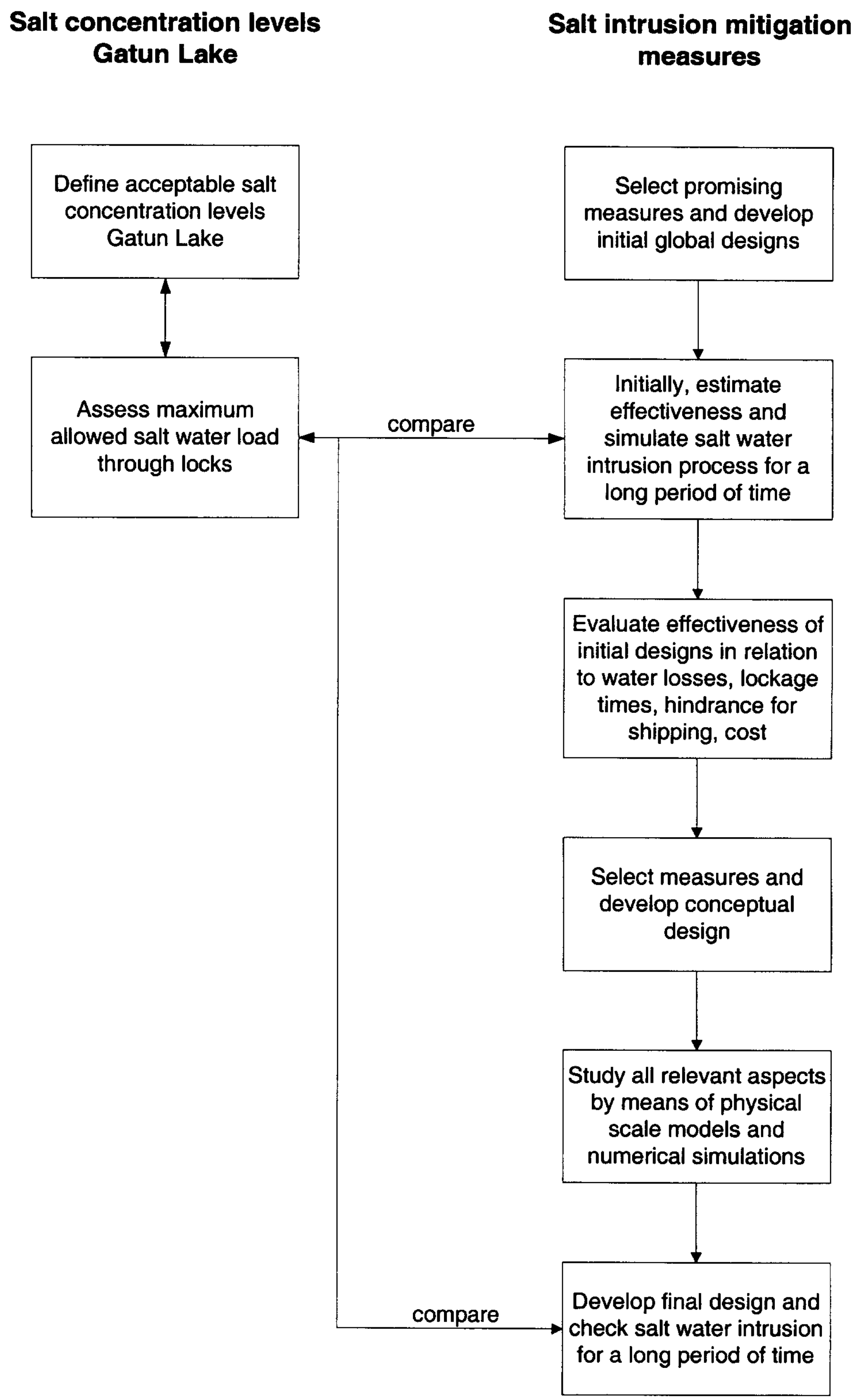
Pneumatic barriers (air bubble screens) are less effective but may be used together with other measures to improve the effectiveness.

3.3.2 Recommendations

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

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

The above activities are reflected in the next schedule:


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

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

Report E, part I

Effect of Water Recycling at the Pacific Side of the Panama Canal

Single-lift, two-lift and three-lift Post-Panamax Locks

Contents Part I

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1 Introduction

Autoridad del Canal de Panamá (ACP) has awarded WL | Delft Hydraulics the contract for 'Salt Water Intrusion Analysis of the Panama Canal Locks, Water Recycling System for Post-Panamax Locks' (contract No SAA-110830, dated 3 June 2003, with extension of February 2004).

The objective of this Consultancy is to provide services to the ACP on the subject of salt water intrusion through the locks of the Panama Canal. The services are focused on the future situation with Post-Panamax Locks in a third shipping lane and comprise:

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

The results of the study on water recycling are presented in the present Part I of Report E; Part II of Report E concerns the study on mitigation measures.

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

Three options for recycling of water are considered by ACP:

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

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

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

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

The following items are adressed in the present part I of Report E:

- review of water recycling system prepared by Consorcio Post-Panamax (CPP)
- extension of the salt-water intrusion simulation model with a water recycling system for Post-Panamax Locks at the Pacific side of the canal (for three configurations of Post-Panamax Locks: three-lift, two-lift and single-lift lock systems, with and without water saving basins)
- selection of salt exchange coefficients for use in the numerical simulations
- simulation of the salt water intrusion for the case that the water recycling system is in operation
- simulation of the salt water intrusion for the case that the water recycling system is in operation and assuming hydraulic conditions that were present in the period 1992 – 2001.

The studies on water recycling and mitigation measures have been executed in the period September 2003 – February 2004.

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

2 Design of water recycling system

2.1 Data provided by ACP

ACP is studying the possibilities for recycling of water that is lost by operation of the Post-Panamax Locks at the Pacific side of the canal. The Consorcio Post-Panamax (CPP) was asked to develop a preliminary design for the recycling system.
The next data with regards to the water recycling system has been provided by ACP:

Reports

Report of meeting R1 on 28 May 2003 (participants: ACP and CPP), including a hard copy of powerpoint presentation 'Recycling Methodology' of CPP

Anonymous
'Pump salt water to Gatun Lake'
Section 33 of report ACP, 2000

Anonymous
'Recycling ponds'
Section 34 of report ACP, 2000

Data of CPP

Documents describing the hydraulic conditions for water recycling simulations (3-lifts with wsb, 2-lifts with wsb, 2-lifts no wsb)

Speadsheets with results of water recycling simulations (2 chambers – 4 wsb, 2 chambers – no wsb, 3 chambers – 9 wsb, 3 chambers – no wsb, all simulations for 1, 5, 10 and 15 ships a day)

Final version of report 'Conceptual design to recycle water in Post-Panamax Locks, Hydraulic Part'
Report R-HY-001, October 03, 2003

Drawings of CPP

Autocad drawings:
D2-0-401-402 (implant and long section), implantation, profil_1, profil_2, profil_3, profil_4, profil_5, profil_6, profil_7

CW – 001 general layout
CW – 002 lower reservoir to upper reservoir pipes : longitudinal profile
CW – 003 reservoir to Gatun Lake pipes : longitudinal profile
CW – 004 Pacific Ocean to Gatun Lake pipes : longitudinal profile

CW – 005 2 step lock system filling culverts - longitudinal profile
CW – 006 2 step lock system emptying culverts - longitudinal profile
CW – 007 3 step lock system filling culverts - longitudinal profile
CW – 008 3 step lock system emptying culverts - longitudinal profile

Traffic projections

A document written by ACP concerning Post-Panamax traffic projections for the next 50 years (revision date 16 January 2003) .

2.2 Description of water recycling system at Pacific side

Three options for water recycling are considered by ACP:

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

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

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

The preliminary design of CPP for the recycling system is shown in Figure 2.1 (plan view) and Figure 2.2 (sketch of recycling option 3)
The lower storage pond is situated in the dredge spoil area, west of the proposed alignment of Post-Panamax Locks. The water level of the lower pond is always below the water level of the tailbay; this facilitates a free flow from the lower lock chamber to the lower pond.
The upper storage pond is situated in the lower reach of River Cocoli. A dam will be constructed in the river and a reservoir will so be formed. The water level of this reservoir (the upper storage pond) is controled by a spillway in the new dam; this water level is sufficiently high to facilitate a free-flow filling of the upper lock chamber.
The lower and upper storage ponds are connected to the filling and emptying system by means of a system of culverts, which are provided with control valves. The flow of water from lower lock to lower pond is controled in such a way that the water level of the lower lock equalizes with the water level of the tailbay. Similarly, the flow of water from upper pond to upper lock chamber is so controled that the water level of the upper lock chamber equalizes with the water level of the forebay.
The valves may - as an alternative – so be operated that the outflow of water from the lower lock chamber or inflow of water into the upper lock chamber stops before the water in the lock chamber has levelled with the water in tailbay or forebay; the remaining water-level difference is directly levelled. Obviously, this method reduces the recycling efficiency.
In the present study we assume that the first method is applied (full recycling). This assumption was also made by CPP: the capacity of the pumping station was so designed that the total pumping flow on a day balances with the total loss of water caused by lock operations on that day. The water recycling system is only active in dry periods, when the supply of fresh water to Gatun Lake is insufficient to keep the water level of the lake above the minimum level that is required for navigation.

The next data was taken by CPP as starting point for water recycling simulations for two-lift and 3-lift locks *(all levels refer to PLD)*:

- Gatun Lake: stationary water level +26.0 m.
- Canal Entrance at the Pacific side: mean sea level +0.30 m, mean high tide +2.40 m, mean low tide –2.32 m.
- Area of lower storage pond 240,000 m^2, area of upper storage pond 500,000 m^2.

CPP executed recycling simulations for 3-lift and 2-lift Post Panamax Locks with and without water saving basins (wsb's). The simulations showed that next continuous pumping flows (in m^3/s) are required:

no of ships per day	*3-lift locks*		*2-lift locks*		*1-lift locks*
	no wsb's (m^3/s)	*3 wsb's per lift (m^3/s)*	*no wsb's (m^3/s)*	*2 wsb's per lift (m^3/s)*	*6 wsb's per lift (m^3/s)*
1	4.7	2.1	4.9	2.5	2.5
5	19.0	7.5	24.3	12.5	12.5
10	34.5	13.8	49.1	24.8	24.8
15	50.1	20.0	73.8	36.3	36.3

Table 2.1 Water recycling system Pacific side: continuous pumping flow

Simulations were not done for 1-lift Post-Panamax Locks, but the water losses of 1-lift locks with 6 wsb's are equal to the losses of 2-lift locks with 2 wsb's per lift; the required pumping flow is thus equal to the pumping flow of the 2-lift lock configuration with 2 wsb's per lift.

2.3 Post-Panamax ship transits

ACP has set up ship transit predictions for points of time of 1 month, 1 year, 5 years, 10 years, 20 years and 50 years after the start of the exploitation of a third, new shipping lane, which is provided with Post-Panamax locks at both sides of the canal. The dimensions of the vessels and the daily traffic intensities can be characterised as follows:

Panamax-Plus vessels

These vessels have similar dimensions as Panamax vessels, but their draught is greater than 12 m (in tropical fresh water). Maximum dimensions: length 294 m, beam 32.3 m and draught 14 m.

Post-Panamax vessels

Maximum dimensions of Post-Panamax vessels are: length 386 m, beam 54 m and draught 15.2 m. Initially, the maximum allowed draught in the Panama Canal will be 14 m; after a period of five years, after deepening of the shipping channel, a maximum draught of 15.2 m will be admitted.

Traffic intensity

The daily traffic intensity (the total number of northbound and southbound ships) in the existing two lanes and the third new lane is assumed to develop as follows after opening of the new lane:

Vessel type	*Present situation*	*Month 1*	*Year 1*	*Year 5*	*Year 10*	*Year 20*	*Year 50*
Existing lanes							
Panamax	13	13	13	13	13	13	13
Regular	23	23	23	23	23	23	23
Total	**36**	**36**	**36**	**36**	**36**	**36**	**36**
New lane							
Post-Panamax*	0	0	1				
Post-Panamax*				2	3	5	10
Panamax-Plus	0	2	4	4	4	4	5
Total	**0**	**2**	**5**	**6**	**7**	**9**	**15**

*) Maximum draught of Post-Panamax vessels initially 14 m; from year 5 onwards 15.2 m

Table 2.2 Expected traffic intensities in existing and new shipping lanes

3 Simulation model

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

3.1 Concept of simulation model

Essentially, the model consists of a number of separate basins, each having a certain water level, water volume and salt concentration, which are mutually connected. 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 transport and salt transport are evaluated after each step of the uplockage or downlockage process.
Water from the lakes 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 a lock chamber is temporarily stored during levelling down, together with a part of the salt content of the lock chamber, and returned into the lock chamber during levelling 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; these are the causes that salt water moves from lower basins to higher basins.

The separate basins of the Panama Canal (lock chambers, water saving basins, forebays and tailbays of locks, lakes, sea entrances, storage ponds of recycling system) are regarded as nodes in the numerical simulation model.
Water levels of the lakes, which vary throughout the year, and fluctuating water levels (tidal movements) and salt concentrations in the seaside tailbays form input for the simulation model. The water level variation in the lakes is the result of inflow and outflow of water.

We assume that salt water intrusion in the lakes is only caused by the locking process. The salt intrusion is the net result of: (i) density currents which occur when the lock gates are open, (ii) exchange of water when the gates are open and vessels move in and out, and (iii) filling and emptying of lock chambers. All other water sources (Madden Lake (Chagres river), creeks and rivers, precipitation, ground water flow) supply fresh water to the lakes.
The outflow of saline water, if any, 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, evaporation) is nill or can be neglected in the analysis.

When water of the Post-Panamax Locks at the Pacific side of the canal is recycled (either with or without the help of storage ponds) an additional source of salt water is introduced.

Ship movements in the simulation model are from Pacific Ocean to Gatun Lake, from Gatun Lake to Atlantic Ocean, from Atlantic Ocean to Gatun Lake and from Gatun Lake to Pacific Ocean. Ships in the new, third shipping lane by-pass Miraflores Lake. When a ship moves up or down water levels, water depths, water volumes and salt concentrations change in the nodes of the simulation model. The value of these nodal parameters is evaluated after each step of the locking process for a single ship movement.

In the nodal-status evaluation is checked whether the maximum or minimum water level in lock chambers is exceeded. If so, the maximum or minimum water level is selected in the evaluation. Similarly, for the wsb's and storage ponds of the water recycling system is checked whether the maximum or minimum water storage volume is exceeded.

The subsequent steps of a ship movement are described in a scenario together with other data relevant to that ship movement, namely shipping lane, dimensions of ship, and duration of the ship movement. Special scenarios are: (i) the scenario that describes a 'turn around' (change from northbound ship transits to southbound ship transits or reverse), and (ii) the scenario that describes water releases at Gatun Dam and Miraflores Dam (water spilled and water used for hydropower generation and cooling). As a part of the present study water recycling options have been put in additional, tailored ship movement scenarios and turn around scenarios.

Scenarios are combined in a day pattern. The start time of each scenario is prescribed in the day pattern. When two scenarios start at the same moment, the simulation model treat them one by one. 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 (see scheme of Figure 3.2). A case contains information on start date and stop date of the simulation. Days are handled one by one; the simulation model runs the daypattern 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 user shall prepare a set of salt exchange coefficients (see Chapters 4 and 5) and define initial values (dimensions of locks etc., water levels, water volumes and salt concentrations). The set of exchange coefficients and the initial values form a part of the case.

At the start of each case nodal status parameters are initialized (see Section 3.15). Computed values of status parameters are written to a file at the end of each scenario (or as desired: day, week, month, 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 status parameters can be presented in tables or graphs as a function of time. The concept of the numerical model is reflected in Figure 3.1.

3.2 Water recycling system in simulation model

When water recycling options are active in the simulation model, recycling actions are executed each time that a ship passes the Post-Panamax Locks at the Pacific side of the canal. The quantity of water that is recycled is equal to the quantity of water that would be spilled into the tailbay when no recycling system was active. Also the water quantity that is lost as a result of a turn around operation is recycled at the moment that the turn around operation is executed. In this way the total quantity of recycled water balances with the total loss of water caused by all lock operations, similar as in the CPP design of the recycling system.

Each of three configurations of Post-Panamax Locks in the simulation model has been extended with a water recycling system at the Pacific side of the canal. The extension of the 3-lift lock system is shown in Figure 3.3. Three recycling options have been modelled:

1. direct recycling of water from the tailbay to the forebay in Gaillard Cut
2. recycling of water from a lower storage pond (LP) to the forebay in Gaillard Cut
3. recycling of water from a lower storage pond (LP) to an upper storage pond (UP)

The extensions of the 2-lift lock system and 1-lift lock system are shown in Figure 3.4 and Figure 3.5 respectively. Only one recycling option has been modelled: recycling of water from lower storage pond (LP) to upper storage pond (UP).
The nodes and the hydraulic connections between the nodes are shown in the schemes of Figures 3.3, 3.4 and 3.5 for 3-lift locks, 2-lift locks and 1-lift locks respectively. In the present study we name the locks as indicated in these figures.

Figures 3.6a and 3.6b present a picture of the transfer of water between the various basins when water is recycled in the simulation model (Figure 3.6a: direct recycling between tailbay and forebay, Figure 3.6b: indirect recycling between lower storage pond and upper storage pond). In Chapter 4 this will be discussed into some greater detail.

3.3 Nodal status parameters

The parameters that describe the status of nodes in the simulation model are defined in this section. All input data of the simulation model is in SI units.

3.3.1 Status parameters general

water level: h (in m to PLD)
water depth: d (in m)
water volume: V (in m^3)
salt concentration: c (in ppt = parts per thousand; c is averaged value for considered water volume in node)
The temparature T is not considered as a separate status parameter in the simulation model.

3.3.2 Other parameters general

spillway discharge: Q (in m^3 per day)
other water use: P (in m^3 per day)

ship volume: S (in m^3; water displacement of a ship)
length of lock or basin: l (in m)
width of lock or basin: b (in m)
area of lock or basin: A (in m^2; area of gate recesses, if any, is included)
maximum water level: maxh (in m to PLD)
minimum water level: minh (in m to PLD)
max. water volume: maxV (in m^3)
min. water volume: minV (in m^3)
floor level or sill level: f (in m to PLD)
time: t (date, hour)

3.3.3 Status parameters of tailbays in Pacific and Atlantic Entrance

water level: $h_{tailbay}$ (is prescribed; input: function (t))
salt concentration: $c_{tailbay}$ (is prescribed; input: table)

3.3.4 Status parameters and other parameters of Miraflores Lake and Gatun Lake

water level: h_{lake} (is prescribed; input: table)
water volume lake: V_{lake} (is function of water level h_{lake}; input: table)
salt concentration lake: c_{lake} (is computed)
spillway discharge: Q_{spill} (is prescribed; input: table)
water for hydro power: P_{hydro} (is prescribed; input: table)
cooling water: $P_{cooling}$ (is prescribed; input: table)

3.3.5 Status parameters and other parameters of tailbays and forebays in Miraflores Lake and Gatun Lake

sill level: f_{sill} (input: table)
area tailbay: $A_{tailbay}$ (input: table)
area forebay: $A_{forebay}$ (input: table)
water level tailbay: $h_{tailbay}$ (is equal to h_{lake})
water level forebay: $h_{forebay}$ (is equal to h_{lake})
water volume tailbay: $V_{tailbay}$ (is computed)
water volume forebay: $V_{forebay}$ (is computed)
concentration tailbay: $c_{tailbay}$ (is computed)
concentration forebay: $c_{forebay}$ (is computed)

3.3.6 Status parameters and other parameters of existing locks and new locks

water level: h_{lock} (is computed)
water depth: d_{lock} (is computed)
water volume: V_{lock} (is computed)
salt concentration: c_{lock} (is computed)
max. water level: $maxh_{lock}$ (input: table)
min. water level: $minh_{lock}$ (input: table)

length: l_{lock} (nominal chamber length; input: table)
width: b_{lock} (width of chamber; input: table)
lock area: A_{lock} (= l_{lock} . b_{lock})
floor level: f_{lock} (input: table)
ship volume: S (is prescribed in scenario)

3.3.7 Status parameters and other parameters of new water saving basins

water volume: V_{wsb} (is computed)
salt concentration: c_{wsb} (is computed)
max. water volume: $maxV_{wsb}$ (input: table)
min. water volume: $minV_{wsb}$ (input: table)

3.3.8 Status parameters and other parameters of storage ponds of water recycling system

water volume: V_{pond} (is computed)
salt concentration: c_{pond} (is computed)
max. water volume: $maxV_{pond}$ (input: table)
min. water volume: $minV_{pond}$ (input: table)

3.4 Function of forebays and tailbays in simulation model

A forebay (or tailbay) functions as a temporarily buffer for salt water between locks and lakes in the simulation model. Without a forebay (or tailbay) the salt water from the locks would in the simulation model instantaneously be distributed over the full lake volume, which is not required. A time-dependent function regulates the inflow / outflow of salt water from forebay (or tailbay) 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.
The forebay (or tailbay) is in open connection with the lake; consequently, the water volume of the forebay (or tailbay) varies with the water level of the lake. Because of the open connection the water volume of the forebay (or tailbay) is not effected in the simulation model by the passage of a ship or withdrawal (or spillage) of water in the water-levelling 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, and water that is spilled into the tailbay is immediately compensated by a flow from tailbay towards the lake.
The ship moves from lock to lake and causes a flow from forebay (or tailbay) to lock and subsequently from lake to forebay (or tailbay). 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 tailbay at the seaside of the locks does not form a real node in the numerical model. The salt concentration $c_{tailbay}$ in the seaside tailbay of Miraflores Locks and Gatun Locks is input for the model.

3.5 Ship movements and turn arounds

Ship movements in the simulation model are from Pacific Ocean to Gatun Lake, from Gatun Lake to Atlantic Ocean, from Atlantic Ocean to Gatun Lake and from Gatun Lake to Pacific Ocean. Each ship movement consists of a sequence of steps, which are described in a scenario together with other data relevant to that ship movement. Ship movements from Pacific Ocean to Gatun Lake and from Atlantic Ocean to Gatun Lake (or reverse) may start at the same time; the simulation model treat them one by one. Uplockage from ocean to Gatun Lake and downlockage from Gatun Lake to the ocean in the same lane and starting at the same time is not allowed. The user must insert a 'turn around' scenario between an uplockage and a downlockage scenario (this is not required for single-lift locks). For a further description of scenarios reference is made to Report A (existing situation), Report B (single-lift Post-Panamax Locks), Report C (three-lift Post-Panamax Locks), and Report D (two-lift Post-Panamax Locks).

Water recycling in the simulation model is a separate step in a ship movement or a turn around scenario. In the present study additional scenarios have been developed which contain a water recycling step. For periods when water recycling is required, the user shall select these scenarios instead of the normal scenarios.
This section presents an overview of the additional ship movement and turn around scenarios. Reference is made to Sections 3.6 – 3.10 for a further description of the separate steps in the additional scenarios.

3.5.1 Three-lift locks: additional scenarios for water recycling

The simulation model for the three-lift lock configuration of Post-Panamax Locks has three options for water recycling at the Pacific side of the canal (Figure 3.3). Twelve additional ship movement scenarios have been developed, each containing a water recycling step. Table 3.1 presents an overview of these ship movements scenarios. The shipping locks can be operated with or without water saving basins.

no	*ship movement*	*lane*	*up- or downlockage*	*remarks*
1	Pacific Ocean to Gatun Lake	new lane	uplockage	no wsb's, direct recycling from tailbay to forebay
2	Gatun Lake to Pacific Ocean	new lane	downlockage	no wsb's, direct recycling from tailbay to forebay
3	Pacific Ocean to Gatun Lake	new lane	uplockage	wsb's, direct recycling from tailbay to forebay
4	Gatun Lake to Pacific Ocean	new lane	downlockage	wsb's, direct recycling from tailbay to forebay
5	Pacific Ocean to Gatun Lake	new lane	uplockage	no wsb's, recycling from lower pond to forebay
6	Gatun Lake to Pacific Ocean	new lane	downlockage	no wsb's, recycling from lower pond to forebay
7	Pacific Ocean to Gatun Lake	new lane	uplockage	wsb's, recycling from lower pond to forebay
8	Gatun Lake to Pacific Ocean	new lane	downlockage	wsb's, recycling from lower pond to forebay
9	Pacific Ocean to Gatun Lake	new lane	uplockage	no wsb's, recycling from lower pond to upper pond
10	Gatun Lake to Pacific Ocean	new lane	downlockage	no wsb's, recycling from lower pond to upper pond
11	Pacific Ocean to Gatun Lake	new lane	uplockage	wsb's, recycling from lower pond to upper pond
12	Gatun Lake to Pacific Ocean	new lane	downlockage	wsb's, recycling from lower pond to upper pond

Table 3.1 Additional ship movement scenarios for new lane with three-lift locks (with and without water saving basins) and recycling systems

A turn around scenario describes the operational steps that are required to adapt the water levels in the lock chambers for a change in ship transit direction. In the case of water recycling a separate recycling step has to be performed. Eight additional turn around scenarios have been developed, which facilitate water recycling during turn around operations (see Table 3.2). The shipping locks can be operated with or without water saving basins.

no	*side of canal*	*turn around*	*lane*	*remarks*
1	Pacific side	change from northbound to southbound traffic	new lane	no wsb's, direct recycling from tailbay to forebay
2	Pacific side	change from northbound to southbound traffic	new lane	wsb's, direct recycling from tailbay to forebay
3	Pacific side	change from northbound to southbound traffic	new lane	no wsb's, recycling from lower pond to forebay
4	Pacific side	change from northbound to southbound traffic	new lane	wsb's, recycling from lower pond to forebay
5	Pacific side	change from northbound to southbound traffic	new lane	no wsb's, recycling from lower pond to upper pond
6	Pacific side	change from southbound to northbound traffic	new lane	no wsb's, recycling from lower pond to upper pond
7	Pacific side	change from northbound to southbound traffic	new lane	wsb's, recycling from lower pond to upper pond
8	Pacific side	change from southbound to northbound traffic	new lane	wsb's, recycling from lower pond to upper pond

Table 3.2 Additional turn around scenarios for new lane with two-lift locks (with and without water saving basins) and recycling systems

3.5.2 Two-lift locks: additional scenarios for water recycling

The simulation model for the two-lift lock configuration of Post-Panamax Locks has only one option for water recycling at the Pacific side of the canal (Figure 3.4). Four additional ship movement scenarios have been developed, each containing a water recycling step. Table 3.3 presents an overview of these ship movements scenarios. The shipping locks can be operated with or without water saving basins.

no	*ship movement*	*lane*	*up- or downlockage*	*remarks*
1	Pacific Ocean to Gatun Lake	new lane	uplockage	no wsb's, recycling from lower pond to upper pond
2	Gatun Lake to Pacific Ocean	new lane	downlockage	no wsb's, recycling from lower pond to upper pond
3	Pacific Ocean to Gatun Lake	new lane	uplockage	wsb's, recycling from lower pond to upper pond
4	Gatun Lake to Pacific Ocean	new lane	downlockage	wsb's, recycling from lower pond to upper pond

Table 3.3 Additional ship movement scenarios for new lane with two-lift locks (with and without water saving basins) and recycling system

Four additional turn around scenarios have been developed, each containing a water recycling step (see Table 3.4). The shipping locks can be operated with or without wsb's.

no	*side of canal*	*turn around*	*lane*	*remarks*
1	Pacific side	change from northbound to southbound traffic	new lane	no wsb's, recycling from lower pond to upper pond
2	Pacific side	change from southbound to northbound traffic	new lane	no wsb's, recycling from lower pond to upper pond
3	Pacific side	change from northbound to southbound traffic	new lane	wsb's, recycling from lower pond to upper pond
4	Pacific side	change from southbound to northbound traffic	new lane	wsb's, recycling from lower pond to upper pond

Table 3.4 Additional turn around scenarios for new lane with two-lift locks (with and without water saving basins) and recycling system

3.5.3 Single-lift locks: additional scenarios for water recycling

The simulation model for the single-lift lock configuration of Post-Panamax Locks has only one option for water recycling at the Pacific side of the canal (Figure 3.5), similar as for the two-lift locks. Four additional ship movement scenarios have been developed, each containing a water recycling step. Table 3.5 presents an overview of these ship movements scenarios. The shipping locks can be operated with or without water saving basins.

no	*ship movement*	*lane*	*up- or downlockage*	*remarks*
1	Pacific Ocean to Gatun Lake	new lane	uplockage	no wsb's, recycling from lower pond to upper pond
2	Gatun Lake to Pacific Ocean	new lane	downlockage	no wsb's, recycling from lower pond to upper pond
3	Pacific Ocean to Gatun Lake	new lane	uplockage	wsb's, recycling from lower pond to upper pond
4	Gatun Lake to Pacific Ocean	new lane	downlockage	wsb's, recycling from lower pond to upper pond

Table 3.5 Additional ship movement scenarios for new lane with single-lift locks (with and without water saving basins) and recycling system

The single-lift locks do not require turn around operations.

3.6 Three-lift locks: steps in ship movement scenarios with water recycling

Three options for water recycling are available in the simulation model for the three-lift Post-Panamax Locks at the Pacific side of the canal (see Figure 3.3):

1. direct recycling of water from the tailbay to the forebay in Gaillard Cut
2. recycling of water from a lower storage pond (LP), which is connected to the lower lock, to the forebay in Gaillard Cut
3. recycling of water from a lower storage pond (LP), which is connected to the lower lock, to an upper storage pond (UP), which is connected to the upper lock

These three options can be combined with ship movement scenarios and turn around scenarios. Next sections present an overview of the subsequent steps of the ship movement scenarios with water recycling. A distinction is made between locks *without* water saving basins and locks *with* water saving basins (wsb's).

3.6.1 Three-lift locks without wsb's

I Direct water recycling

Next table shows the subsequent steps (recycle step in bold) in the uplockage scenario 'ship movement Pacific Ocean → Gatun Lake':

Low basin	*High basin*	*Operation (Remarks)*
Tailbay Lock G	Lock G	Equalize water levels
Tailbay Lock G	Lock G	Move ship
Lock G	Lock H	Equalize water levels
Lock G	Lock H	Move ship
Lock H	Lock J	Equalize water levels
Lock H	Lock J	Move ship
Lock J	Forebay Lock J	Equalize water levels
Lock J	Forebay Lock J	Move ship
Tailbay Lock G	**Forebay Lock J**	**Recycle water**
Forebay Lock J	Gatun Lake	(Density flows)

Table 3.6 Uplockage. Pacific Ocean → Gatun Lake. New lane, three-lift locks without wsb. Direct water recycling.

The subsequent steps in the downlockage scenario 'ship movement Gatun Lake → Pacific Ocean' are shown in next table:

High basin	*Low basin*	*Operation (Remarks)*
Gatun Lake	Forebay Lock J	(Density flows)
Forebay Lock J	Lock J	Equalize water levels
Forebay Lock J	Lock J	Move ship
Lock J	Lock H	Equalize water levels
Lock J	Lock H	Move ship
Lock H	Lock G	Equalize water levels
Lock H	Lock G	Move ship
Lock G	Tailbay Lock G	Equalize water levels
Lock G	Tailbay Lock G	Move ship
Forebay Lock J	**Tailbay Lock G**	**Recycle water**

Table 3.7 Downlockage. Gatun Lake → Paciific Ocean. New lane, three-lift locks without wsb. Direct water recycling.

2 Recycling of water from lower pond (LP) to forebay

Subsequent steps in uplockage scenario 'ship movement Gatun Lake → Pacific Ocean':

Low basin	*High basin*	*Operation (Remarks)*
Lower Pond	Lock G	Equalize water levels
Tailbay Lock G	Lock G	Move ship
Lock G	Lock H	Equalize water levels
Lock G	Lock H	Move ship
Lock H	Lock J	Equalize water levels
Lock H	Lock J	Move ship
Lock J	Forebay Lock J	Equalize water levels
Lock J	Forebay Lock J	Move ship
Lower Pond	**Forebay Lock J**	**Recycle water**
Forebay Lock J	Gatun Lake	(Density flows)

Table 3.8 Uplockage. Pacific Ocean → Gatun Lake. New lane, three-lift locks without wsb. Recycling of water from LP to forebay.

Subsequent steps in downlockage scenario 'ship movement Gatun Lake → Pacific Ocean':

High basin	*Low basin*	*Operation (Remarks)*
Gatun Lake	Forebay Lock J	(Density flows)
Forebay Lock J	Lock J	Equalize water levels
Forebay Lock J	Lock J	Move ship
Lock J	Lock H	Equalize water levels
Lock J	Lock H	Move ship
Lock H	Lock G	Equalize water levels
Lock H	Lock G	Move ship
Lock G	Lower Pond	Equalize water levels
Lock G	Tailbay Lock G	Move ship
Forebay Lock J	**Lower Pond**	**Recycle water**

Table 3.9 Downlockage. Gatun Lake → Paciific Ocean. New lane, three-lift locks without wsb. Recycling of water from LP to forebay.

3 Recycling of water from lower pond (LP) to upper pond (UP)

Subsequent steps in uplockage scenario 'ship movement Gatun Lake → Pacific Ocean':

Low basin	*High basin*	*Operation (Remarks)*
Lower Pond	Lock G	Equalize water levels
Tailbay Lock G	Lock G	Move ship
Lock G	Lock H	Equalize water levels
Lock G	Lock H	Move ship
Lock H	Lock J	Equalize water levels
Lock H	Lock J	Move ship
Lock J	Upper Pond	Equalize water levels
Lock J	Forebay Lock J	Move ship
Lower Pond	**Upper Pond**	**Recycle water**
Forebay Lock J	Gatun Lake	(Density flows)

Table 3.10 Uplockage. Pacific Ocean → Gatun Lake. New lane, three-lift locks without wsb. Recycling of water from LP to UP.

Subsequent steps in downlockage scenario 'ship movement Gatun Lake → Pacific Ocean':

High basin	*Low basin*	*Operation (Remarks)*
Gatun Lake	Forebay Lock J	(Density flows)
Upper Pond	Lock J	Equalize water levels
Forebay Lock J	Lock J	Move ship
Lock J	Lock H	Equalize water levels
Lock J	Lock H	Move ship
Lock H	Lock G	Equalize water levels
Lock H	Lock G	Move ship
Lock G	Lower Pond	Equalize water levels
Lock G	Tailbay Lock G	Move ship
Upper Pond	**Lower Pond**	**Recycle water**

Table 3.11 Downlockage. Gatun Lake → Paciific Ocean. New lane, three-lift locks without wsb. Recycling of water from LP to UP.

3.6.2 Three-lift locks with wsb's

Next tables show the subsequent steps in uplockage and downlockage scenarios:

I Direct water recycling

Low basin	*High basin*	*Operation (Remarks)*
Tailbay Lock G	Lock G	Fill wsb's of lock G
Tailbay Lock G	Lock G	Equalize water levels
Tailbay Lock G	Lock G	Move ship
Lock G	Lock H	Empty wsb's of lock G
Lock G	Lock H	Fill wsb's of lock H
Lock G	Lock H	Equalize water levels
Lock G	Lock H	Move ship
Lock H	Lock J	Empty wsb's of lock H
Lock H	Lock J	Fill wsb's of lock J
Lock H	Lock J	Equalize water levels
Lock H	Lock J	Move ship
Lock J	Forebay Lock J	Empty wsb's of lock J
Lock J	Forebay Lock J	Equalize water levels
Lock J	Forebay Lock J	Move ship
Tailbay Lock G	**Forebay Lock J**	**Recycle water**
Forebay Lock J	Gatun Lake	(Density flows)

Table 3.12 Uplockage. Pacific Ocean → Gatun Lake. New lane, three-lift locks with wsb. Direct water recycling.

High basin	*Low basin*	*Operation (Remarks)*
Gatun Lake	Forebay Lock J	(Density flows)
Forebay Lock J	Lock J	Empty wsb's of lock J
Forebay Lock J	Lock J	Equalize water levels
Forebay Lock J	Lock J	Move ship
Lock J	Lock H	Fill wsb's of lock J
Lock J	Lock H	Empty wsb's of lock H
Lock J	Lock H	Equalize water levels
Lock J	Lock H	Move ship
Lock H	Lock G	Fill wsb's of lock H
Lock H	Lock G	Empty wsb's of lock G
Lock H	Lock G	Equalize water levels
Lock H	Lock G	Move ship
Lock G	Tailbay Lock G	Fill wsb's of lock G
Lock G	Tailbay Lock G	Equalize water levels
Lock G	Tailbay Lock G	Move ship
Forebay Lock J	**Tailbay Lock G**	**Recycle water**

Table 3.13 Downlockage. Gatun Lake → Pacific Ocean. New lane, three-lift locks with wsb. Direct water recycling.

2 Recycling of water from lower pond (LP) to forebay

Low basin	*High basin*	*Operation (Remarks)*
Tailbay Lock G	Lock G	Fill wsb's of lock G
Lower Pond	Lock G	Equalize water levels
Tailbay Lock G	Lock G	Move ship
Lock G	Lock H	Empty wsb's of lock G
Lock G	Lock H	Fill wsb's of lock H
Lock G	Lock H	Equalize water levels
Lock G	Lock H	Move ship
Lock H	Lock J	Empty wsb's of lock H
Lock H	Lock J	Fill wsb's of lock J
Lock H	Lock J	Equalize water levels
Lock H	Lock J	Move ship
Lock J	Forebay Lock J	Empty wsb's of lock J
Lock J	Forebay Lock J	Equalize water levels
Lock J	Forebay Lock J	Move ship
Lower Pond	**Forebay Lock J**	**Recycle water**
Forebay Lock J	Gatun Lake	(Density flows)

Table 3.14 Uplockage. Pacific Ocean → Gatun Lake. New lane, three-lift locks with wsb. Recycling of water from LP to forebay.

High basin	*Low basin*	*Operation (Remarks)*
Gatun Lake	Forebay Lock J	(Density flows)
Forebay Lock J	Lock J	Empty wsb's of lock J
Forebay Lock J	Lock J	Equalize water levels
Forebay Lock J	Lock J	Move ship
Lock J	Lock H	Fill wsb's of lock J
Lock J	Lock H	Empty wsb's of lock H
Lock J	Lock H	Equalize water levels
Lock J	Lock H	Move ship
Lock H	Lock G	Fill wsb's of lock H
Lock H	Lock G	Empty wsb's of lock G
Lock H	Lock G	Equalize water levels
Lock H	Lock G	Move ship
Lock G	Tailbay Lock G	Fill wsb's of lock G
Lock G	Lower Pond	Equalize water levels
Lock G	Tailbay Lock G	Move ship
Forebay Lock J	**Lower Pond**	**Recycle water**

Table 3.15 Downlockage. Gatun Lake → Pacific Ocean. New lane, three-lift locks with wsb. Recycling of water from LP to forebay.

3 Recycling of water from lower pond (LP) to upper pond (UP)

Low basin	*High basin*	*Operation (Remarks)*
Tailbay Lock G	Lock G	Fill wsb's of lock G
Lower Pond	Lock G	Equalize water levels
Tailbay Lock G	Lock G	Move ship
Lock G	Lock H	Empty wsb's of lock G
Lock G	Lock H	Fill wsb's of lock H
Lock G	Lock H	Equalize water levels
Lock G	Lock H	Move ship
Lock H	Lock J	Empty wsb's of lock H
Lock H	Lock J	Fill wsb's of lock J
Lock H	Lock J	Equalize water levels
Lock H	Lock J	Move ship
Lock J	Forebay Lock J	Empty wsb's of lock J
Lock J	Upper Pond	Equalize water levels
Lock J	Forebay Lock J	Move ship
Lower Pond	**Upper Pond**	**Recycle water**
Forebay Lock J	Gatun Lake	(Density flows)

Table 3.16 Uplockage. Pacific Ocean → Gatun Lake. New lane, three-lift locks with wsb. Recycling of water from LP to UP.

High basin	*Low basin*	*Operation (Remarks)*
Gatun Lake	Forebay Lock J	(Density flows)
Forebay Lock J	Lock J	Empty wsb's of lock J
Upper Pond	Lock J	Equalize water levels
Forebay Lock J	Lock J	Move ship
Lock J	Lock H	Fill wsb's of lock J
Lock J	Lock H	Empty wsb's of lock H
Lock J	Lock H	Equalize water levels
Lock J	Lock H	Move ship
Lock H	Lock G	Fill wsb's of lock H
Lock H	Lock G	Empty wsb's of lock G
Lock H	Lock G	Equalize water levels
Lock H	Lock G	Move ship
Lock G	Tailbay Lock G	Fill wsb's of lock G
Lock G	Lower Pond	Equalize water levels
Lock G	Tailbay Lock G	Move ship
Upper Pond	**Lower Pond**	**Recycle water**

Table 3.17 Downlockage. Gatun Lake → Pacific Ocean. New lane, three-lift locks with wsb. Recycling of water from LP to UP.

3.7 Two-lift locks: steps in ship movement scenarios with water recycling

One option for water recycling is available in the simulation model for the two-lift Post-Panamax Locks at the Pacific side of the canal (see Figure 3.4):

1. recycling of water from a lower storage pond (LP), which is connected to the lower lock, to an upper storage pond (UP), which is connected to the upper lock

This option is put into additional ship movement scenarios. Next sections present an overview of the subsequent steps of the ship movement scenarios with water recycling. A distinction is made between locks *without* water saving basins and locks *with* water saving basins (wsb's).

3.7.1 Two-lift locks without wsb's

Recycling of water from lower pond (LP) to upper pond (UP)

Low basin	*High basin*	*Operation (Remarks)*
Lower Pond	Lock P	Equalize water levels
Tailbay Lock P	Lock P	Move ship
Lock P	Lock Q	Equalize water levels
Lock P	Lock Q	Move ship
Lock Q	Upper Pond	Equalize water levels
Lock Q	Forebay Lock Q	Move ship
Lower Pond	**Upper Pond**	**Recycle water**
Forebay Lock Q	Gatun Lake	(Density flows)

Table 3.18 Uplockage. Pacific Ocean → Gatun Lake. New lane, two-lift locks without wsb. Recycling of water from LP to UP.

High basin	*Low basin*	*Operation (Remarks)*
Gatun Lake	Forebay Lock Q	(Density flows)
Upper Pond	Lock Q	Equalize water levels
Forebay Lock Q	Lock Q	Move ship
Lock Q	Lock P	Equalize water levels
Lock Q	Lock P	Move ship
Lock P	Lower Pond	Equalize water levels
Lock P	Tailbay Lock P	Move ship
Upper Pond	**Lower Pond**	**Recycle water**

Table 3.19 Downlockage. Gatun Lake → Paciific Ocean. New lane, two-lift locks without wsb. Recycling of water from LP to UP.

3.7.2 Two-lift locks with wsb's

Recycling of water from lower pond (LP) to upper pond (UP)

Low basin	*High basin*	*Operation (Remarks)*
Tailbay Lock P	Lock P	Fill wsb's of lock P
Lower Pond	Lock P	Equalize water levels
Tailbay Lock P	Lock P	Move ship
Lock P	Lock Q	Empty wsb's of lock P
Lock P	Lock Q	Fill wsb's of lock Q
Lock P	Lock Q	Equalize water levels
Lock P	Lock Q	Move ship
Lock Q	Forebay Lock Q	Empty wsb's of lock Q
Lock Q	Upper Pond	Equalize water levels)
Lock Q	Forebay Lock Q	Move ship
Lower Pond	**Upper Pond**	**Recycle water**
Forebay Lock Q	Gatun Lake	(Density flows)

Table 3.20 Uplockage. Pacific Ocean → Gatun Lake. New lane, two-lift locks with wsb. Recycling of water from LP to UP.

High basin	*Low basin*	*Operation (Remarks)*
Gatun Lake	Forebay Lock Q	(Density flows)
Forebay Lock Q	Lock Q	Empty wsb's of lock Q
Upper Pond	Lock Q	Equalize water levels
Forebay Lock Q	Lock Q	Move ship
Lock Q	Lock P	Fill wsb's of lock Q
Lock Q	Lock P	Empty wsb's of lock P
Lock Q	Lock P	Equalize water levels
Lock Q	Lock P	Move ship
Lock P	Tailbay Lock P	Fill wsb's of lock P
Lock P	Lower Pond	Equalize water levels
Lock P	Tailbay Lock P	Move ship
Upper Pond	**Lower Pond**	**Recycle water**

Table 3.21 Downlockage. Gatun Lake → Pacific Ocean. New lane, two-lift locks with wsb. Recycling of water from LP to UP.

3.8 Single-lift locks: steps in ship movement scenarios with water recycling

One option for water recycling is available in the simulation model for the single-lift Post-Panamax Locks at the Pacific side of the canal (see Figure 3.5):

1. recycling of water from a lower storage pond (LP), which is connected to the lower lock, to an upper storage pond (UP), which is connected to the upper lock

This option is put into additional ship movement scenarios. Next sections present an overview of the subsequent steps of the ship movement scenarios with water recycling. A distinction is made between locks *without* water saving basins and locks *with* water saving basins (wsb's). The subsequent steps in uplockage and downlockage scenarios are shown in next tables:

3.8.1 Single-lift locks without wsb's

Recycling of water from lower pond (LP) to upper pond (UP)

Low basin	*High basin*	*Operation (Remarks)*
Lower Pond	Lock N	Equalize water levels
Tailbay Lock N	Lock N	Move ship
Lock N	Upper Pond	Equalize water levels
Lock N	Forebay Lock N	Move ship
Lower Pond	**Upper Pond**	**Recycle water**
Forebay Lock N	Gatun Lake	(Density flows)

Table 3.22 Uplockage. Pacific Ocean → Gatun Lake. New lane, single-lift locks without wsb. Recycling of water from LP to UP.

High basin	*Low basin*	*Operation (Remarks)*
Gatun Lake	Forebay Lock N	(Density flows)
Upper Pond	Lock N	Equalize water levels
Forebay Lock N	Lock N	Move ship
Lock N	Lower Pond	Equalize water levels
Lock N	Tailbay Lock N	Move ship
Upper Pond	**Lower Pond**	**Recycle water**

Table 3.23 Downlockage. Gatun Lake → Paciific Ocean. New lane, single-lift locks without wsb. Recycling of water from LP to UP.

3.8.2 Single-lift locks with wsb's

Recycling of water from lower pond (LP) to upper pond (UP)

Low basin	*High basin*	*Operation (Remarks)*
Tailbay Lock N	Lock N	Fill wsb's of lock N
Lower Pond	Lock N	Equalize water levels
Tailbay Lock N	Lock N	Move ship
Lock N	Forebay Lock N	Empty wsb's of lock N
Lock N	Upper Pond	Equalize water levels
Lock N	Forebay Lock N	Move ship
Lower Pond	**Upper Pond**	**Recycle water**
Forebay Lock N	Gatun Lake	(Density flows)

Table 3.24 Uplockage. Pacific Ocean → Gatun Lake. New lane, single-lift locks with wsb. Recycling of water from LP to UP.

High basin	*Low basin*	*Operation (Remarks)*
Gatun Lake	Forebay Lock N	(Density flows)
Forebay Lock N	Lock N	Empty wsb's of lock N
Upper Pond	Lock N	Equalize water levels
Forebay Lock N	Lock N	Move ship
Lock N	Tailbay Lock N	Fill wsb's of lock N
Lock N	Lower Pond	Equalize water levels
Lock N	Tailbay Lock N	Move ship
Upper Pond	**Lower Pond**	**Recycle water**

Table 3.25 Downlockage. Gatun Lake → Pacific Ocean. New lane, single-lift locks with wsb. Recycling of water from LP to UP.

3.9 Three-lift locks: steps in turn around scenarios with water recycling

Turn around scenarios contain the subsequent steps which are required to prepare the locks for a change in ship transit direction. Three options for water recycling are available in the simulation model. Next sections present an overview of the subsequent steps of the turn around scenarios with water recycling. A distinction is made between locks *without* water saving basins and locks *with* water saving basins (wsb's).

3.9.1 Three-lift locks without wsb's

I Direct water recycling

Turn around scenario: 'Pacific side, change from northbound (uplockage) to southbound (downlockage)'. After the last northbound vessel has passed the locks (uplockage) the water levels in lock chambers G, H and J are high. The water levels in lock chambers G and H have to be lowered. Two recycle steps (in bold) are required:

Low basin	*High basin*	*Operation*
Tailbay Lock G	Lock G	Equalize water levels
Tailbay Lock G	**Forebay Lock J**	**Recycle water**
Lock G	Lock H	Equalize water levels
Tailbay Lock G	Lock G	Equalize water levels
Tailbay Lock G	**Forebay Lock J**	**Recycle water**
Forebay Lock J	Gatun Lake	(Density flows)

Table 3.26 Turn around Pacific side. Change from northbound (uplockage) to southbound (downlockage). New lane, three-lift locks without wsb. Direct recycling.

Turn around scenario: 'Pacific side, change from southbound (downlockage) to northbound (uplockage)'. After passage of the last southbound ship (downlockage) the water levels in lock chambers G, H and J are low. The water levels in lock chambers H and J have to be raised. These lock operations do not cause water losses to the tailbay; for that reason recycling of water is not required.

2 Recycling of water from lower pond (LP) to forebay

Turn around scenario: 'Pacific side, change from northbound (uplockage) to southbound (downlockage)'.

Low basin	*High basin*	*Operation*
Lower Pond	Lock G	Equalize water levels
Lower Pond	**Forebay Lock J**	**Recycle water**
Lock G	Lock H	Equalize water levels
Lower Pond	Lock G	Equalize water levels
Lower Pond	**Forebay Lock J**	**Recycle water**
Forebay Lock J	Gatun Lake	(Density flows)

Table 3.27 Turn around Pacific side. Change from northbound (uplockage) to southbound (downlockage). New lane, three-lift locks without wsb. Recycling of water from LP to forebay.

Turn around scenario: 'Pacific side, change from southbound (downlockage) to northbound (uplockage)'. No water losses to the tailbay; for that reason water recycling is not required.

3 Recycling of water from lower pond (LP) to upper pond (UP)

Turn around scenario: 'Pacific side, change from northbound (uplockage) to southbound (downlockage)'.

Low basin	*High basin*	*Operation*
Lower Pond	Lock G	Equalize water levels
Lower Pond	**Upper Pond**	**Recycle water**
Lock G	Lock H	Equalize water levels
Lower Pond	Lock G	Equalize water levels
Lower Pond	**Upper Pond**	**Recycle water**
Forebay Lock J	Gatun Lake	(Density flows)

Table 3.28 Turn around Pacific side. Change from northbound (uplockage) to southbound (downlockage). New lane, three-lift locks without wsb. Recycling of water from LP to UP.

Turn around scenario: 'Pacific side, change from southbound (downlockage) to northbound (uplockage)'. No water losses to the tailbay, but water withdrawal from UP to upper chamber requires an additional turn around scenario:

High basin	*Low basin*	*Operation*
Upper Pond	Lock J	Equalize water levels
Lock J	Lock H	Equalize water levels
Upper Pond	Lock J	Equalize water levels
Gatun Lake	Forebay Lock J	(Density flows)

Table 3.29 Turn around Pacific side. Change from southbound (downlockage) to northbound (uplockage). New lane, three-lift locks without wsb. Recycling of water from LP to UP.

3.9.2 Three-lift locks with wsb's

I Direct water recycling

Turn around scenario: 'Pacific side, change from northbound (uplockage) to southbound (downlockage)'. After the last northbound vessel has passed the locks (uplockage) the water levels in lock chambers G, H and J are high and the corresponding wsb's are empty. The water levels in lock chambers G and H have to be lowered and the wsb's filled. Two recycle steps (in bold) are required:

Low basin	*High basin*	*Operation*
Tailbay Lock G	Lock G	Fill wsb's of lock G
Tailbay Lock G	Lock G	Equalize water levels
Tailbay Lock G	**Forebay Lock J**	**Recycle water**
Lock G	Lock H	Empty wsb's of lock G
Lock G	Lock H	Fill wsb's of lock H
Lock G	Lock H	Equalize water levels
Tailbay Lock G	Lock G	Fill wsb's of lock G
Tailbay Lock G	Lock G	Equalize water levels
Tailbay Lock G	**Forebay Lock J**	**Recycle water**
Forebay Lock J	Gatun Lake	(Density flows)

Table 3.30 Turn around Pacific side. Change from northbound (uplockage) to southbound (downlockage). New lane, three-lift locks with wsb. Direct water recycling.

Turn around scenario: 'Pacific side, change from southbound (downlockage) to northbound (uplockage)'. After passage of the last southbound ship (downlockage) the water levels in lock chambers G, H and J are low and the corresponding wsb's are filled. The water levels in lock chambers H and J have to be raised and the wsb's emptied. These lock operations do not cause water losses to the tailbay; for that reason water recycling is not required.

2 Recycling of water from lower pond (LP) to forebay

Turn around scenario: 'Pacific side, change from northbound (uplockage) to southbound (downlockage)'.

Low basin	*High basin*	*Operation*
Tailbay Lock G	Lock G	Fill wsb's of lock G
Lower Pond	Lock G	Equalize water levels
Lower Pond	**Forebay Lock J**	**Recycle water**
Lock G	Lock H	Empty wsb's of lock G
Lock G	Lock H	Fill wsb's of lock H
Lock G	Lock H	Equalize water levels
Tailbay Lock G	Lock G	Fill wsb's of lock G
Lower Pond	Lock G	Equalize water levels
Lower Pond	**Forebay Lock J**	**Recycle water**
Forebay Lock J	Gatun Lake	(Density flows)

Table 3.31 Turn around Pacific side. Change from northbound (uplockage) to southbound (downlockage). New lane, three-lift locks with wsb. Recycling of water from LP to forebay.

Turn around scenario: 'Pacific side, change from southbound (downlockage) to northbound (uplockage)'. No water losses to the tailbay; for that reason water recycling is not required.

3 Recycling of water from lower pond (LP) to upper pond (UP)

Turn around scenario: 'Pacific side, change from northbound (uplockage) to southbound (downlockage)'.

Low basin	*High basin*	*Operation*
Tailbay Lock G	Lock G	Fill wsb's of lock G
Lower Pond	Lock G	Equalize water levels
Lower Pond	**Upper Pond**	**Recycle water**
Lock G	Lock H	Empty wsb's of lock G
Lock G	Lock H	Fill wsb's of lock H
Lock G	Lock H	Equalize water levels
Tailbay Lock G	Lock G	Fill wsb's of lock G
Lower Pond	Lock G	Equalize water levels
Lower Pond	**Upper Pond**	**Recycle water**
Forebay Lock J	Gatun Lake	(Density flows)

Table 3.32 Turn around Pacific side. Change from northbound (uplockage) to southbound (downlockage). New lane, three-lift locks with wsb. Recycling of water from LP to UP.

Turn around scenario: 'Pacific side, change from southbound (downlockage) to northbound (uplockage)'. No water losses to the tailbay, but water withdrawal from UP to upper chamber requires an additional turn around scenario:

High basin	*Low basin*	*Operation*
Forebay Lock J	Lock J	Empty wsb's of lock J
Upper Pond	Lock J	Equalize water levels
Lock J	Lock H	Fill wsb's of lock J
Lock J	Lock H	Empty wsb's of lock H
Lock J	Lock H	Equalize water levels
Forebay Lock J	Lock J	Empty wsb's of lock J
Upper Pond	Lock J	Equalize water levels
Gatun Lake	Forebay Lock J	(Density flows)

Table 3.33 Turn around Pacific side. Change from southbound (downlockage) to northbound (uplockage). New lane, three-lift locks with wsb. Recycling of water from LP to UP.

3.10 Two-lift locks: steps in turn around scenarios with water recycling

One option for water recycling is available in the simulation model. Next sections present an overview of the subsequent steps of the turn around scenarios with water recycling.

3.10.1 Two-lift locks without wsb's

Recycling of water from lower pond (LP) to upper pond (UP)

Turn around scenario 'Pacific side, change from northbound (uplockage) to southbound (downlockage)' After the last northbound vessel has passed the locks (uplockage) the water levels in lock chambers P and Q are high. The water level in lock chamber P has to be lowered. One recycle step (in bold) is required:

Low basin	*High basin*	*Operation*
Lower Pond	Lock P	Equalize water levels
Lower Pond	**Upper Pond**	**Recycle water**
Forebay Lock J	Gatun Lake	(Density flows)

Table 3.34 Turn around Pacific side. Change from northbound (uplockage) to southbound (downlockage). New lane, two-lift locks without wsb. Recycling of water from LP to UP.

Turn around scenario 'Pacific side, change from southbound (downlockage) to northbound (uplockage)'. After passage of the last southbound ship (downlockage) the water levels in lock chambers P and Q are low. The water level in lock chamber Q has to be raised. These lock operations do not cause water losses to the tailbay, but water withdrawal from UP to upper chamber requires an additional turn around scenario:

High basin	*Low basin*	*Operation*
Upper Pond	Lock Q	Equalize water levels
Gatun Lake	Forebay Lock Q	(Density flows)

Table 3.35 **Turn around Pacific side. Change from southbound (downlockage) to northbound (uplockage). New lane, two-lift locks without wsb. Recycling of water from LP to UP.**

3.10.2 Two-lift locks with wsb's

Recycling of water from lower pond (LP) to upper pond (UP)

Turn around scenario 'Pacific side, change from northbound (uplockage) to southbound (downlockage)'. After the last northbound vessel has passed the locks (uplockage) the water levels in lock chambers P and Q are high and the corresponding wsb's are empty. The water level in lock chamber P has to be lowered and the wsb filled. One recycle step (in bold) is required:

Low basin	*High basin*	*Operation*
Tailbay Lock P	Lock P	Fill wsb's of lock P
Lower Pond	Lock P	Equalize water levels
Lower Pond	**Upper Pond**	**Recycle water**
Forebay Lock J	Gatun Lake	(Density flows)

Table 3.36 **Turn around Pacific side. Change from northbound (uplockage) to southbound (downlockage). New lane, two-lift locks with wsb. Recycling of water from LP to UP.**

Turn around scenario 'Pacific side, change from southbound (downlockage) to northbound (uplockage)'. After passage of the last southbound ship (downlockage) the water levels in lock chambers P and Q are low and the corresponding wsb's are filled. The water level in lock chamber Q has to be raised and the wsb emptied These lock operations do not cause water losses to the tailbay, but water withdrawal from UP to upper chamber requires an additional turn around scenario:

High basin	*Low basin*	*Operation*
Forebay Lock Q	Lock Q	Empty wsb's of lock Q
Upper Pond	Lock Q	Equalize water levels
Gatun Lake	Forebay Lock Q	(Density flows)

Table 3.37 **Turn around Pacific side. Change from southbound (downlockage) to northbound (uplockage). New lane, two-lift locks with wsb. Recycling of water from LP to UP.**

3.11 Available vessel types in simulation model

Various types of vessels pass the Panama Canal. The ship dimensions are of importance for the salt water intrusion. Both the quantity of water that is displaced when the ship moves from basin to basin (e.g. from lock to lock) and the density flows between basins depend on the ship dimensions. Exchange coefficients which are applied in step II of the lockage process (movement of ship between two adjacent basins), are defined in the simulation model as a function of the ratio S/V_{ref} (S = water displacement of ship, V_{ref} = reference volume); in this way the effect of ship dimensions on density flows is included.

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 3.38 Types of vessels in simulation model (existing lanes)

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

The vessels which use the new shipping lane, are represented by three additional vessel classes (see Table 3.39). Vessel class IV represents the Panamax-Plus vessels, class VII the Post-Panamax vessels with limited draught (only applicable in first four years after opening of the new lane in view of limited depth of shipping channel), and class VIII the Post-Panamax vessels. Ship classes V and VI are extra classes which allow for a more detailed specification of the ship traffic in the new lane. The development of the daily transit frequency of these vessels over a period of 50 years after opening of the new lane is shown in Table 2.2.

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 3.39 Post-Panamax types of vessels in simulation model (new lane)

3.12 Dimensions of locks, wsb's, forebays / tailbays, storage ponds

The dimensions of locks, wsb's and forebays in the new shipping lane are prescribed in the simulation model through a table 'Initial values'. The dimensions which are selected for use in the simulation model are presented in Report B (single-lift Post-Panamax Locks), Report C (three-lift Post-Panamax Locks) and Report D (two-lift Post-Panamax Locks). The selected dimensions of locks and forebays / tailbays in the existing lanes are presented in Report A.

The dimensions of lower storage pond (LP) and upper storage pond (UP) of the water recycling system are selected starting from the assumption that the capacity of the storage pond equals three times the quantity of water that - on the average - is spilled to the tailbay during uplockage or downlockage of a single ship. Normal high water level of the lower pond is selected as PLD-2.4 m (pond 2/3 full), normal low water level of the upper pond is selected as PLD+26.0 m (pond 1/3 full).

Selected dimensions of LP and UP of 3-lift Post-Panamax Locks

basin	*nominal length (m)*	*width (m)*	*bottom level (m to PLD)*	*normal high water level (m to PLD)*	*normal low water level (m to PLD)*
Lower Pond	1000	250	-4.8	-2.4	-3.6
Upper Pond	2000	250	+25.4	+26.6	+26.0

Table 3.40 Dimensions of upper and lower pond of 3-lift locks

In the simulations we put for lower pond (LP):

V_{LP} = $A_{LP} \cdot d_{LP} = l_{LP} \cdot b_{LP} \cdot d_{LP}$
l_{LP} = 1000 m
b_{LP} = 250 m
$maxV_{LP}$ = maximum water volume of lower pond =900.000 m^3
$minV_{LP}$ = minimum water volume of lower pond = 50.000 m^3

and for upper pond (UP):

V_{UP} = $A_{UP} \cdot d_{UP} = l_{UP} \cdot b_{UP} \cdot d_{UP}$
l_{UP} = 2000 m
b_{UP} = 250 m
$maxV_{UP}$ = maximum water volume of upper pond =900.000 m^3
$minV_{UP}$ = minimum water volume of upper pond = 50.000 m^3

Selected dimensions of LP and UP of 2-lift Post-Panamax Locks

basin	*nominal length* *(m)*	*width* *(m)*	*bottom level* *(m to PLD)*	*normal high water level* *(m to PLD)*	*normal low water level* *(m to PLD)*
Lower Pond	1000	250	-6.0	-2.4	-4.2
Upper Pond	2000	250	+25.1	+26.9	+26.0

Table 3.41 Dimensions of upper and lower pond of 2-lift locks

In the simulations we put for lower pond (LP):

V_{LP} = $A_{LP} . d_{LP} = l_{LP} . b_{LP} . d_{LP}$
l_{LP} = 1000 m
b_{LP} = 250 m
$maxV_{LP}$ = maximum water volume of lower pond = 1.350.000 m^3
$minV_{LP}$ = minimum water volume of lower pond = 75.000 m^3

and for upper pond (UP):

V_{UP} = $A_{UP} . d_{UP} = l_{UP} . b_{UP} . d_{UP}$
l_{UP} = 2000 m
b_{UP} = 250 m
$maxV_{UP}$ = maximum water volume of upper pond = 1.350.000 m^3
$minV_{UP}$ = minimum water volume of upper pond = 75.000 m^3

Selected dimensions of LP and UP of 1-lift Post-Panamax Locks

basin	*nominal length* *(m)*	*width* *(m)*	*bottom level* *(m to PLD)*	*normal high water level* *(m to PLD)*	*normal low water level* *(m to PLD)*
Lower Pond	1000	250	-9.6	-2.4	-6.0
Upper Pond	2000	250	+24.2	+27.8	+26.0

Table 3.42 Dimensions of upper and lower pond of 1-lift locks

In the simulations we put for lower pond (LP):

V_{LP} = $A_{LP} . d_{LP} = l_{LP} . b_{LP} . d_{LP}$
l_{LP} = 1000 m
b_{LP} = 250 m
$maxV_{LP}$ = maximum water volume of lower pond = 2.700.000 m^3
$minV_{LP}$ = minimum water volume of lower pond = 150.000 m^3

and for upper pond (UP):

V_{UP} = $A_{UP} . d_{UP} = l_{UP} . b_{UP} . d_{UP}$

l_{UP} = 2000 m
b_{UP} = 250 m
$maxV_{UP}$ = maximum water volume of upper pond = 2.700.000 m^3
$minV_{UP}$ = minimum water volume of upper pond = 150.000 m^3

3.13 Miraflores Lake and Gatun Lake

3.13.1 Water levels and water volumes

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, evapo-transpiration, industrial water use, cooling water, ground water flow and spillage of water through 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.
A constant water level of PLD+16.58 m (+54.4 ft) is used in the simulation model. The corresponding water volume amounts to 23.80 x 10^6 m^3 (840.65 x 10^6 ft^3).

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 (water is spilled through Gatun Spillway when a water level of about PLD+26.7 m (+87.5 ft) is exceeded). During the last decade the mean water level of Gatun Lake was about PLD+26.1 m (+85.6 ft); the corresponding water volume amounts to 5.25 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, see Table 3.43, have been used in the validation of the simulation model (existing situation, see Report A); they were regarded as typical values representing the water level variation of Gatun Lake throughout the year.

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 3.43 Gatun Lake: representative water levels and corresponding water volumes

The constant water level of Miraflores Lake and the fluctuating water level of Gatun Lake (Table 3.43) are maintained in simulations for the future situation with Post-Panamax Locks; they are shown in Figure 3.6.

3.13.2 Water releases and water recycling

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 for cooling.

Miraflores Lake

The daily spilled water quantities of Miraflores Lake and the water quantities used for cooling at Miraflores are shown in Table 3.44. 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)*	*Total (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 3.44 Miraflores Lake: daily spilled / used water quantities in 2001

The values in Table 3.44 are not used 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 total released water quantity over the year 2001 using the distribution of averaged monthly values 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). Than 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, 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 3.45; these values are regarded as representative values and are used in the simulation model (see also Figure 3.7). Since the new shipping lane does not effect the water level of Miraflores Lake the water release quantities are as well valid for the future situation.

Month	Spilled water (10^6 m^3 per day)	Cooling water (10^6 m^3 per day)	Total (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

Table 3.45 Miraflores Lake: representative quantities of daily spilled water and water used for cooling

Gatun Lake

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, see Table 3.46, have been used in the validation of the simulation model (existing situation, see Report A); they were regarded as typical, representative values.

Month	Spilled water (10^6 m^3 per day)	Hydropower (10^6 m^3 per day)	Total (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

Table 3.46 Gatun Lake: representative values of daily spilled water quantities and water quantities used for hydropower

Since the Post-Panamax Locks on the new shipping lane cause extra water losses, the 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 water level of Gatun Lake. As an alternative the water that is lossed by lock operations in the new lane at the Pacific side of the canal may be recycled; this option is only considered for dry periods when there is a shortage of fresh water.

Scenarios for the control of the water level of Gatun Lake

An overview of scenarios for the control of the water level of Gatun Lake is presented in Table 3.47. These scenarios may be applied after the new shipping lane with Post-Panamax Locks has come in operation; the scenarios in **bold** are applied in the present recycling study, the scenarios in *italic* have been applied in earlier salt-water intrusion simulations (see Reports B, C and D).

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

Table 3.47 Gatun Lake: different scenarios for control of the water level of Gatun Lake

In the *baseline scenario* (scenario 1) all water losses from Gatun Lake caused by operation of the new Post-Panamax Locks (the new locks are provided with wsb's), are compensated

by a supply of fresh water from new water sources. Scenario 2 is like scenario 1, but in scenario 2 the Post-Panamax Locks have no wsb's.
In scenario 3 (locks with wsb's) and scenario 4 (locks without wsb's) the extra water losses caused by operation of the new locks are partly or fully compensated by a lesser water release at Gatun Dam; the remaining portion, if any, is supplied to Gatun Lake from new water sources.
In scenarios 5, 7 and 9 (locks with wsb's) and 6, 8 and 10 (locks without wsb's) the extra water losses caused by the new locks are compensated by a lesser water release at Gatun Dam; if insufficient, in dry periods, the water lost by operation of the new locks at the Pacific side is recycled; in the case that this is still insufficient the remaining portion is supplied to Gatun Lake from new water sources.

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

The extra water losses caused by the new locks are growing when the Post-Panamax traffic intensity increases. Table 3.48 presents the extra water losses of the new locks 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. In that case each transiting ship causes a water loss of (25.7 m / n) * l_{lock} * 61 m * 2 * (1-s), where n = number of lifts, and s = water saving rate of wsb's each lift. The chamber length l_{lock} is inclusive the area of the gate recesses. The losses are reduced with a factor 2 when water is recycled at the Pacific side of the canal. 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).

Post-Panamax Lock configuration	*Representative chamber length (m)*	*Number of wsb's each lift and water saving rate each 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)*
3-lift locks / rolling gates	505	3 – 60%	0.53	0.21
2-lift locks / miter gates	515	2 – 50%	0.81	0.40
1-lift locks / rolling gates	540	6 – 75%	1.69	0.42

Table 3.48 Extra water losses caused by a single ship transfer in third, new lane with Post-Panamax Locks

The effects of water recycling on the salt concentration levels of Gatun Lake and Miraflores Lake will be studied for ship traffic intensities of 1, 5, 10 and 15 ship transfers a day in the new shipping lane. The present traffic intensities in the existing two shipping lanes (36 ship

transfers a day for both lanes) will be maintained in the salt intrusion simulations. The results of the simulations will mutually be compared.
A traffic intensity of 15 ship transfers a day in the new shipping lane is expected for year 50 after opening of the new lane (see Table 2.2). The mutual comparison of results for different scenarios for the control of the water level of Gatun Lake will be done for year 50.

Figure 3.11 presents the mean quantities of water which are daily released at Gatun Dam (spillway and power station) and the mean extra water quantities a day which have to be supplied to Gatun Lake from fresh water sources; the water quantities are shown for all water level control scenarios of Gatun Lake (see Table 3.47). Figure 3.11 is valid for year 50 after opening of the new shipping lane and represents a ship traffic intensity of 15 ship transfers (Post-Panamax type) a day in the new lane; the values for the 3-lift lock configuration of Post-Panamax Locks are shown. Figures 3.12 and 3.13 present the same quantities for the 2-lift locks and 1-lift locks respectively.
From Figures 3.11 – 3.13 it appears that extra fresh water supplies are still required when water is recycled at the Pacific side of the canal.

The mean daily quantity of recycled water in year 50 is shown in Figure 3.15 for 3-lift, 2-lift and 1-lift lock configurations (ship traffic intensity 15 Post-Panamax ships a day); the corresponding number of recycling days a month is shown in Figure 3.14. Notice that scenario 5 gives almost similar results for 2-lift locks with 2 wsb's per lift and 1-lift locks with 6 wsb's.

Tables 3.49 – 3.52 (valid for three-lift Post-Panamax Locks) present the mean quantities of water that are released each day of a month at Gatun Dam, recycled at the Pacific side of the canal, and supplied from fresh water sources to Gatun Lake for ship traffic intensities of 15, 10, 5 and 1 Post-Panamax ships a day and various water control scenarios. Also the number of days in a month that recycling is required is shown. When this number of days is smaller than the total number of days in the considered month, *the real daily recycle quantity is greater than the mean daily recycle quantity shown in the table* (this latter quantity is obtained by averaging the total quantity of recycled water in the considered month over the full number of days in that month). The quantities shown in the tables are considered as representative quantities valid for a long period of time. For reasons of comparison the water release quantities of the baseline scenario (scenario 1, see Table 3.47) is taken up in the tables. Notice that the water release quantities of scenario 2 are equal to those of scenario 1. Similarly, water release quantities of scenario 3 are equal to those of scenarios 5, 7 and 9, while water release quantities of scenario 4 are equal to those of scenarios 6, 8 and 10.

Released water quantities, recycled water quantities and supplied water quantities have also been computed for 2-lift Post-Panamax Locks and 1-lift Post-Panamax Locks. The results are presented in Tables 3.53 – 3.60.

	Scenario 1 baseline	*Scenarios 5, 7 and 9 locks with wsb's*				*Scenarios 6, 8 and 10 locks without wsb's*			
	released	*released*	*recycled*	*supplied*	*number of rec. days*	*released*	*recycled*	*supplied*	*number of rec. days*
January	4.61	1.44	0.00	0.00	0.00	0.00	3.31	0.00	25.90
February	0.60	0.00	1.58	0.98	28.00	0.00	3.96	3.36	28.00
March	0.20	0.00	1.58	1.38	31.00	0.00	3.96	3.76	31.00
April	0.16	0.00	1.58	1.42	30.00	0.00	3.96	3.80	30.00
May	0.94	0.00	1.58	0.64	31.00	0.00	3.96	3.02	31.00
June	3.63	0.46	0.00	0.00	0.00	0.00	3.96	0.33	30.00
July	5.55	2.39	0.00	0.00	0.00	0.00	2.37	0.00	18.52
August	6.58	3.41	0.00	0.00	0.00	0.00	1.34	0.00	10.49
September	8.32	5.15	0.00	0.00	0.00	0.40	0.00	0.00	0.00
October	8.23	5.06	0.00	0.00	0.00	0.31	0.00	0.00	0.00
November	11.59	8.43	0.00	0.00	0.00	3.67	0.00	0.00	0.00
December	12.64	9.47	0.00	0.00	0.00	4.72	0.00	0.00	0.00

Table 3.49 Gatun Lake: mean daily released, recycled and supplied water quantities in 10^6 m^3/day and number of recycling days; 15 ships a day, 3-lift Post-Panamax Locks.

	Scenario 1 baseline	*Scenarios 5, 7 and 9 locks with wsb's*				*Scenarios 6, 8 and 10 locks without wsb's*			
	released	*released*	*recycled*	*supplied*	*number of rec. days*	*released*	*recycled*	*supplied*	*number of rec. days*
January	4.61	2.50	0.00	0.00	0.00	0.00	0.67	0.00	7.85
February	0.60	0.00	1.06	0.45	28.00	0.00	2.64	2.04	28.00
March	0.20	0.00	1.06	0.86	31.00	0.00	2.64	2.44	31.00
April	0.16	0.00	1.06	0.89	30.00	0.00	2.64	2.48	30.00
May	0.94	0.00	1.06	0.12	31.00	0.00	2.64	1.70	31.00
June	3.63	1.52	0.00	0.00	0.00	0.00	1.65	0.00	18.77
July	5.55	3.44	0.00	0.00	0.00	0.27	0.00	0.00	0.00
August	6.58	4.47	0.00	0.00	0.00	1.30	0.00	0.00	0.00
September	8.32	6.21	0.00	0.00	0.00	3.04	0.00	0.00	0.00
October	8.23	6.12	0.00	0.00	0.00	2.95	0.00	0.00	0.00
November	11.59	9.48	0.00	0.00	0.00	6.31	0.00	0.00	0.00
December	12.64	10.52	0.00	0.00	0.00	7.36	0.00	0.00	0.00

Table 3.50 Gatun Lake: mean daily released, recycled and supplied water quantities in 10^6 m^3/day and number of recycling days; 10 ships a day, 3-lift Post-Panamax Locks.

	Scenario 1 baseline	*Scenarios 5, 7 and 9 locks with wsb's*				*Scenarios 6, 8 and 10 locks without wsb's*			
	released	*released*	*recycled*	*supplied*	*number of rec. days*	*released*	*recycled*	*supplied*	*number of rec. days*
January	4.61	3.56	0.00	0.00	0.00	1.97	0.00	0.00	0.00
February	0.60	0.00	0.45	0.00	24.09	0.00	1.32	0.72	28.00
March	0.20	0.00	0.53	0.33	31.00	0.00	1.32	1.12	31.00
April	0.16	0.00	0.53	0.36	30.00	0.00	1.32	1.16	30.00
May	0.94	0.00	0.12	0.00	6.81	0.00	1.32	0.38	31.00
June	3.63	2.57	0.00	0.00	0.00	0.99	0.00	0.00	0.00
July	5.55	4.50	0.00	0.00	0.00	2.91	0.00	0.00	0.00
August	6.58	5.52	0.00	0.00	0.00	3.94	0.00	0.00	0.00
September	8.32	7.26	0.00	0.00	0.00	5.68	0.00	0.00	0.00
October	8.23	7.17	0.00	0.00	0.00	5.59	0.00	0.00	0.00
November	11.59	10.54	0.00	0.00	0.00	8.95	0.00	0.00	0.00
December	12.64	11.58	0.00	0.00	0.00	10.00	0.00	0.00	0.00

Table 3.51 Gatun Lake: mean daily released, recycled and supplied water quantities in 10^6 m^3/day and number of recycling days; 5 ships a day, 3-lift Post-Panamax Locks.

	Scenario 1 baseline	*Scenarios 5, 7 and 9 locks with wsb's*				*Scenarios 6, 8 and 10 locks without wsb's*			
	released	*released*	*recycled*	*supplied*	*number of rec. days*	*released*	*recycled*	*supplied*	*number of rec. days*
January	4.61	4.40	0.00	0.00	0.00	4.08	0.00	0.00	0.00
February	0.60	0.39	0.00	0.00	0.00	0.07	0.00	0.00	0.00
March	0.20	0.00	0.01	0.00	3.49	0.00	0.26	0.06	31.00
April	0.16	0.00	0.05	0.00	13.30	0.00	0.26	0.10	30.00
May	0.94	0.73	0.00	0.00	0.00	0.41	0.00	0.00	0.00
June	3.63	3.42	0.00	0.00	0.00	3.10	0.00	0.00	0.00
July	5.55	5.34	0.00	0.00	0.00	5.03	0.00	0.00	0.00
August	6.58	6.37	0.00	0.00	0.00	6.05	0.00	0.00	0.00
September	8.32	8.11	0.00	0.00	0.00	7.79	0.00	0.00	0.00
October	8.23	8.02	0.00	0.00	0.00	7.70	0.00	0.00	0.00
November	11.59	11.38	0.00	0.00	0.00	11.07	0.00	0.00	0.00
December	12.64	12.43	0.00	0.00	0.00	12.11	0.00	0.00	0.00

Table 3.52 Gatun Lake: mean daily released, recycled and supplied water quantities in 10^6 m^3/day and number of recycling days; 1 ship a day, 3-lift Post-Panamax Locks.

	Scenario 1 baseline	*Scenario 5 locks with wsb's*				*Scenario6 locks without wsb's*			
	released	*released*	*recycled*	*supplied*	*number of rec. days*	*released*	*recycled*	*supplied*	*number of rec. days*
January	4.61	0.00	1.44	0.00	14.77	0.00	6.05	1.44	31.00
February	0.60	0.00	3.03	2.42	28.00	0.00	6.05	5.45	28.00
March	0.20	0.00	3.03	2.83	31.00	0.00	6.05	5.85	31.00
April	0.16	0.00	3.03	2.86	30.00	0.00	6.05	5.89	30.00
May	0.94	0.00	3.03	2.09	31.00	0.00	6.05	5.11	31.00
June	3.63	0.00	2.42	0.00	24.03	0.00	6.05	2.42	30.00
July	5.55	0.00	0.50	0.00	5.10	0.00	6.05	0.50	31.00
August	6.58	0.53	0.00	0.00	0.00	0.00	5.53	0.00	28.30
September	8.32	2.27	0.00	0.00	0.00	0.00	3.79	0.00	18.77
October	8.23	2.18	0.00	0.00	0.00	0.00	3.87	0.00	19.85
November	11.59	5.54	0.00	0.00	0.00	0.00	0.51	0.00	2.53
December	12.64	6.58	0.00	0.00	0.00	0.53	0.00	0.00	0.00

Table 3.53 Gatun Lake: mean daily released, recycled and supplied water quantities in 10^6 m^3/day and number of recycling days; 15 ships a day, 2-lift Post-Panamax Locks.

	Scenario 1 baseline	*Scenario 5 locks with wsb's*				*Scenario6 locks without wsb's*			
	released	*released*	*recycled*	*supplied*	*number of rec. days*	*released*	*recycled*	*supplied*	*number of rec. days*
January	4.61	0.58	0.00	0.00	0.00	0.00	3.46	0.00	26.57
February	0.60	0.00	2.02	1.42	28.00	0.00	4.04	3.43	28.00
March	0.20	0.00	2.02	1.82	31.00	0.00	4.04	3.84	31.00
April	0.16	0.00	2.02	1.85	30.00	0.00	4.04	3.87	30.00
May	0.94	0.00	2.02	1.08	31.00	0.00	4.04	3.10	31.00
June	3.63	0.00	0.41	0.00	6.05	0.00	4.04	0.41	30.00
July	5.55	1.52	0.00	0.00	0.00	0.00	2.52	0.00	19.32
August	6.58	2.54	0.00	0.00	0.00	0.00	1.49	0.00	11.45
September	8.32	4.28	0.00	0.00	0.00	0.25	0.00	0.00	0.00
October	8.23	4.20	0.00	0.00	0.00	0.16	0.00	0.00	0.00
November	11.59	7.56	0.00	0.00	0.00	3.52	0.00	0.00	0.00
December	12.64	8.60	0.00	0.00	0.00	4.57	0.00	0.00	0.00

Table 3.54 Gatun Lake: mean daily released, recycled and supplied water quantities in 10^6 m^3/day and number of recycling days; 10 ships a day, 2-lift Post-Panamax Locks.

	Scenario 1 baseline	*Scenario 5 locks with wsb's*				*Scenario6 locks without wsb's*			
	released	*released*	*recycled*	*supplied*	*number of rec. days*	*released*	*recycled*	*supplied*	*number of rec. days*
January	4.61	2.59	0.00	0.00	0.00	0.58	0.00	0.00	0.00
February	0.60	0.00	1.01	0.41	28.00	0.00	2.02	1.42	28.00
March	0.20	0.00	1.01	0.81	31.00	0.00	2.02	1.82	31.00
April	0.16	0.00	1.01	0.84	30.00	0.00	2.02	1.85	30.00
May	0.94	0.00	1.01	0.07	31.00	0.00	2.02	1.08	31.00
June	3.63	1.61	0.00	0.00	0.00	0.00	0.41	0.00	6.05
July	5.55	3.54	0.00	0.00	0.00	1.52	0.00	0.00	0.00
August	6.58	4.56	0.00	0.00	0.00	2.54	0.00	0.00	0.00
September	8.32	6.30	0.00	0.00	0.00	4.28	0.00	0.00	0.00
October	8.23	6.21	0.00	0.00	0.00	4.20	0.00	0.00	0.00
November	11.59	9.58	0.00	0.00	0.00	7.56	0.00	0.00	0.00
December	12.64	10.62	0.00	0.00	0.00	8.60	0.00	0.00	0.00

Table 3.55 Gatun Lake: mean daily released, recycled and supplied water quantities in 10^6 m^3/day and number of recycling days; 5 ships a day, 2-lift Post-Panamax Locks.

	Scenario 1 baseline	*Scenario 5 locks with wsb's*				*Scenario6 locks without wsb's*			
	released	*released*	*recycled*	*supplied*	*number of rec. days*	*released*	*recycled*	*supplied*	*number of rec. days*
January	4.61	4.21	0.00	0.00	0.00	3.80	0.00	0.00	0.00
February	0.60	0.20	0.00	0.00	0.00	0.00	0.21	0.00	14.25
March	0.20	0.00	0.20	0.00	31.00	0.00	0.40	0.20	31.00
April	0.16	0.00	0.20	0.04	30.00	0.00	0.40	0.24	30.00
May	0.94	0.54	0.00	0.00	0.00	0.13	0.00	0.00	0.00
June	3.63	3.22	0.00	0.00	0.00	2.82	0.00	0.00	0.00
July	5.55	5.15	0.00	0.00	0.00	4.75	0.00	0.00	0.00
August	6.58	6.18	0.00	0.00	0.00	5.77	0.00	0.00	0.00
September	8.32	7.91	0.00	0.00	0.00	7.51	0.00	0.00	0.00
October	8.23	7.83	0.00	0.00	0.00	7.42	0.00	0.00	0.00
November	11.59	11.19	0.00	0.00	0.00	10.79	0.00	0.00	0.00
December	12.64	12.23	0.00	0.00	0.00	11.83	0.00	0.00	0.00

Table 3.56 Gatun Lake: mean daily released, recycled and supplied water quantities in 10^6 m^3/day and number of recycling days; 1 ship a day, 2-lift Post-Panamax Locks.

	Scenario 1 baseline	*Scenario 5 locks with wsb's*			
	released	*released*	*recycled*	*supplied*	*number of rec. days*
January	4.61	0.00	1.74	0.00	16.97
February	0.60	0.00	3.17	2.57	28.00
March	0.20	0.00	3.17	2.98	31.00
April	0.16	0.00	3.17	3.01	30.00
May	0.94	0.00	3.17	2.23	31.00
June	3.63	0.00	2.72	0.00	25.71
July	5.55	0.00	0.79	0.00	7.75
August	6.58	0.23	0.00	0.00	0.00
September	8.32	1.97	0.00	0.00	0.00
October	8.23	1.88	0.00	0.00	0.00
November	11.59	5.25	0.00	0.00	0.00
December	12.64	6.29	0.00	0.00	0.00

Table 3.57 Gatun Lake: mean daily released, recycled and supplied water quantities in 10^6 m^3/day and number of recycling days; 15 ships a day, 1-lift Post-Panamax Locks.

	Scenario 1 baseline	*Scenario 5 locks with wsb's*			
	released	*released*	*recycled*	*supplied*	*number of rec. days*
January	4.61	0.38	0.00	0.00	0.00
February	0.60	0.00	2.12	1.51	28.00
March	0.20	0.00	2.12	1.92	31.00
April	0.16	0.00	2.12	1.95	30.00
May	0.94	0.00	2.12	1.18	31.00
June	3.63	0.00	0.60	0.00	8.57
July	5.55	1.32	0.00	0.00	0.00
August	6.58	2.35	0.00	0.00	0.00
September	8.32	4.09	0.00	0.00	0.00
October	8.23	4.00	0.00	0.00	0.00
November	11.59	7.36	0.00	0.00	0.00
December	12.64	8.40	0.00	0.00	0.00

Table 3.58 Gatun Lake: mean daily released, recycled and supplied water quantities in 10^6 m^3/day and number of recycling days; 10 ships a day, 1-lift Post-Panamax Locks.

	Scenario 1 baseline	*Scenario 5 locks with wsb's*			
	released	*released*	*recycled*	*supplied*	*number of rec. days*
January	4.61	2.49	0.00	0.00	0.00
February	0.60	0.00	1.06	0.46	28.00
March	0.20	0.00	1.06	0.86	31.00
April	0.16	0.00	1.06	0.89	30.00
May	0.94	0.00	1.06	0.12	31.00
June	3.63	1.51	0.00	0.00	0.00
July	5.55	3.44	0.00	0.00	0.00
August	6.58	4.46	0.00	0.00	0.00
September	8.32	6.20	0.00	0.00	0.00
October	8.23	6.11	0.00	0.00	0.00
November	11.59	9.48	0.00	0.00	0.00
December	12.64	10.52	0.00	0.00	0.00

Table 3.59 Gatun Lake: mean daily released, recycled and supplied water quantities in 10^6 m^3/day and number of recycling days; 5 ships a day, 1-lift Post-Panamax Locks.

	Scenario 1 baseline	*Scenario 5 locks with wsb's*			
	released	*released*	*recycled*	*supplied*	*number of rec. days*
January	4.61	4.19	0.00	0.00	0.00
February	0.60	0.18	0.00	0.00	0.00
March	0.20	0.00	0.21	0.01	31.00
April	0.16	0.00	0.21	0.05	30.00
May	0.94	0.52	0.00	0.00	0.00
June	3.63	3.20	0.00	0.00	0.00
July	5.55	5.13	0.00	0.00	0.00
August	6.58	6.16	0.00	0.00	0.00
September	8.32	7.89	0.00	0.00	0.00
October	8.23	7.81	0.00	0.00	0.00
November	11.59	11.17	0.00	0.00	0.00
December	12.64	12.21	0.00	0.00	0.00

Table 3.60 Gatun Lake: mean daily released, recycled and supplied water quantities in 10^6 m^3/day and number of recycling days; 1 ship a day, 1-lift Post-Panamax Locks.

3.13.3 Effect of water level changes, water releases and water recycling

Water levels and corresponding water volumes of Gatun Lake and Miraflores Lake are prescribed for each day of a case in the simulation model; these water levels are inclusive the effects of water releases, water losses caused by lock operation, and water supplies. The effect of water level changes on the salt concentration of the lakes is evaluated at the start of each day. The effect of inflow and outflow of salt water is evaluated when the ship movement scenarios, turn around scenarios and water-release scenarios are executed.

3.14 Water levels 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. To that purpose sinusoïdal 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 3.8).

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:

$h_{tailbay}$	= tidal movement (m to PLD)
A	= amplitude 1st component = 0.16 m
B	= amplitude 2nd component = 0.04 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 –0.14 m and a maximum value of PLD +0.26 m (see Figure 3.9).

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 simulation model:

Month	*Salt concentration tailbays Pacific side (ppt)*	*Salt concentration tailbasy 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 3.61 Salt concentration in tailbays at Pacific and Atlantic side

The salt concentrations presented in the above table are also shown in Figure 3.10.

3.15 Initialization at the start of a simulation run

Water levels of Miraflores Lake, Gatun Lake, and tailbays at the Pacific and Atlantic side, as well as salt concentrations of tailbays at the Pacific and Atlantic side are prescribed through input tables or input functions (see preceeding sections).
At the start of a simulation run, however, an initial value must also be given to the water levels in the lock chambers and the water volumes in the wsb's and recycling ponds. In addition, an initial value must be given to the salt concentrations in the lock chambers and wsb's, the recycling ponds, Miraflores Lake and Gatun Lake. To that purpose the user of the simulation model prepares the table 'Initial Values'.

We put that the first day of a case starts with uplockage of ships in all shipping lanes, both at the Pacific side and the Atlantic side. This condition implies that the water level is high in all lock chambers at the start of the simulation, and the water level of wsb's is low. In addition, the water level of the lower recycling pond is low and the water level of the upper pond is high. Initial water levels in the lock chambers are selected from the tables 'Initial Values' (nominal, mean high water level in chambers); initial water volumes of wsb's, lower recycling pond and upper recycling pond are computed from the set initial water levels.

4 Evaluation of nodal status parameters

4.1 Introductory remarks

As explained before, a case in the numerical model is built up of a series of day patterns; each day pattern consists of a number of scenarios. A scenario describes the different steps of the locking process of a single ship and contains also other relevant data which is necessary for the execution of the scenario. Turn-around scenarios describe the steps which are required to prepare the locks for a change in shipping direction. Water recycling forms a part of special ship movement and turn around scenarios.
The salt concentrations and water levels of tailbays at the seaside of the locks, as well as water levels and water volumes of the lakes form input for the simulation model. At the start of a case the initial value of the status parameters of locks, water saving basins, storage ponds, forebays and lakes are prescribed. The effect of lock operations on the salt concentration of the lakes is analysed at the time that the ship movement or turn around scenarios are executed.
Salt water may be spilled through the spillways of Miraflores Lake and Gatun Lake. Water used for hydropower generation or cooling may also contain salt. These different water release operations form input for the simulation model and are prescribed through special water-release scenarios. The effect of water releases on the salt concentration of the lakes is evaluated at the time that the water-release scenarios are executed.
The effect of water level changes of the lakes on the salt concentration is evaluated at the start of each day.

A scenario is simulated as a series of subsequent steps in the numerical model. The value of the status parameters of the nodes (water level, water depth, water volume, salt concentration) is computed after each step of the scenario. In the explanation in the following sections, status parameters are indicated with subscript 1 at the beginning of a step and subscript 2 at the end of a step. 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 (see Chapter 5) 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, water storage ponds, forebays, lakes). The abbreviation wsb is used for the water saving basins.

Salt concentrations are volume-averaged values (in basins). A salt concentration multiplied by a water volume represents a quantity of salt; salt is transferred from one basin to another.

The equations which are used in the evaluation of nodal status parameters are presented in a general form in next sections. Subscript 'high' refers to the higher basin of two adjacent basins, subscript 'low' to the lower basin. The subscript 'wsbhigh' refers to the wsb connected to the high basin, the subscript 'wsblow' refers to the the wsb connected to the

low basin. Subscript 'LP' refers to the lower water storage pond of the recycling system, subscript 'UP' to the upper storage pond.
Use is made of a reference exchange volume V_{ref} in the salt balance 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}. The water quantity that is recycled is referred to as $V_{recycle}$.

The general equations for ship movements and turn arounds in the *existing* shipping lanes are explained in Report A; the general equations for ship movements and turn arounds in the *new* shipping lane are discussed in Reports B, C and D. In the present report the equations related to water recycling at the Pacific side of the canal are shown.

4.2 Uplockage of ships

Three basic steps can be distinguished in the uplockage process:

I the water level in the low basin (with ship) is equalized with the water level in the high basin (without ship); 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 low basin to high basin; a net water quantity equal to the ship volume S is displaced from high basin to low basin and density flows develop

III if relevant, water that is lost by the operation of the locks at the Pacific side of the canal is recycled (three options are available)

The time-dependent exchange of salt water between forebays / tailbays and lakes is handled in a 'special step'. This holds both for the salt water in forebays and tailbays of the lakes that is intruded through lock operations, and the salt water that enters the forebay of the Post-Panamax Locks at the Pacific side of the canal when water is recycled to the forebay.

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

- a water volume V_{ref} is exchanged between two adjacent locks when wsb's are not active
- when wsb's are active a water volume V_{save} is spilled to and supplied from the wsb's of adjacent locks; V_{save} is equal to maximum s% of the water volume V_{ref} (s = 60% for 3-lift locks with 3 wsb's, 50% for 2-lift locks with 2 wsb's and 75% for 1-lift locks with 6 wsb's); consequently, the quantity of water that is exchanged between two adjacent locks 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 and from the wsb's and a greater quantity of water exchanged between the locks
- when low basin is tailbay and high basin is lock, V_{ref} or $V_{ref} - V_{save}$ is transferred from the lower lock to the tailbay
- when low basin is lock and high basin is forebay, V_{ref} or $V_{ref} - V_{save}$ is transferred from forebay to lock
- in the case of water storage ponds a quantity $V_{store} = V_{ref}$ or $V_{store} = V_{ref} - V_{save}$ is transferred from the lower lock to the lower pond and a quantity $V_{draw} = V_{ref}$ or $V_{draw} = V_{ref} - V_{save}$ is transferred from the upper pond to the upper lock

- a quantity $V_{recycle} = V_{ref}$ or $V_{recycle} = V_{ref} - V_{save}$ is transferred from tailbay to forebay (direct recycling), or transferred from lower pond to forebay (pond to forebay recycling), or transferred from lower pond to upper pond (pond to pond recycling), see also Figures 3.6a and 3.6b
- when the water storage ponds get full or have insufficient water (this is checked in the simulation) a lesser quantity of water is stored in the lower pond or withdrawn from the upper pond, or recycled

The exchange coefficient e_x used in formulas in **step II** is dependent on the ship volume S. Input for the simulationmodel is the value of e_x for S = 0. The value of e_x applied in the computation is:

$$e_x = \left(1 - \frac{S}{V_{ref}}\right) \cdot e_{x0}$$

with: e_{x0} = value of e_x for S = 0

Step III, recycling of water, is executed at the end of a ship movement or turn around scenario (see description of subsequent steps in Sections 3.6 – 3.10).

Definition of the exchange coefficient e_x:

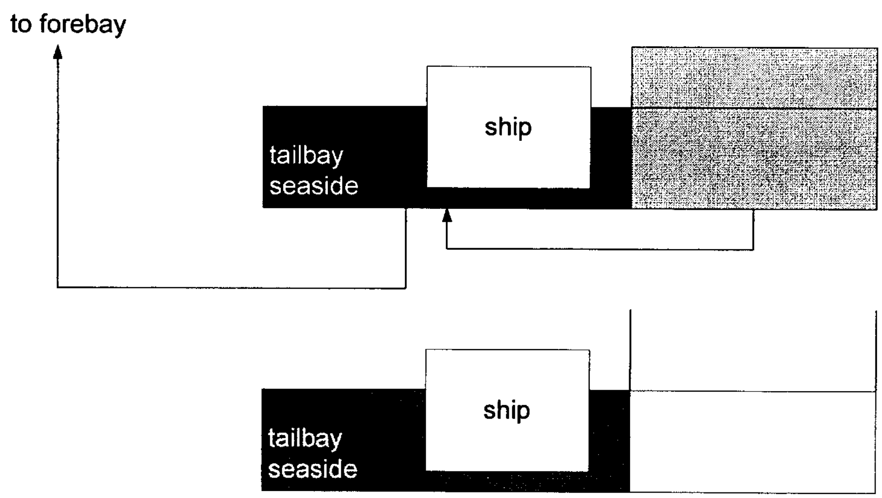
- a positive value of e_x in the formulas of **step I** means salt transfer from high basin to low basin, salt feeding to the wsb or lower storage pond that is filled, and salt withdrawal from the wsb or the upper storage pond that is emptied
- a positive value of e_x in the formulas of **step II** means 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 reverse direction
- a positive value in the formulas of **step III** means salt transfer from lower storage pond to upper storage pond, salt transfer from lower pond to forebay or salt transfer from tailbay to forebay

The equations which describe the water balance and the salt balance in case of water recycling (three options) are presented in next sections. Only those steps which are effected by water recycling, are shown.
The equations are equally valid for 1-lift, 2-lift and 3-lift configurations of Post-Panamax Locks at the Pacific side of the canal.

4.2.1 Uplockage, locks without wsb's

Option 1: Direct water recycling

Low basin = tailbay seaside, high basin = lock; recycling from tailbay to forebay
Step I



water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}, and $h_{tailbay}$ (= input)

$h_{high2} = h_{tailbay}$
check: $h_{high2} > maxh_{high}$?
if yes, $h_{high2} = maxh_{high}$
check: $h_{high2} < minh_{high}$?
if yes, $h_{high2} = minh_{high}$
note: in practice lock operations will be delayed until the tide has sufficiently changed
$d_{high2} = h_{high2} - f_{high}$
$V_{high2} = d_{high2} \cdot A_{high}$
$V_{ref} = (h_{high1} - h_{high2}) \cdot A_{high}$

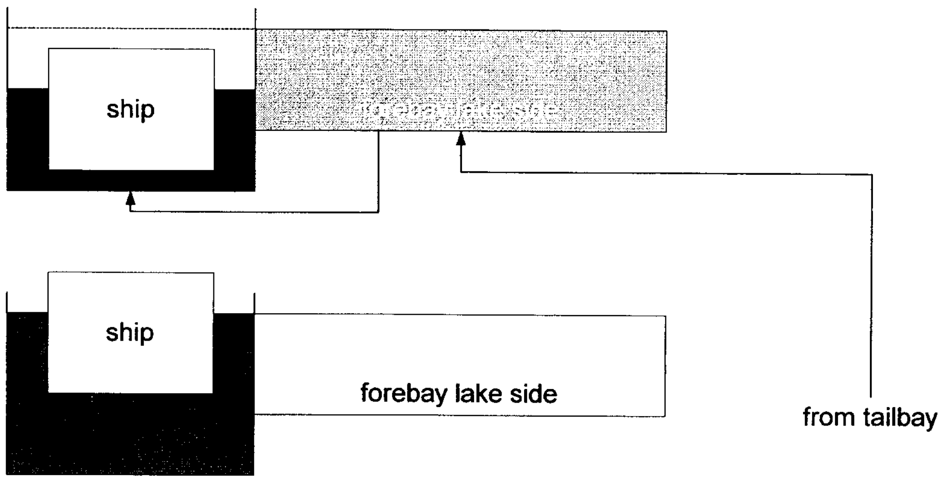
$V_{recycle} = V_{ref}$

salt balance

Known value at the beginning of step: c_{high1}

$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_x \cdot V_{ref} \cdot c_{high1})}{V_{high2}}$$

Low basin = lock, high basin = forebay lake side; recycling from tailbay to forebay
Step I



water balance

Known values at the beginning of step: h_{lake} (= input), V_{lake} (= input), h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}

$h_{low2} = h_{lake}$
check: $h_{low2} > maxh_{low}$?
if yes, $h_{low2} = maxh_{low}$
note: in practice the water level in the lake shall be lowered
$h_{high2} = h_{high1} = h_{lake}$
$d_{low2} = h_{low2} - f_{low}$
$V_{low2} = (d_{low2} \cdot A_{low}) - S$
$d_{high2} = d_{high1} = d_{forebay} = (h_{lake} - f_{sill})$
$V_{high2} = V_{high1} = V_{forebay} = d_{high2} \cdot A_{forebay}$
$V_{ref} = (h_{low2} - h_{low1}) \cdot A_{low}$

salt balance

Known values at the beginning of step: c_{high1} (= $c_{forebay1}$), c_{low1}, c_{lake1}

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

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

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

Low basin = tailbay seaside, high basin = forebay lake side; recycling from tailbay to forebay

Step III: Recycle step after the ship has passed the forebay (after step II)

water balance

Known values at the beginning of step: $V_{tailbay}$ (not a real variable!), $V_{forebay}$

$$V_{tailbay} = V_{tailbay}$$
$$V_{forebay} = V_{forebay}$$

salt balance

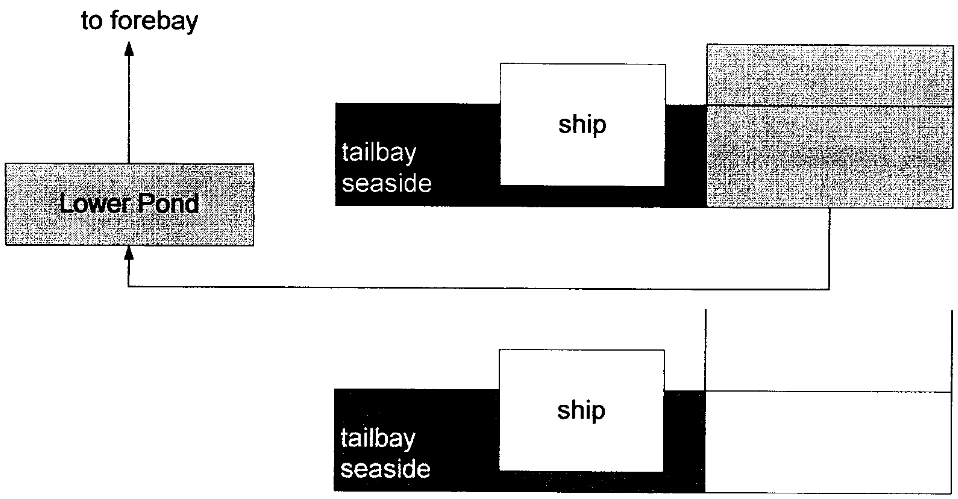
Known values at the beginning of step: $c_{tailbay}$ (= input), $c_{forebay1}$

$$c_{tailbay} = c_{tailbay}$$

$$c_{forebay2} = \frac{(V_{forebay} \cdot c_{forebay1}) + (e_{direct} \cdot V_{recycle} \cdot c_{tailbay})}{V_{forebay}}$$

Option 2: Recycling of water from lower storage pond (LP) to forebay

Low basin = tailbay seaside, high basin = lock; recycling from LP to forebay
Step I



water balance

Known values at the beginning of step: V_{LP1}, h_{high1}, d_{high1}, V_{high1}, and $h_{tailbay}$ (= input)

$h_{high2} = h_{tailbay}$
check: $h_{high2} > maxh_{high}$?
if yes, $h_{high2} = maxh_{high}$
check: $h_{high2} < minh_{high}$?
if yes, $h_{high2} = minh_{high}$
note: in practice lock operations will be delayed until the tide has sufficiently changed
$d_{high2} = h_{high2} - f_{high}$
$V_{high2} = d_{high2} \cdot A_{high}$
$V_{ref} = (h_{high1} - h_{high2}) \cdot A_{high}$

$V_{store} = V_{ref}$
$V_{LP2} = V_{LP1} + V_{store}$
Check: $V_{LP2} > maxV_{LP}$?
if yes: $V_{LP2} = maxV_{LP}$
$V_{store} = V_{LP2} - V_{LP1}$
$V_{recycle} = V_{ref}$

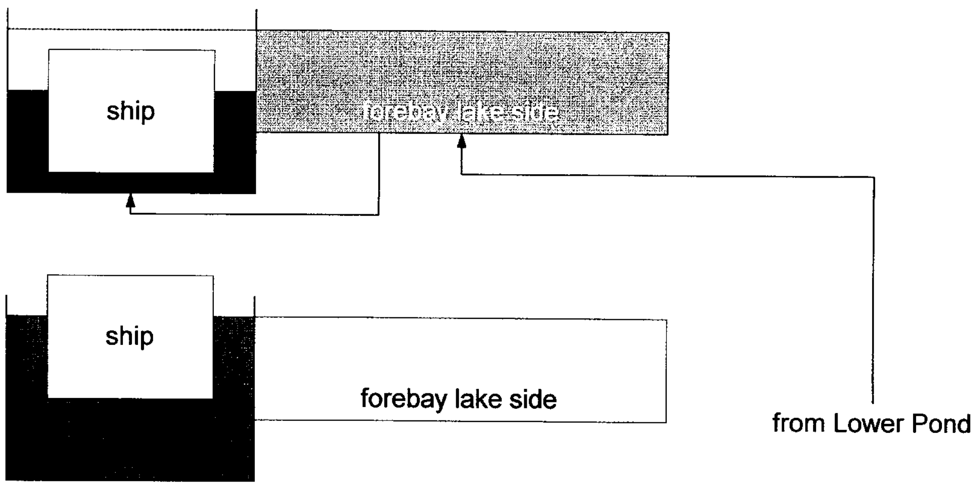
salt balance

Known values at the beginning of step: c_{high1}, c_{LP1}

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

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

Low basin = lock, high basin = forebay lake side; recycling from LP to forebay Step I



water balance

Known values at the beginning of step: h_{lake} (= input), V_{lake} (= input), h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}

$h_{low2} = h_{lake}$
check: $h_{low2} > maxh_{low}$?
if yes, $h_{low2} = maxh_{low}$
note: in practice the water level in the lake shall be lowered
$h_{high2} = h_{high1} = h_{lake}$
$d_{low2} = h_{low2} - f_{low}$
$V_{low2} = (d_{low2} . A_{low}) - S$
$d_{high2} = d_{high1} = d_{forebay} = (h_{lake} - f_{sill})$
$V_{high2} = V_{high1} = V_{forebay} = d_{high2} . A_{forebay}$
$V_{ref} = (h_{low2} - h_{low1}) . A_{low}$

salt balance

Known values at the beginning of step: c_{high1} (= $c_{forebay1}$), c_{low1}, c_{lake1}

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

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

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

Low basin = lower storage pond, high basin = forebay lake side; recycling from LP to forebay
Step III: Recycle step after the ship has passed the forebay (after step II)

water balance

Known values at the beginning of step: V_{LP1}, $V_{forebay}$

$$
\begin{aligned}
&V_{LP2} = V_{LP1} - V_{recycle} \\
&\text{check: } V_{LP2} < \min V_{LP}\ ? \\
&\qquad \text{if yes: } V_{LP2} = \min V_{LP} \\
&\qquad\qquad\quad V_{recycle} = V_{LP2} - V_{LP1} \\
&V_{forebay} = V_{forebay}
\end{aligned}
$$

salt balance

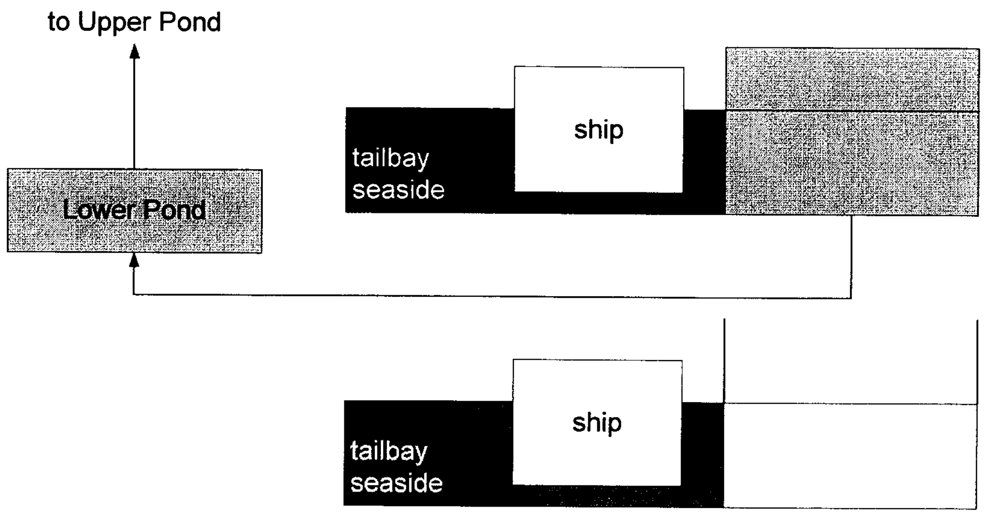
Known values at the beginning of step: c_{LP1}, $c_{forebay1}$

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

$$c_{forebay2} = \frac{(V_{forebay} \cdot c_{forebay1}) + (e_{LPempty} \cdot V_{recycle} \cdot c_{LP1})}{V_{forebay}}$$

Option 3: Recycling of water from lower storage pond (LP) to upper storage pond (UP)

Low basin = tailbay seaside, high basin = lock; recycling from LP to UP
Step I



water balance

Known values at the beginning of step: V_{LP1}, h_{high1}, d_{high1}, V_{high1}, and $h_{tailbay}$ (= input)

$h_{high2} = h_{tailbay}$
check: $h_{high2} > maxh_{high}$?
if yes, $h_{high2} = maxh_{high}$
check: $h_{high2} < minh_{high}$?
if yes, $h_{high2} = minh_{high}$
note: in practice lock operations will be delayed until the tide has, sufficiently changed
$d_{high2} = h_{high2} - f_{high}$
$V_{high2} = d_{high2} \cdot A_{high}$
$V_{ref} = (h_{high1} - h_{high2}) \cdot A_{high}$

$V_{store} = V_{ref}$
$V_{LP2} = V_{LP1} + V_{store}$
check: $V_{LP2} > maxV_{LP}$?
if yes: $V_{LP2} = maxV_{LP}$
$V_{store} = V_{LP2} - V_{LP1}$
$V_{recycle} = V_{ref}$

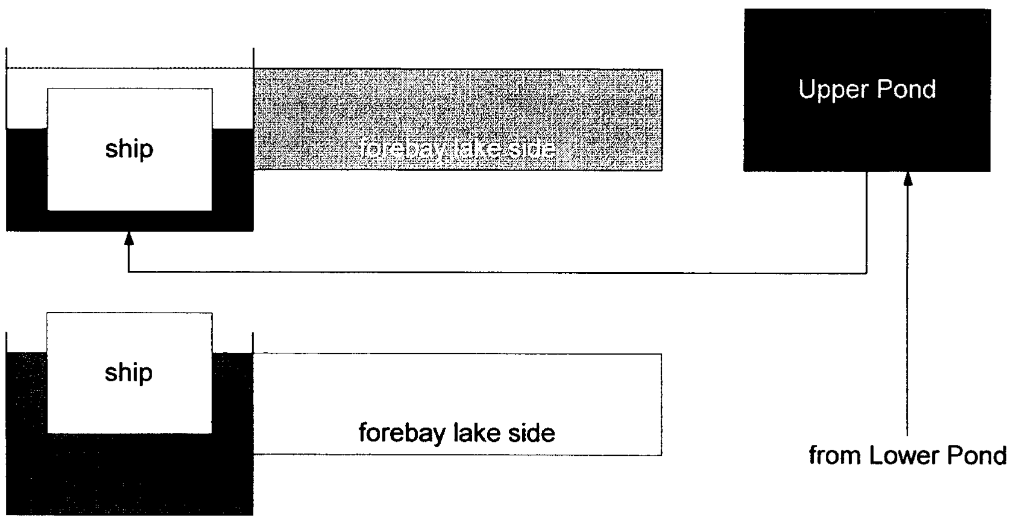
salt balance

Known values at the beginning of step: c_{high1}, c_{LP1}

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

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

Low basin = lock, high basin = forebay lake side; recycling from LP to UP
Step I



water balance

Known values at the beginning of step: V_{UP1}, h_{lake} (= input), V_{lake} (= input), h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}

$h_{low2} = h_{lake}$

check: $h_{low2} > maxh_{low}$?

if yes, $h_{low2} = maxh_{low}$

note: in practice the water level in the lake shall be lowered

$h_{high2} = h_{high1} = h_{lake}$

$d_{low2} = h_{low2} - f_{low}$

$V_{low2} = (d_{low2} \cdot A_{low}) - S$

$d_{high2} = d_{high1} = d_{forebay} = (h_{lake} - f_{sill})$

$V_{high2} = V_{high1} = V_{forebay} = d_{high2} \cdot A_{forebay}$

$V_{ref} = (h_{low2} - h_{low1}) \cdot A_{low}$

$V_{draw} = V_{ref}$

$V_{UP2} = V_{UP1} - V_{draw}$
check: $V_{UP2} < minV_{UP}$?
if yes: $V_{UP2} = minV_{UP}$
$V_{draw} = V_{UP2} - V_{UP1}$

salt balance

Known values at the beginning of step: c_{UP1}, c_{high1} (= $c_{forebay1}$), c_{low1}, c_{lake1}

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

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

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

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

Low basin = lower storage pond, high basin = upper storage pond; recycling from LP to UP
Step III: Recycle step after the ship has passed the forebay (after step II)

water balance

Known values at the beginning of step: V_{LP1}, V_{UP1}

$V_{LP2} = V_{LP1} - V_{recycle}$
check: $V_{LP2} < minV_{LP}$?
if yes: $V_{LP2} = minV_{LP}$
$V_{recycle} = V_{LP2} - V_{LP1}$
$V_{UP2} = V_{UP1} + V_{recycle}$
check: $V_{UP2} > maxV_{UP}$?
if yes: $V_{UP2} = maxV_{UP}$
$V_{recycle} = V_{UP2} - V_{UP1}$
$V_{LP2} = V_{LP1} - V_{recycle}$

salt balance

Known values at the beginning of step: c_{LP1}, c_{UP1}

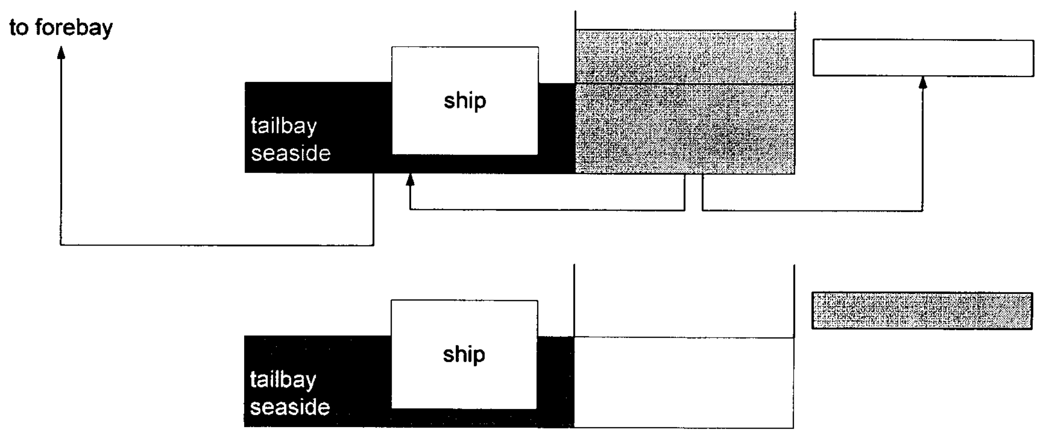
$$c_{LP2} = \frac{(V_{LP1} \cdot c_{LP1}) - (e_{LP\text{-}UP} \cdot V_{recycle} \cdot c_{LP1})}{V_{LP2}}$$

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

4.2.2 Uplockage, locks with wsb's

Option I: Direct water recycling

Low basin = tailbay seaside, high basin = lock; recycling from tailbay to forebay
Step 1



water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}, $h_{tailbay}$ (= input), $V_{wsbhigh1}$

$h_{high2} = h_{tailbay}$

check: $h_{high2} > maxh_{high}$?

if yes: $h_{high2} = maxh_{high}$

check: $h_{high2} < minh_{high}$?

if yes: $h_{high2} = minh_{high}$

note: in practice lock operations will be delayed until the tide has sufficiently been changed

$d_{high2} = h_{high2} - f_{high}$

$V_{high2} = d_{high2} \, . \, A_{high}$

$V_{ref} = (h_{high1} - h_{high2}) \, . \, A_{high}$

$V_{save} = s \, . \, V_{ref}$ s = 0.6, 0.5 or 0.75 for 3-lift, 2-lift and 1-lift locks respectively

$V_{wsbhigh2} = V_{wsbhigh1} + V_{save}$

check: $V_{wsbhigh2} > maxV_{wsbhigh}$?

if yes: $V_{wsbhigh2} = maxV_{wsbhigh}$

$V_{save} = V_{wsbhigh2} - V_{wsbhigh1}$

$V_{recycle} = V_{ref} - V_{save}$

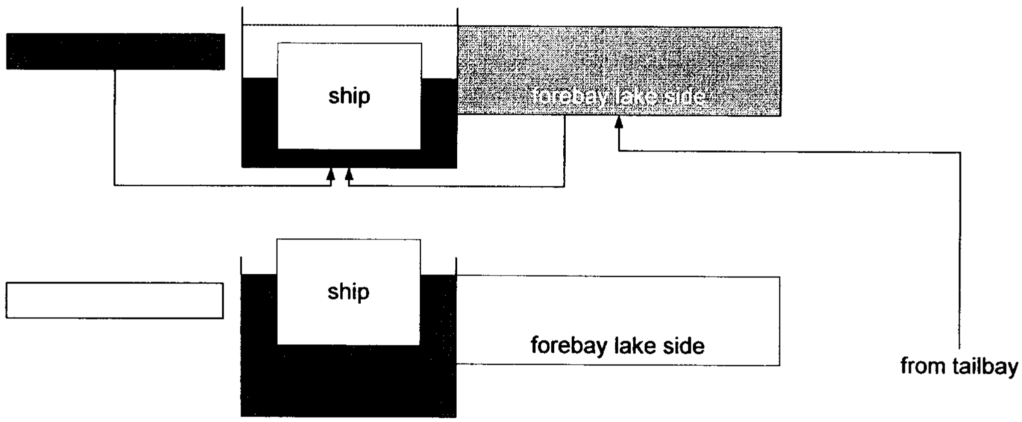
salt balance

Known value at the beginning of step: c_{high1} and $c_{wsbhigh1}$

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

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

Low basin = lock, high basin = forebay lake side; recycling from tailbay to forebay
Step I



water balance

Known values at the beginning of step: h_{lake} (= input), V_{lake} (= input), h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}, $V_{wsblow1}$

$h_{low2} = h_{lake}$
check: $h_{low2} > maxh_{low}$?
if yes: $h_{low2} = maxh_{low}$
note: in practice the water level in the lake shall be lowered
$h_{high2} = h_{high1} = h_{lake}$
$d_{low2} = h_{low2} - f_{low}$
$V_{low2} = (d_{low2} \,.\, A_{low}) - S$
$d_{high2} = d_{high1} = d_{forebay} = (h_{lake} - f_{sill})$
$V_{high2} = V_{high1} = V_{forebay} = d_{high2} \,.\, A_{forebay}$
$V_{ref} = (h_{low2} - h_{low1}) \,.\, A_{low}$

$V_{save} = s \,.\, V_{ref}$ $s = 0.6$, 0.5 or 0.75 for 3-lift, 2-lift and 1-lift locks respectively
$V_{wsblow2} = V_{wsblow1} - V_{save}$

check: $V_{wsblow2} < \min V_{wsblow}$?
if yes: $V_{wsblow2} = \min V_{wsblow}$
$V_{save} = V_{wsblow1} - V_{wsblow2}$

salt balance

Known values at the beginning of step: c_{high1} ($= c_{forebay1}$), c_{low1}, c_{lake1}, $c_{wsblow1}$

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

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

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

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

Low basin = tailbay seaside, high basin = forebay lake side; recycling from tailbay to forebay
Step III: Recycle step after the ship has passed the forebay (after step II)

water balance

Known values at the beginning of step: $V_{tailbay}$ (not a real variable!), $V_{forebay}$

$V_{tailbay} = V_{tailbay}$
$V_{forebay} = V_{forebay}$

salt balance

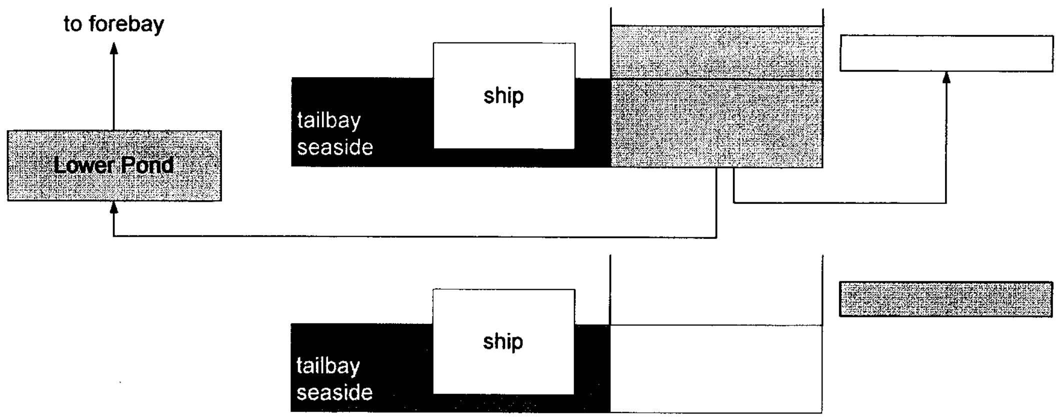
Known values at the beginning of step: $c_{tailbay}$ (= input), $c_{forebay1}$

$c_{tailbay} = c_{tailbay}$

$$c_{forebay2} = \frac{(V_{forebay} \cdot c_{forebay1}) + (e_{direct} \cdot V_{recycle} \cdot c_{tailbay})}{V_{forebay}}$$

Option 2 Recycling from lower storage pond (LP) to forebay

Low basin = tailbay seaside, high basin = lock; recycling from LP to forebay
Step 1



water balance

Known values at the beginning of step: V_{LP1}, h_{high1}, d_{high1}, V_{high1}, $h_{tailbay}$ (= input), $V_{wsbhigh1}$

$h_{high2} = h_{tailbay}$
check: $h_{high2} > maxh_{high}$?
if yes: $h_{high2} = maxh_{high}$
check: $h_{high2} < minh_{high}$?
if yes: $h_{high2} = minh_{high}$
note: in practice lock operations will be delayed until the tide has sufficiently been changed
$d_{high2} = h_{high2} - f_{high}$
$V_{high2} = d_{high2} \cdot A_{high}$
$V_{ref} = (h_{high1} - h_{high2}) \cdot A_{high}$

$V_{save} = s \cdot V_{ref}$ s = 0.6, 0.5 or 0.75 for 3-lift, 2-lift and 1-lift locks respectively
$V_{wsbhigh2} = V_{wsbhigh1} + V_{save}$
check: $V_{wsbhigh2} > maxV_{wsbhigh}$?
if yes: $V_{wsbhigh2} = maxV_{wsbhigh}$
$V_{save} = V_{wsbhigh2} - V_{wsbhigh1}$

$V_{store} = V_{ref} - V_{save}$
$V_{LP2} = V_{LP1} + V_{store}$
Check: $V_{LP2} > maxV_{LP}$?
if yes: $V_{LP2} = maxV_{LP}$
$V_{store} = V_{LP2} - V_{LP1}$
$V_{recycle} = V_{ref} - V_{save}$

salt balance

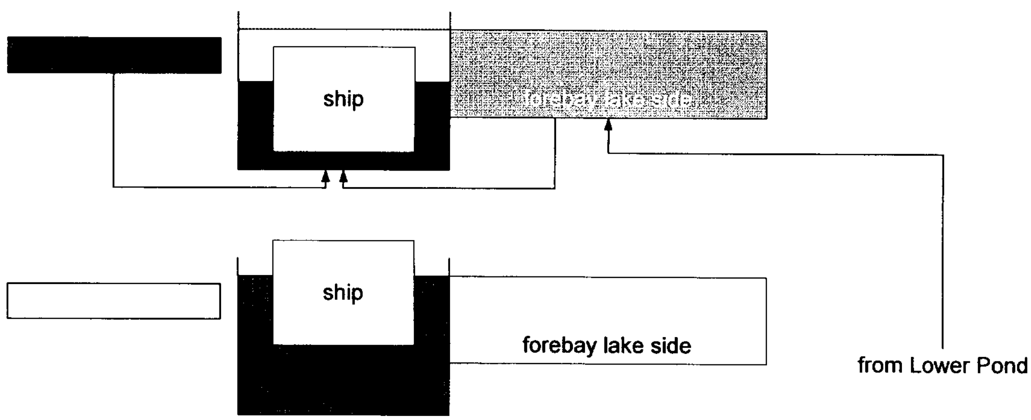
Known value at the beginning of step: c_{LP1}, c_{high1} and $c_{wsbhigh1}$

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

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

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

Low basin = lock, high basin = forebay lake side; recycling from LP to forebay
Step I



water balance

Known values at the beginning of step: h_{lake} (= input), V_{lake} (= input), h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}, $V_{wsblow1}$

$h_{low2} = h_{lake}$
check: $h_{low2} > maxh_{low}$?
if yes: $h_{low2} = maxh_{low}$
note: in practice the water level in the lake shall be lowered
$h_{high2} = h_{high1} = h_{lake}$
$d_{low2} = h_{low2} - f_{low}$
$V_{low2} = (d_{low2} \,.\, A_{low}) - S$
$d_{high2} = d_{high1} = d_{forebay} = (h_{lake} - f_{sill})$
$V_{high2} = V_{high1} = V_{forebay} = d_{high2} \,.\, A_{forebay}$
$V_{ref} = (h_{low2} - h_{low1}) \,.\, A_{low}$

$V_{save} = s \,.\, V_{ref}$ $s = 0.6$, 0.5 or 0.75 for 3-lift, 2-lift and 1-lift locks respectively

$V_{wsblow2} = V_{wsblow1} - V_{save}$
check: $V_{wsblow2} < minV_{wsblow}$?
if yes: $V_{wsblow2} = minV_{wsblow}$
$V_{save} = V_{wsblow1} - V_{wsblow2}$

salt balance

Known values at the beginning of step: c_{high1} ($= c_{forebay1}$), c_{low1}, c_{lake1}, $c_{wsblow1}$

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

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

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

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

Low basin = lower storage pond, high basin = forebay lake side; recycling from LP to forebay
Step III: Recycle step after the ship has passed the forebay (after step II):

water balance

Known values at the beginning of step: V_{LP1}, $V_{forebay}$

$V_{LP2} = V_{LP1} - V_{recycle}$
check: $V_{LP2} < minV_{LP}$?
if yes: $V_{LP2} = minV_{LP}$
$V_{recycle} = V_{LP2} - V_{LP1}$
$V_{forebay} = V_{forebay}$

salt balance

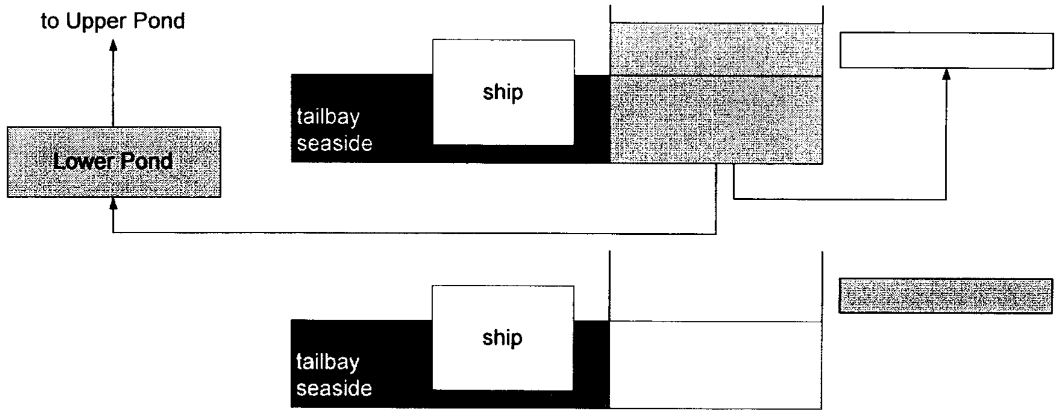
Known values at the beginning of step: c_{LP1}, $c_{forebay1}$

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

$$c_{forebay2} = \frac{(V_{forebay} \cdot c_{forebay1}) + (e_{LPempty} \cdot V_{recycle} \cdot c_{LP1})}{V_{forebay}}$$

Option 3: Recycling from lower storage pond (LP) to upper storage pond (UP)

Low basin = tailbay seaside, high basin = lock; recycling from LP to UP
Step I



water balance

Known values at the beginning of step: V_{LP1}, h_{high1}, d_{high1}, V_{high1}, $h_{tailbay}$ (= input), $V_{wsbhigh1}$

$h_{high2} \quad = h_{tailbay}$
check: $h_{high2} > maxh_{high}$?
    if yes: $h_{high2} \quad = maxh_{high}$
check: $h_{high2} < minh_{high}$?
    if yes: $h_{high2} \quad = minh_{high}$
    note: in practice lock operations will be delayed until the tide has sufficiently been changed
$d_{high2} \quad = h_{high2} - f_{high}$
$V_{high2} \quad = d_{high2} \cdot A_{high}$
$V_{ref} \quad = (h_{high1} - h_{high2}) \cdot A_{high}$

$V_{save} \quad = s \cdot V_{ref}$ s = 0.6, 0.5 or 0.75 for 3-lift, 2-lift and 1-lift locks respectively
$V_{wsbhigh2} = V_{wsbhigh1} + V_{save}$
check: $V_{wsbhigh2} > maxV_{wsbhigh}$?
    if yes: $V_{wsbhigh2} = maxV_{wsbhigh}$
        $V_{save} \quad = V_{wsbhigh2} - V_{wsbhigh1}$

$V_{store} \quad = V_{ref} - V_{save}$
$V_{LP2} \quad = V_{LP1} + V_{store}$
Check: $V_{LP2} > maxV_{LP}$?
    if yes: $V_{LP2} \quad = maxV_{LP}$
        $V_{store} \quad = V_{LP2} - V_{LP1}$
$V_{recycle} = V_{ref} - V_{save}$

salt balance

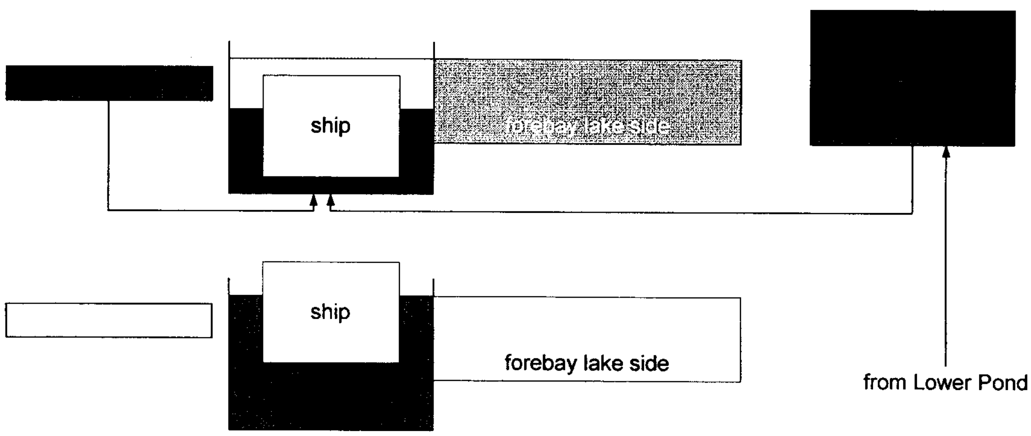
Known value at the beginning of step: c_{LP1}, c_{high1} and $c_{wsbhigh1}$

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

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

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

Low basin = lock, high basin = forebay lake side; recycling from LP to UP
Step I



water balance

Known values at the beginning of step: h_{lake} (= input), V_{lake} (= input), h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}, $V_{wsblow1}$

h_{low2} $= h_{lake}$
check: $h_{low2} > maxh_{low}$?
if yes: $h_{low2} = maxh_{low}$
note: in practice the water level in the lake shall be lowered
h_{high2} $= h_{high1} = h_{lake}$
d_{low2} $= h_{low2} - f_{low}$
V_{low2} $= (d_{low2} \,.\, A_{low}) - S$
d_{high2} $= d_{high1} = d_{forebay} = (h_{lake} - f_{sill})$
V_{high2} $= V_{high1} = V_{forebay} = d_{high2} \,.\, A_{forebay}$
V_{ref} $= (h_{low2} - h_{low1}) \,.\, A_{low}$

$V_{save} = s \, . \, V_{ref}$ s = 0.6, 0.5 or 0.75 for 3-lift, 2-lift and 1-lift locks respectively
$V_{wsblow2} = V_{wsblow1} - V_{save}$
check: $V_{wsblow2} < minV_{wsblow}$?
if yes: $V_{wsblow2} = minV_{wsblow}$
$V_{save} = V_{wsblow1} - V_{wsblow2}$

$V_{draw} = V_{ref} - V_{save}$
$V_{UP2} = V_{UP1} - V_{draw}$
check: $V_{UP2} < minV_{UP}$?
if yes: $V_{UP2} = minV_{UP}$
$V_{draw} = V_{UP2} - V_{UP1}$

salt balance

Known values at the beginning of step: c_{UP1}, c_{high1} (= $c_{forebay1}$), c_{low1}, c_{lake1}, $c_{wsblow1}$

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

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

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

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

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

Low basin = lower storage pond, high basin = upper storage pond; recycling from LP to UP
Step III: Recycle step after the ship has passed the forebay (after step II)

water balance

Known values at the beginning of step: V_{LP1}, V_{UP1}

$V_{LP2} = V_{LP1} - V_{recycle}$
check: $V_{LP2} < minV_{LP}$?
if yes: $V_{LP2} = minV_{LP}$
$V_{recycle} = V_{LP2} - V_{LP1}$
$V_{UP2} = V_{UP1} + V_{recycle}$
check: $V_{UP2} > maxV_{UP}$?
if yes: $V_{UP2} = maxV_{UP}$
$V_{recycle} = V_{UP2} - V_{UP1}$
$V_{LP2} = V_{LP1} - V_{recycle}$

salt balance

Known values at the beginning of step: c_{LP1}, c_{UP1}

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

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

4.2.3 Special step uplockage: water containing salt is exchanged between forebay and lake

The forebay of the upper locks is in open connection with Gatun Lake. After an uplocking ship has passed the forebay or after a turn around the salt concentration in the forebay has changed. In the case of water recycling salt water is pumped into the forebay (recycling options 1 and 2). The quantity of salt that is exchanged between forebay and lake is dependent on the density difference and is also a function of time. Next formulas are used in the simulation model to describe the exchange of salt water.

low basin is forebay, high basin = lake

salt balance

Known values at the beginning of step: c_{lake1}, $c_{forebay1}$

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

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

time aspect

The exchange coefficient e_x ($0 \geq e_x \geq 1$) is a function of the time difference between two subsequent ship passages in the same lane (ships sail in the same direction, northbound or southbound), or between a ship movement and a turn around in the same lane. These scenarios may include recycling of water. The start time of scenarios is selected to determine the time difference. Exchange coefficient: $e_x = 0$ 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 the simulation:

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

with:

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

If $\Delta t/T > 1$ then $\Delta t = T$, and $e_x = e_{xfull}$.
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.

4.3 Downlockage of ships

Three basic steps can be distinguished in the downlockage process:

I the water level in the low basin (without ship) is equalized with the water level in the high basin (with ship); 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 high basin to low basin; a net water quantity equal to the ship volume S is displaced from low basin to high basin and density flows develop

III if relevant, water that is lost by the operation of the locks at the Pacific side of the canal is recycled (three options are available)

The time-dependent exchange of salt water between forebays / tailbays and lakes is handled in a 'special step'. This holds both for the salt water in forebays and tailbays of the lakes that is intruded through lock operations, and the salt water that enters the forebay of the Post-Panamax Locks at the Pacific side of the canal when water is recycled to the forebay.

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

- a water volume V_{ref} is exchanged between two adjacent locks when wsb's are not active
- when wsb's are active a water volume V_{save} is spilled to and supplied from the wsb's of adjacent locks; V_{save} is equal to maximum s% of the water volume V_{ref} (s = 60% for 3-lift locks with 3 wsb's, 50% for 2-lift locks with 2 wsb's and 75% for 1-lift locks with 6 wsb's); consequently, the quantity of water that is exchanged between two adjacent locks 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 and from the wsb's and a greater quantity of water exchanged between the locks
- when low basin is tailbay and high basin is lock, V_{ref} or $V_{ref} - V_{save}$ is transferred from the lower lock to the tailbay
- when low basin is lock and high basin is forebay, V_{ref} or $V_{ref} - V_{save}$ is transferred from forebay to lock
- in the case of water storage ponds a quantity $V_{store} = V_{ref}$ or $V_{store} = V_{ref} - V_{save}$ is transferred from the lower lock to the lower pond and a quantity $V_{draw} = V_{ref}$ or $V_{draw} = V_{ref} - V_{save}$ is transferred from the upper pond to the upper lock
- a quantity $V_{recycle} = V_{ref}$ or $V_{recycle} = V_{ref} - V_{save}$ is transferred from tailbay to forebay (direct recycling), or transferred from lower pond to forebay (pond to forebay recycling), or transferred from lower pond to upper pond (pond to pond recycling), see also Figures 3.6a and 3.6b
- when the water storage ponds get full or have insufficient water (this is checked in the simulation) a lesser quantity of water is stored in the lower pond or withdrawn from the upper pond, or recycled

The exchange coefficient e_x used in formulas in **step II** is dependent on the ship volume S. Input for the simulationmodel is the value of e_x for S = 0. The value of e_x applied in the computation is:

$$e_x = \left(1 - \frac{S}{V_{ref}}\right) . e_{x0}$$

with: e_{x0} = value of e_x for S = 0

Step III, recycling of water, is executed at the end of a ship movement scenario (see description of subsequent steps in Sections 3.6 – 3.8.

Definition of the exchange coefficient e_x:

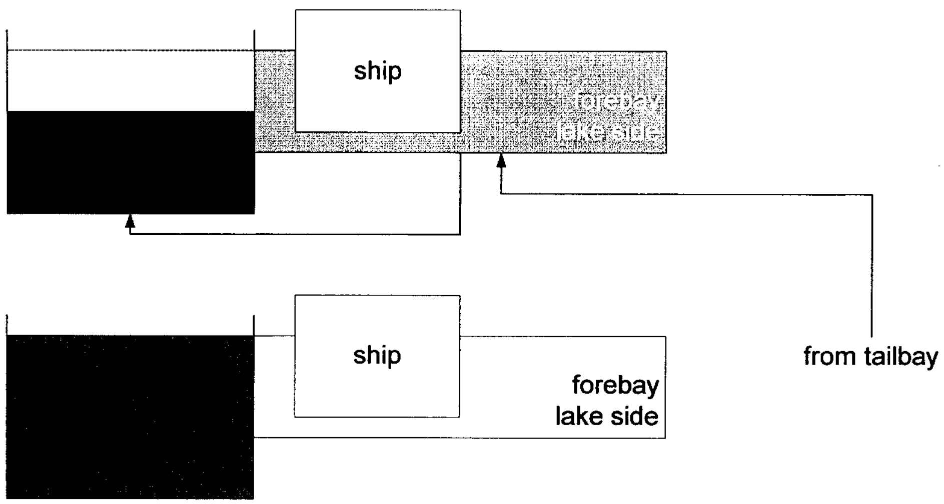
- a positive value of e_x in the formulas of **step I** means salt transfer from high basin to low basin, salt feeding to the wsb or lower storage pond that is filled, and salt withdrawal from the wsb or the upper storage pond that is emptied
- a positive value of e_x in the formulas of **step II** means 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 reverse direction
- a positive value in the formulas of **step III** means salt transfer from lower storage pond to upper storage pond, salt transfer from lower pond to forebay or salt transfer from tailbay to forebay

The equations which describe the water balance and the salt balance in case of water recycling (three options) are presented in next sections. Only those steps which are effected by water recycling, are shown.
The equations are equally valid for 1-lift, 2-lift and 3-lift configurations of Post-Panamax Locks at the Pacific side of the canal.

4.3.1 Downlockage, locks without wsb's

Option 1: Direct water recycling

High basin = forebay lake side, low basin = lock; recycling from tailbay to forebay
Step I



water balance

Known values at the beginning of step: h_{lake} (= input), V_{lake} (= input), h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}

$h_{high2} = h_{high1} = h_{lake}$
$h_{low2} = h_{lake}$
check: $h_{low2} > maxh_{low}$?
if yes, $h_{low2} = maxh_{low}$
note: in practice the water level in the lake shall be lowered
$d_{high2} = d_{high1} = d_{forebay} = (h_{lake} - f_{sill})$
$V_{high2} = V_{high1} = V_{forebay} = d_{high2} \cdot A_{forebay}$
$d_{low2} = h_{low2} - f_{low}$
$V_{low2} = d_{low2} \cdot A_{low}$
$V_{ref} = (h_{low2} - h_{low1}) \cdot A_{low}$

salt balance

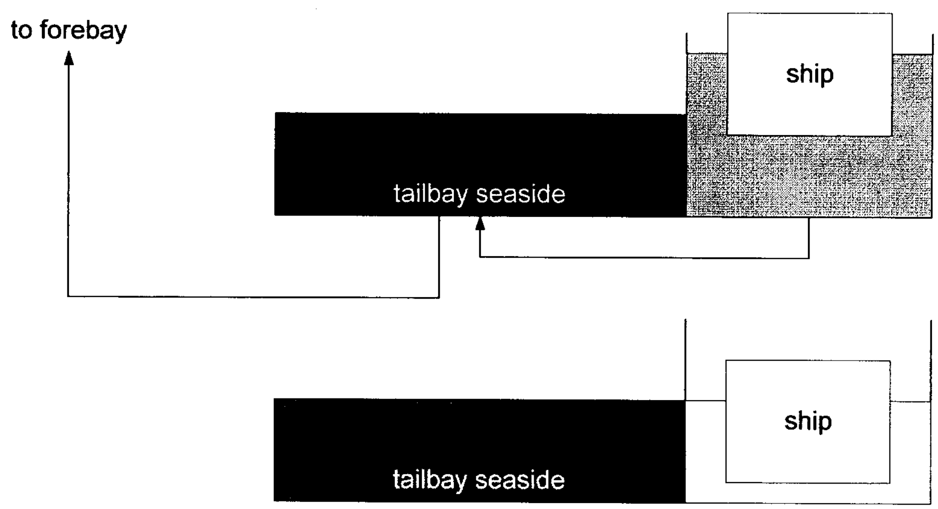
Known values at the beginning of step: c_{high1} (= $c_{forebay1}$), c_{low1}, c_{lake1}

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

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

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

High basin = lock, low basin = tailbay sea; recycling from tailbay to forebay
Step I



water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}, and $h_{tailbay}$ (= input)

h_{high2} $= h_{tailbay}$
check: $h_{high2} > maxh_{high}$?
if yes, $h_{high2} = maxh_{high}$
check: $h_{high2} < minh_{high}$?
if yes, $h_{high2} = minh_{high}$
note: in practice lock operations will be delayed until the tide has sufficiently changed
d_{high2} $= h_{high2} - f_{high}$
V_{high2} $= d_{high2} . A_{high} - S$
V_{ref} $= (h_{high1} - h_{high2}) . A_{high}$

$V_{recycle}$ $= V_{ref}$

salt balance

Known value at the beginning of step: c_{high1}

$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_x \cdot V_{ref} \cdot c_{high1})}{V_{high2}}$$

High basin = forebay lake side, low basin = tailbay seaside; recycling from tailbay to forebay

Step III: Recycle step after the ship has passed the tailbay (after step II)

water balance

Known values at the beginning of step: $V_{tailbay}$ (not a real variable!), $V_{forebay}$

$$V_{tailbay} = V_{tailbay}$$
$$V_{forebay} = V_{forebay}$$

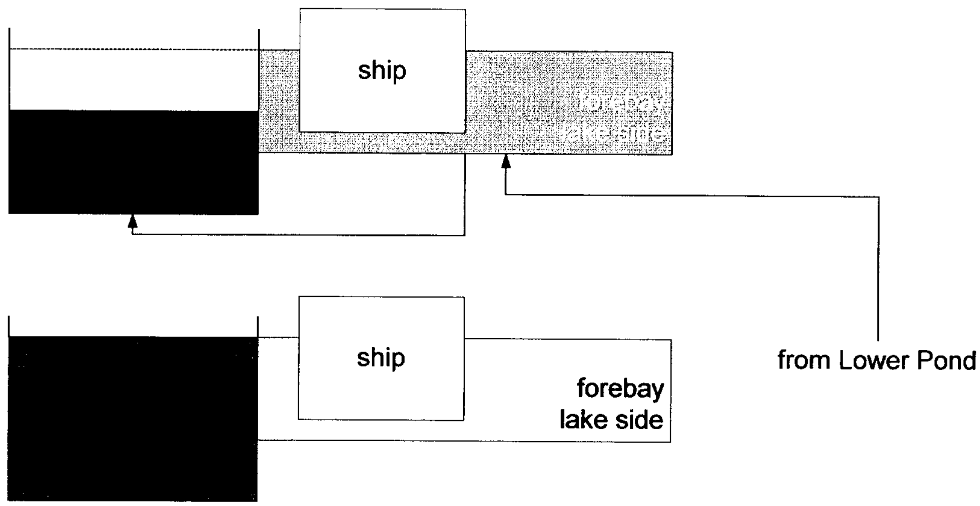
salt balance

Known values at the beginning of step: $c_{tailbay}$ (= input), $c_{forebay1}$

$$c_{tailbay} = c_{tailbay}$$
$$c_{forebay2} = \frac{(V_{forebay} \cdot c_{forebay1}) + (e_{direct} \cdot V_{recycle} \cdot c_{tailbay})}{V_{forebay}}$$

Option 2: Recycling from lower storage pond (LP) to forebay

High basin = forebay lake side, low basin = lock; recycling from LP to forebay
Step I



water balance

Known values at the beginning of step: h_{lake} (= input), V_{lake} (= input), h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}

$h_{high2} = h_{high1} = h_{lake}$
$h_{low2} = h_{lake}$
check: $h_{low2} > maxh_{low}$?
if yes, $h_{low2} = maxh_{low}$
note: in practice the water level in the lake shall be lowered
$d_{high2} = d_{high1} = d_{forebay} = (h_{lake} - f_{sill})$
$V_{high2} = V_{high1} = V_{forebay} = d_{high2} \cdot A_{forebay}$
$d_{low2} = h_{low2} - f_{low}$
$V_{low2} = d_{low2} \cdot A_{low}$
$V_{ref} = (h_{low2} - h_{low1}) \cdot A_{low}$

salt balance

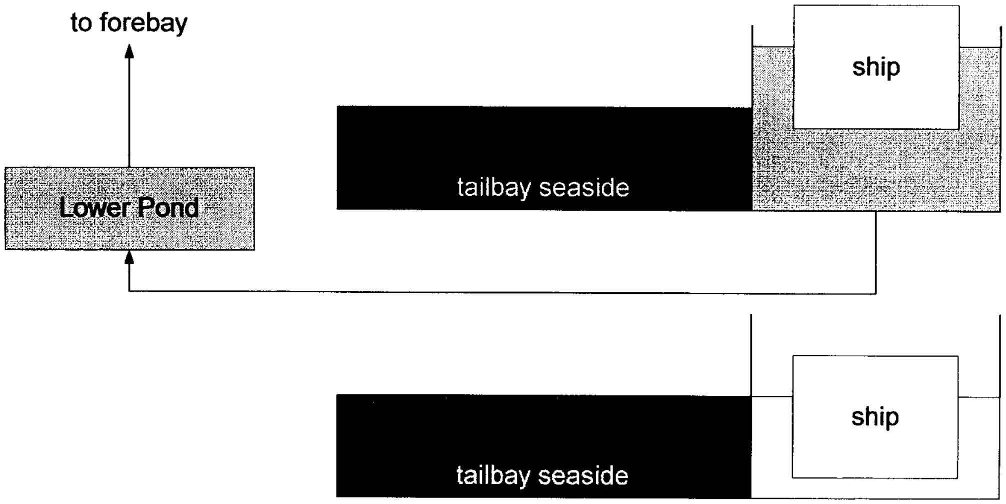
Known values at the beginning of step: c_{high1} (= $c_{forebay1}$), c_{low1}, c_{lake1}

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

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

$$c_{lake2} = c_{lake1} - \frac{V_{ref}}{V_{lake}} \cdot c_{lake1}$$

High basin = lock, low basin = tailbay sea; recycling from LP to forebay
Step I



water balance

Known values at the beginning of step: V_{LP1}, h_{high1}, d_{high1}, V_{high1}, and $h_{tailbay}$ (= input)

$h_{high2} = h_{tailbay}$
check: $h_{high2} > maxh_{high}$?
if yes, $h_{high2} = maxh_{high}$
check: $h_{high2} < minh_{high}$?
if yes, $h_{high2} = minh_{high}$
note: in practice lock operations will be delayed until the tide has sufficiently changed
$d_{high2} = h_{high2} - f_{high}$
$V_{high2} = d_{high2} \cdot A_{high} - S$
$V_{ref} = (h_{high1} - h_{high2}) \cdot A_{high}$

$V_{store} = V_{ref}$
$V_{LP2} = V_{LP1} + V_{store}$
Check: $V_{LP2} > maxV_{LP}$?
if yes: $V_{LP2} = maxV_{LP}$
$V_{store} = V_{LP2} - V_{LP1}$
$V_{recycle} = V_{ref}$

salt balance

Known values at the beginning of step: c_{high1}, c_{LP1}

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

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

High basin = forebay lake side, low basin = lower storage pond; recycling from LP to forebay
Step III: Recycle step after the ship has passed the tailbay (after step II)

water balance

Known values at the beginning of step: V_{LP1}, $V_{forebay}$

$V_{LP2} = V_{LP1} - V_{recycle}$
check: $V_{LP2} < minV_{LP}$?
if yes: $V_{LP2} = minV_{LP}$
$V_{recycle} = V_{LP2} - V_{LP1}$
$V_{forebay} = V_{forebay}$

salt balance

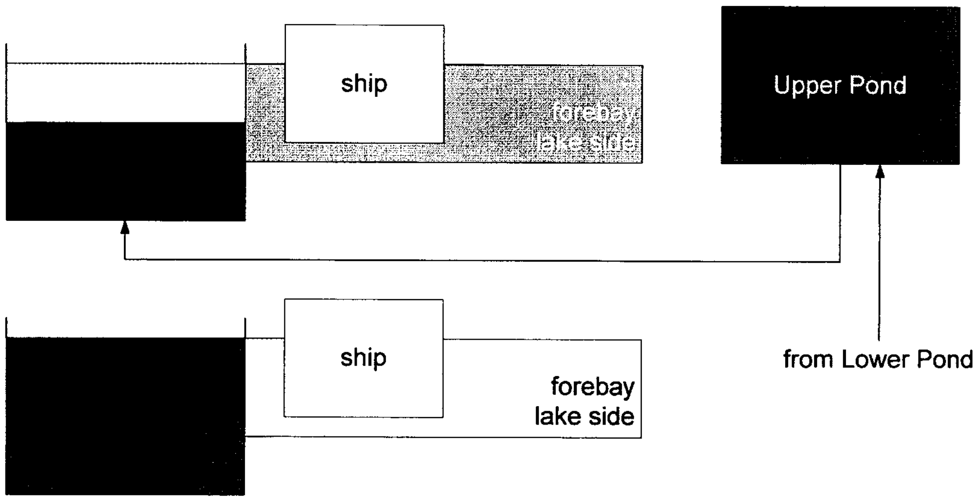
Known values at the beginning of step: c_{LP1}, $c_{forebay1}$

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

$$c_{forebay2} = \frac{(V_{forebay} \cdot c_{forebay1}) + (e_{LPempty} \cdot V_{recycle} \cdot c_{LP1})}{V_{forebay}}$$

Option 3: Recycling from lower storage pond (LP) to upper storage pond (UP)

High basin = forebay lake side, low basin = lock; recycling from LP to UP
Step I



water balance

Known values at the beginning of step: V_{UP1}, h_{lake} (= input), V_{lake} (= input), h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}

$h_{high2} = h_{high1} = h_{lake}$
$h_{low2} = h_{lake}$
check: $h_{low2} > maxh_{low}$?
if yes, $h_{low2} = maxh_{low}$
note: in practice the water level in the lake shall be lowered
$d_{high2} = d_{high1} = d_{forebay} = (h_{lake} - f_{sill})$
$V_{high2} = V_{high1} = V_{forebay} = d_{high2} \cdot A_{forebay}$
$d_{low2} = h_{low2} - f_{low}$
$V_{low2} = d_{low2} \cdot A_{low}$
$V_{ref} = (h_{low2} - h_{low1}) \cdot A_{low}$

$V_{draw} = V_{ref}$
$V_{UP2} = V_{UP1} - V_{draw}$
check: $V_{UP2} < minV_{UP}$?
if yes: $V_{UP2} = minV_{UP}$
$V_{draw} = V_{UP2} - V_{UP1}$

salt balance

Known values at the beginning of step: c_{UP1}, c_{high1} (= $c_{forebay1}$), c_{low1}, c_{lake1}

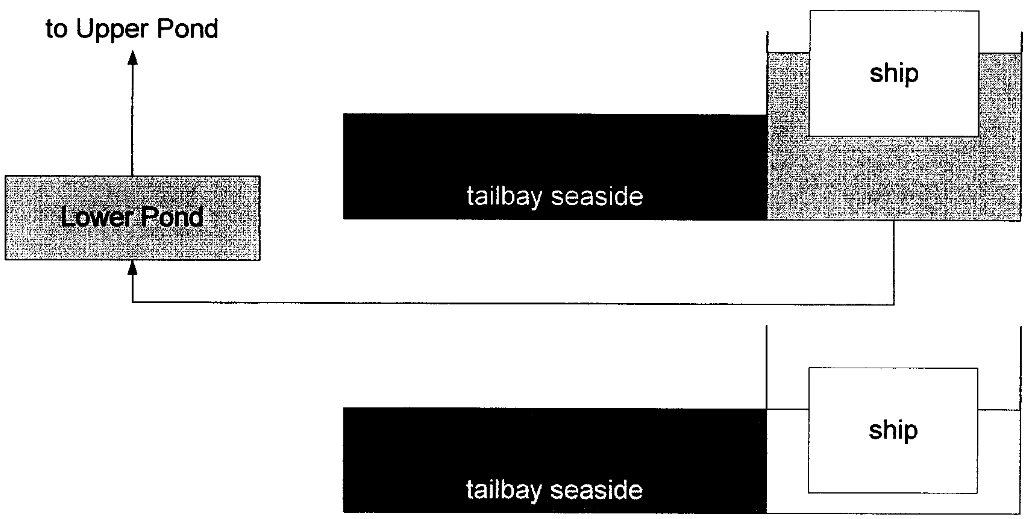
$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_x \cdot (V_{ref} - V_{draw}) \cdot c_{high1}) + ((V_{ref} - V_{draw}) \cdot c_{lake1})}{V_{high2}} = c_{forebay2}$$

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

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

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

High basin = lock, low basin = tailbay sea; recycling from LP to UP
Step I



water balance

Known values at the beginning of step: V_{LP1}, h_{high1}, d_{high1}, V_{high1}, and $h_{tailbay}$ (= input)

h_{high2} = $h_{tailbay}$

check: $h_{high2} > maxh_{high}$?

if yes, $h_{high2} = maxh_{high}$

check: $h_{high2} < minh_{high}$?

if yes, $h_{high2} = minh_{high}$

note: in practice lock operations will be delayed until the tide has sufficiently changed

d_{high2} = $h_{high2} - f_{high}$

V_{high2} = $d_{high2} . A_{high} - S$

$V_{ref} = (h_{high1} - h_{high2}) \,.\, A_{high}$

$V_{store} = V_{ref}$

$V_{LP2} = V_{LP1} + V_{store}$

Check: $V_{LP2} > maxV_{LP}$?

if yes: $V_{LP2} = maxV_{LP}$

$V_{store} = V_{LP2} - V_{LP1}$

$V_{recycle} = V_{ref}$

salt balance

Known values at the beginning of step: c_{high1}, c_{LP1}

$$c_{high2} = \frac{(V_{high1} \,.\, c_{high1}) - (e_{LPfill} \,.\, V_{store} \,.\, c_{high1}) - (e_x \,.\, (V_{ref} - V_{store}) \,.\, c_{high1})}{V_{high2}}$$

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

High basin = upper storage pond, low basin = lower storage pond; recycling from LP to UP

Step III: Recycle step after the ship has passed the tailbay (after step II)

water balance

Known values at the beginning of step: V_{LP1}, V_{UP1}

$V_{LP2} = V_{LP1} - V_{recycle}$

check: $V_{LP2} < minV_{LP}$?

if yes: $V_{LP2} = minV_{LP}$

$V_{recycle} = V_{LP2} - V_{LP1}$

$V_{UP2} = V_{UP1} + V_{recycle}$

check: $V_{UP2} > maxV_{UP}$?

if yes: $V_{UP2} = maxV_{UP}$

$V_{recycle} = V_{UP2} - V_{UP1}$

$V_{LP2} = V_{LP1} - V_{recycle}$

salt balance

Known values at the beginning of step: c_{LP1}, c_{UP1}

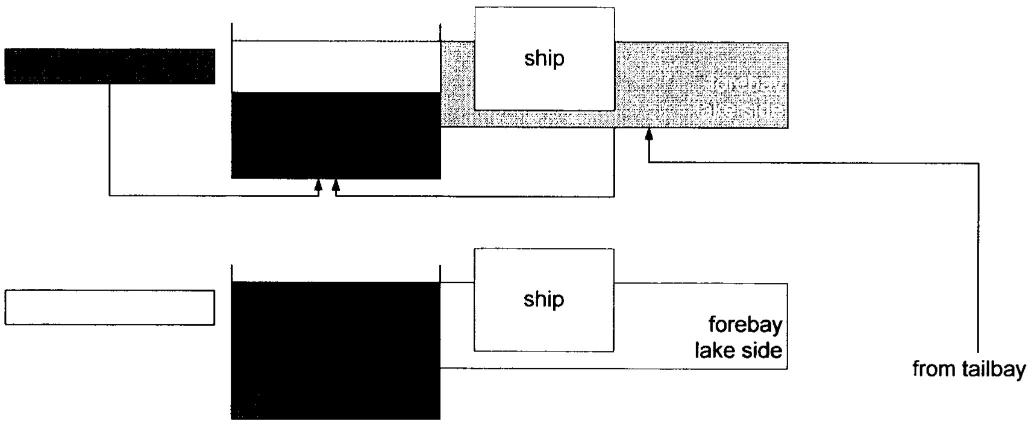
$$c_{LP2} = \frac{(V_{LP1} \,.\, c_{LP1}) - (e_{LP\text{-}UP} \,.\, V_{recycle} \,.\, c_{LP1})}{V_{LP2}}$$

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

4.3.2 Downlockage, locks with wsb's

Option I: Direct water recycling

High basin = forebay lake side, low basin = lock; recycling from tailbay to forebay
Step I



water balance

Known values at the beginning of step: h_{lake} (= input), V_{lake} (= input), h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}, $V_{wsblow1}$

$h_{high2} = h_{high1} = h_{lake}$
$h_{low2} = h_{lake}$
check: $h_{low2} > maxh_{low}$?
if yes: $h_{low2} = maxh_{low}$
note: in practice the water level in the lake shall be lowered
$d_{high2} = d_{high1} = d_{forebay} = (h_{lake} - f_{sill})$
$V_{high2} = V_{high1} = V_{forebay} = d_{high2} \cdot A_{forebay}$
$d_{low2} = h_{low2} - f_{low}$
$V_{low2} = d_{low2} \cdot A_{low}$
$V_{ref} = (h_{low2} - h_{low1}) \cdot A_{low}$

$V_{save} = s \cdot V_{ref}$ s = 0.6, 0.5 or 0.75 for 3-lift, 2-lift and 1-lift locks respectively
$V_{wsblow2} = V_{wsblow1} - V_{save}$
check: $V_{wsblow2} < minV_{wsblow}$?
if yes: $V_{wsblow2} = minV_{wsblow}$
$V_{save} = V_{wsblow1} - V_{wsblow2}$

salt balance

Known values at the beginning of step: c_{high1} (= $c_{forebay1}$), c_{low1}, c_{lake1}, $c_{wsblow1}$

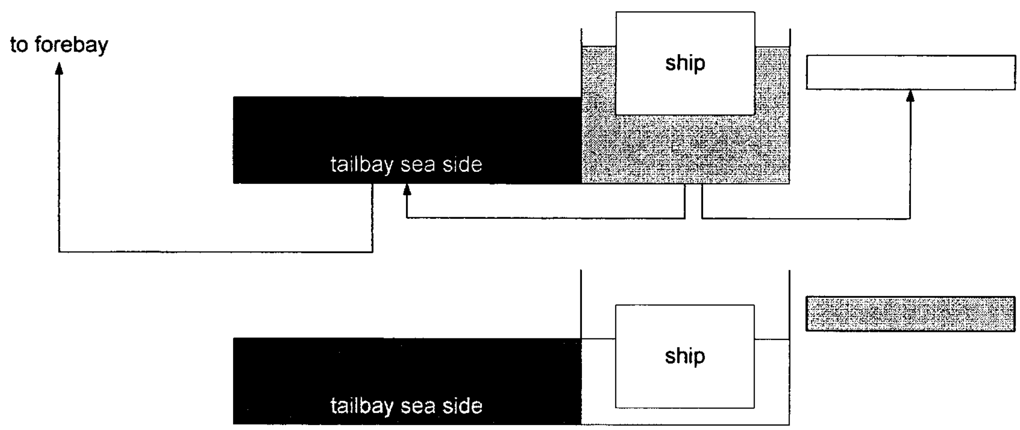
$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_x \cdot (V_{ref} - V_{save}) \cdot c_{high1}) + ((V_{ref} - V_{save}) \cdot c_{lake1})}{V_{high2}} = c_{forebay2}$$

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

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

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

High basin = lock, low basin = tailbay sea; recycling from tailbay to forebay
Step I



water balance

Known values at the beginning of step: h_{high1}, d_{high1}, V_{high1}, $h_{tailbay}$ (= input), $V_{wsbhigh1}$

h_{high2} $= h_{tailbay}$
check: $h_{high2} > maxh_{high}$?
if yes: $h_{high2} = maxh_{high}$
check: $h_{high2} < minh_{high}$?
if yes: $h_{high2} = minh_{high}$
note: in practice lock operations will be delayed until the tide has sufficiently changed
d_{high2} $= h_{high2} - f_{high}$
V_{high2} $= d_{high2} \cdot A_{high} - S$
V_{ref} $= (h_{high1} - h_{high2}) \cdot A_{high}$

$V_{save} = s \, . \, V_{ref}$ s = 0.6, 0.5 or 0.75 for 3-lift, 2-lift and 1-lift locks respectively
$V_{wsbhigh2} = V_{wsbhigh1} + V_{save}$
check: $V_{wsbhigh2} > maxV_{wsbhigh}$?
if yes: $V_{wsbhigh2} = maxV_{wsbhigh}$
$V_{save} = V_{wsbhigh2} - V_{wsbhigh1}$

$V_{recycle} = V_{ref} - V_{save}$

salt balance

Known value at the beginning of step: c_{high1}, $c_{wsbhigh1}$

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

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

High basin = forebay lake side, low basin = tailbay seaside; recycling from tailbay to forebay
Step III: Recycle step after the ship has passed the tailbay (after step II)

water balance

Known values at the beginning of step: $V_{tailbay}$ (not a real variable!), $V_{forebay}$

$V_{tailbay} = V_{tailbay}$
$V_{forebay} = V_{forebay}$

salt balance

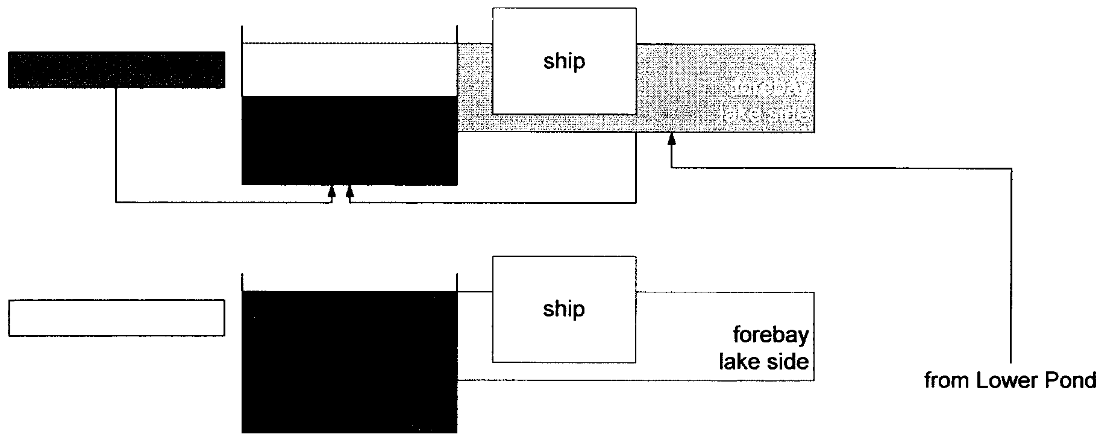
Known values at the beginning of step: $c_{tailbay}$ (= input), $c_{forebay1}$

$c_{tailbay} = c_{tailbay}$

$$c_{forebay2} = \frac{(V_{forebay} \cdot c_{forebay1}) + (e_{direct} \cdot V_{recycle} \cdot c_{tailbay})}{V_{forebay}}$$

Option 2: Recycling from lower storage pond (LP) to forebay

High basin = forebay lake side, low basin = lock; recycling from LP to forebay
Step I



water balance

Known values at the beginning of step: h_{lake} (= input), V_{lake} (= input), h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}, $V_{wsblow1}$

$h_{high2} = h_{high1} = h_{lake}$
$h_{low2} = h_{lake}$
check: $h_{low2} > maxh_{low}$?
if yes: $h_{low2} = maxh_{low}$
note: in practice the water level in the lake shall be lowered
$d_{high2} = d_{high1} = d_{forebay} = (h_{lake} - f_{sill})$
$V_{high2} = V_{high1} = V_{forebay} = d_{high2} \cdot A_{forebay}$
$d_{low2} = h_{low2} - f_{low}$
$V_{low2} = d_{low2} \cdot A_{low}$
$V_{ref} = (h_{low2} - h_{low1}) \cdot A_{low}$

$V_{save} = s \cdot V_{ref}$ s = 0.6, 0.5 or 0.75 for 3-lift, 2-lift and 1-lift locks respectively
$V_{wsblow2} = V_{wsblow1} - V_{save}$
check: $V_{wsblow2} < minV_{wsblow}$?
if yes: $V_{wsblow2} = minV_{wsblow}$
$V_{save} = V_{wsblow1} - V_{wsblow2}$

salt balance

Known values at the beginning of step: c_{high1} (= $c_{forebay1}$), c_{low1}, c_{lake1}, $c_{wsblow1}$

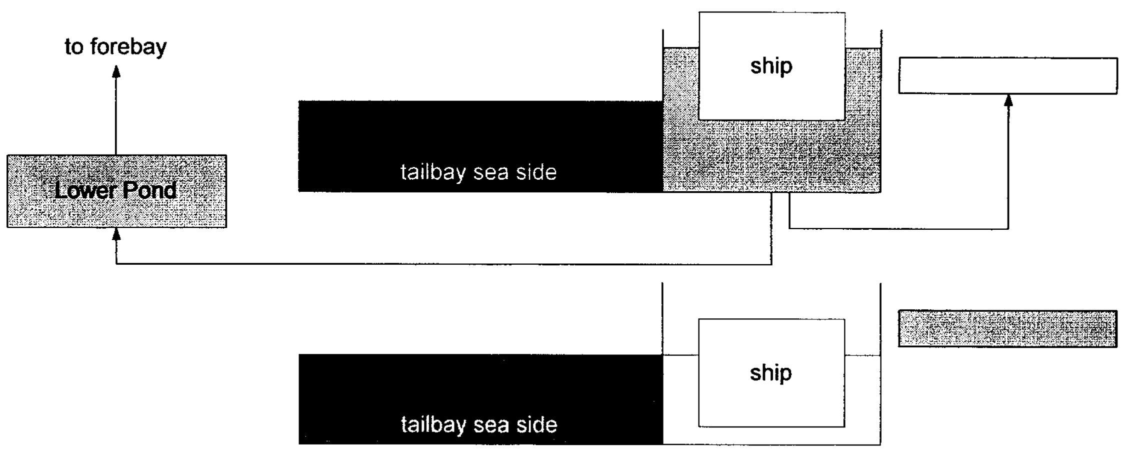
$$c_{high2} = \frac{(V_{high1} \cdot c_{high1}) - (e_x \cdot (V_{ref} - V_{save}) \cdot c_{high1}) + ((V_{ref} - V_{save}) \cdot c_{lake1})}{V_{high2}} = c_{forebay2}$$

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

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

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

High basin = lock, low basin = tailbay sea; recycling from LP to forebay
Step I



water balance

Known values at the beginning of step: V_{LP1}, h_{high1}, d_{high1}, V_{high1}, $h_{tailbay}$ (= input), $V_{wsbhigh1}$

h_{high2} $= h_{tailbay}$
check: $h_{high2} > maxh_{high}$?
if yes: $h_{high2} = maxh_{high}$
check: $h_{high2} < minh_{high}$?
if yes: $h_{high2} = minh_{high}$
note: in practice lock operations will be delayed until the tide has sufficiently changed
d_{high2} $= h_{high2} - f_{high}$
V_{high2} $= d_{high2} \cdot A_{high} - S$
V_{ref} $= (h_{high1} - h_{high2}) \cdot A_{high}$

$V_{save} = s \, . \, V_{ref}$ s = 0.6, 0.5 or 0.75 for 3-lift, 2-lift and 1-lift locks respectively

$V_{wsbhigh2} = V_{wsbhigh1} + V_{save}$

check: $V_{wsbhigh2} > maxV_{wsbhigh}$?

if yes: $V_{wsbhigh2} = maxV_{wsbhigh}$

$V_{save} = V_{wsbhigh2} - V_{wsbhigh1}$

$V_{store} = V_{ref} - V_{save}$

$V_{LP2} = V_{LP1} + V_{store}$

Check: $V_{LP2} > maxV_{LP}$?

if yes: $V_{LP2} = maxV_{LP}$

$V_{store} = V_{LP2} - V_{LP1}$

$V_{recycle} = V_{ref} - V_{save}$

salt balance

Known value at the beginning of step: c_{LP1}, c_{high1}, $c_{wsbhigh1}$

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

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

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

High basin = forebay lake side, low basin = lower storage pond; recycling from LP to forebay

Step III: Recycle step after the ship has passed the tailbay (after step II)

water balance

Known values at the beginning of step: V_{LP1}, $V_{forebay}$

$V_{LP2} = V_{LP1} - V_{recycle}$

check: $V_{LP2} < minV_{LP}$?

if yes: $V_{LP2} = minV_{LP}$

$V_{recycle} = V_{LP2} - V_{LP1}$

$V_{forebay} = V_{forebay}$

salt balance

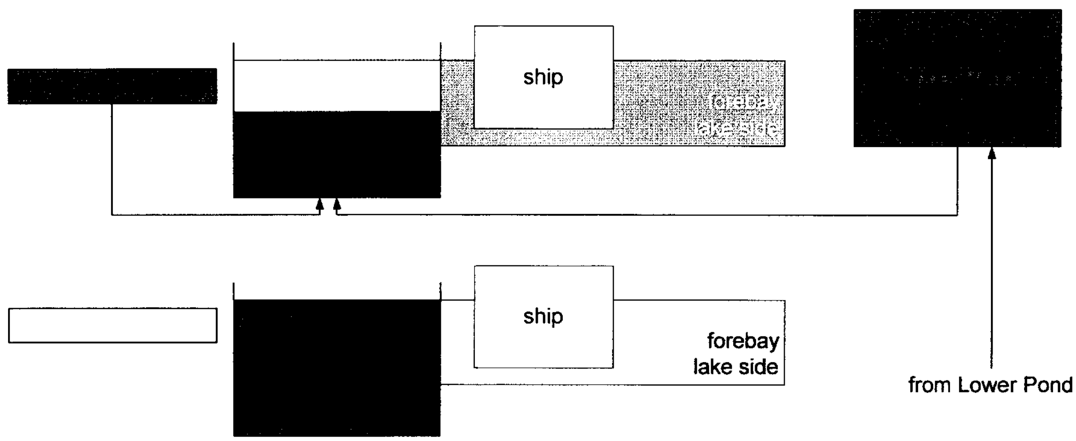
Known values at the beginning of step: c_{LP1}, $c_{forebay1}$

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

$$c_{forebay2} = \frac{(V_{forebay} \cdot c_{forebay1}) + (e_{LPempty} \cdot V_{recycle} \cdot c_{LP1})}{V_{forebay}}$$

3 Recycling from lower storage pond (LP) to upper storage pond (UP)

High basin = forebay lake side, low basin = lock; recycling from LP to UP
Step I



water balance

Known values at the beginning of step: V_{UP1}, h_{lake} (= input), V_{lake} (= input), h_{high1}, d_{high1}, V_{high1}, h_{low1}, d_{low1}, V_{low1}, $V_{wsblow1}$

$h_{high2} = h_{high1} = h_{lake}$
$h_{low2} = h_{lake}$
check: $h_{low2} > maxh_{low}$?
if yes: $h_{low2} = maxh_{low}$
note: in practice the water level in the lake shall be lowered
$d_{high2} = d_{high1} = d_{forebay} = (h_{lake} - f_{sill})$
$V_{high2} = V_{high1} = V_{forebay} = d_{high2} \cdot A_{forebay}$
$d_{low2} = h_{low2} - f_{low}$
$V_{low2} = d_{low2} \cdot A_{low}$
$V_{ref} = (h_{low2} - h_{low1}) \cdot A_{low}$

$V_{save} = s \cdot V_{ref}$ s = 0.6, 0.5 or 0.75 for 3-lift, 2-lift and 1-lift locks respectively
$V_{wsblow2} = V_{wsblow1} - V_{save}$
check: $V_{wsblow2} < minV_{wsblow}$?
if yes: $V_{wsblow2} = minV_{wsblow}$
$V_{save} = V_{wsblow1} - V_{wsblow2}$

$V_{draw} = V_{ref} - V_{save}$
$V_{UP2} = V_{UP1} - V_{draw}$
check: $V_{UP2} < minV_{UP}$?
if yes: $V_{UP2} = minV_{UP}$
$V_{draw} = V_{UP2} - V_{UP1}$

salt balance

Known values at the beginning of step: c_{UP1}, c_{high1} (= $c_{forebay1}$), c_{low1}, c_{lake1}, $c_{wsblow1}$

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

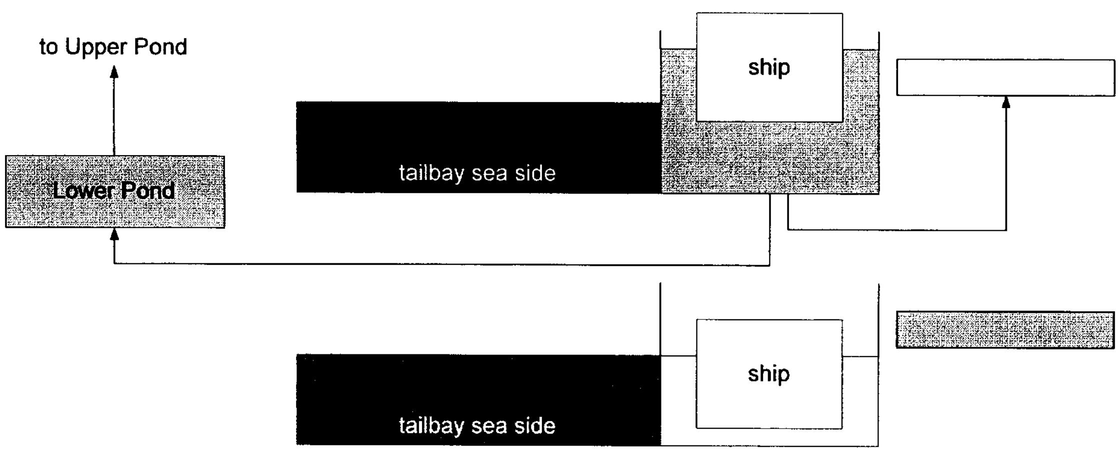
$$c_{low2} = \frac{(V_{low1} \cdot c_{low1}) + (e_{wsbempty} \cdot V_{save} \cdot c_{wsblow1}) + (e_{UPempty} \cdot V_{draw} \cdot c_{UP1}) + (e_x \cdot (V_{ref} - V_{save}\ V_{draw}) \cdot c_{high1})}{V_{low2}}$$

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

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

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

High basin = lock, low basin = tailbay sea; recycling from LP to UP
Step I



water balance

Known values at the beginning of step: V_{LP1}, h_{high1}, d_{high1}, V_{high1}, $h_{tailbay}$ (= input), $V_{wsbhigh1}$

h_{high2} = $h_{tailbay}$
check: $h_{high2} > maxh_{high}$?
if yes: $h_{high2} = maxh_{high}$
check: $h_{high2} < minh_{high}$?
if yes: $h_{high2} = minh_{high}$
note: in practice lock operations will be delayed until the tide has sufficiently changed

$d_{high2} = h_{high2} - f_{high}$
$V_{high2} = d_{high2} \,.\, A_{high} - S$
$V_{ref} = (h_{high1} - h_{high2}) \,.\, A_{high}$

$V_{save} = s \,.\, V_{ref}$ s = 0.6, 0.5 or 0.75 for 3-lift, 2-lift and 1-lift locks respectively
$V_{wsbhigh2} = V_{wsbhigh1} + V_{save}$
check: $V_{wsbhigh2} > maxV_{wsbhigh}$?
if yes: $V_{wsbhigh2} = maxV_{wsbhigh}$
$V_{save} = V_{wsbhigh2} - V_{wsbhigh1}$

$V_{store} = V_{ref} - V_{save}$
$V_{LP2} = V_{LP1} + V_{store}$
Check: $V_{LP2} > maxV_{LP}$?
if yes: $V_{LP2} = maxV_{LP}$
$V_{store} = V_{LP2} - V_{LP1}$
$V_{recycle} = V_{ref} - V_{save}$

salt balance

Known value at the beginning of step: c_{LP1}, c_{high1}, $c_{wsbhigh1}$

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

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

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

High basin = upper storage pond, low basin = lower storage pond; recycling from LP to UP
Step III: Recycle step after the ship has passed the tailbay (after step II)

water balance

Known values at the beginning of step: V_{LP1}, V_{UP1}

$V_{LP2} = V_{LP1} - V_{recycle}$
check: $V_{LP2} < minV_{LP}$?
if yes: $V_{LP2} = minV_{LP}$
$V_{recycle} = V_{LP2} - V_{LP1}$
$V_{UP2} = V_{UP1} + V_{recycle}$
check: $V_{UP2} > maxV_{UP}$?
if yes: $V_{UP2} = maxV_{UP}$
$V_{recycle} = V_{UP2} - V_{UP1}$
$V_{LP2} = V_{LP1} - V_{recycle}$

salt balance

Known values at the beginning of step: c_{LP1}, c_{UP1}

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

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

4.3.3 Special step: water containing salt is exchanged between forebay and lake

The forebay of the upper locks is in open connection with Gatun Lake. After a downlocking ship has passed the forebay or after a turn around the salt concentration in the forebay has changed. In the case of water recycling salt water is pumped into the forebay (recycling options 1 and 2). The quantity of salt that is exchanged between forebay and lake is dependent on the density difference and is also a function of time. Next formulas are used in the simulation model to describe the exchange of salt water. They are equal to the formulas which are applied for uplockage.

high basin = lake, low basin is forebay

salt balance

Known values at the beginning of step: c_{lake1}, $c_{forebay1}$

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

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

time aspect

The exchange coefficient e_x ($0 \geq e_x \geq 1$) is a function of the time difference between two subsequent ship passages in the same lane (ships sail in the same direction, northbound or southbound), or between a ship movement and a turn around in the same lane. These scenarios may include recycling of water. The start time of scenarios is selected to determine the time difference. Exchange coefficient: $e_x = 0$ 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 the simulation:

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

with:

e_x = exchange coefficient used in simulation

e_{xfull} = maximum value of exchange coefficient (full salt exchange)

Δt = time difference (s) between two subsequent ship passages or between a ship passage and a turn around

T = exchange time

If $\Delta t/T > 1$ then $\Delta t = T$, and $e_x = e_{xfull}$.
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.

5 Exchange coefficients

As explained in Chapter 4 salt exchange coefficients are used in the formulas that describe the salt transfer between the various basins. The selection of exchange coefficients for the existing situation was based on salinity measurements in the locks and canal area in wet and dry season and on computations with the numerical program Delft3D (see Report A); the exchange coefficients for the locks on the new shipping lane were selected on the basis of additional Delft3D density-flow computations, taking also into account the experiences with the existing locks (see Reports B, C and D). In the present report additional exchange coefficients are derived for the situation that a water recycling system is in operation at the Pacific side of the canal.

5.1 Delft3D computations

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

It is therefore that a number of computations has been made with the Delft3D numerical programme. This programme enables the calculation of density-driven flows and advective and diffusive transport on a three dimensional computational grid. Boundary conditions can be prescribed in such a way that both a continuous inflow / outflow can be simulated and an intermittent inflow / outflow. The computations are schematized in the sense that the bathymetry of Gaillard Cut is not fully reproduced, and the water level is kept constant.
A part of the existing Gaillard Cut up to Pedro Miguel Locks, and the new bypass canal along Miraflores Lake towards the new locks have been modelled. Water that is recycled (inflow) and water that is lost by lock operations (Post-Panamax Locks and Pedro Miguel Locks, outflow) balance in the computations with the inflow of water at the upstream side of Gaillard Cut. The computations predict the salt concentration level in the forebay of the Post-Panamax Locks at the Pacific side for various schematized conditions.

5.1.1 Description of model

The modelled part of Gaillard Cut has a length of 6000 m up to the point where the bypass canal joins Gaillard Cut (hereafter called 'bifurcation'). The part of Gaillard Cut from the bifurcation till Pedro Miguel Locks has a length of 2080 m. The new bypass canal has a length of 3515 m, measured between the bifurcation and the new Post-Panamax Locks. See also Figures 5.a / b on page 5-3. The still-water depth is 20 m.

Grid

The computational grid is curvilinear. The grid was designed using a compound channel axis; the channel banks are located at a distance of 110 m left and right of this axis. The axis was obtained from available x,y points at relevant locations of the canal (these points were read from the satellite image of the canal in which CPP has drawn the new bypass and the location of the Post-Panamax Locks). The construction of the computational grid was based upon the following considerations:

- use of adequate cell sizes for a good schematisation of the hydraulic, convective and diffusive processes
- use of an adequate grid size for reasonable computation times
- use of appropriate grid characteristics required for the numerical computation

A top view of the grid is presented in Figure 5.a. Figure 5.b shows a detail of the grid near the bifurcation.

Cells

From expert judgement it was decided to use 10 grid cells in cross-sectional direction both in the new bypass and in Gaillard Cut from the bifurcation till Pedro Miguel Locks. The width of the bypass is approximately 220 m (read from satellite image), which results in a grid cell width of 22 m in this section. For Gaillard Cut also a total width of 220 m has been adopted. The number of cells in cross-sectional direction of the upper part of Gaillard Cut is 22 (10 cells from each of the two branches plus 2 cells, which were needed to realise the bifurcation). The grid cells in the upper part of Gaillard Cut are thus approximately 10 m wide. For accuracy reasons the ratio grid cell length to width, the so-called aspect ratio, should be less than about 5. In the two branches an aspect ratio of less than 1.7 was achieved. In the upper part of Gaillard Cut the maximum aspect ratio is less than 5.5. This is slightly higher than the criterion, but since the main interest lies in the bypass section and in view of acceptable computation times, this was accepted.

Grid characteristics

For accuracy reasons criteria related to the grid characteristics should be satisfied:

- Variations in the cell sizes may affect the accuracy of the numerical computation and cause internal reflections during dynamical computation procedures. In order to reduce these effects, a smooth transition of cell width and length throughout the grid is required. The ratio of the lengths of two neighbouring cells, referred to as the non-smoothness, should be kept below 1.2.
- Another grid characteristic is the grid orthogonality. The numerical discretisation is based on the assumption that the computational grid is orthogonal (i.e. the grid lines are perpendicular to each other). The non-orthogonality is defined as the cosine of the angle between the gridlines. In general, the orthogonality is less important than the smoothness, especially in steady state computations.

Both the smoothness and orthogonality demands were met in the relevant part of the grid.

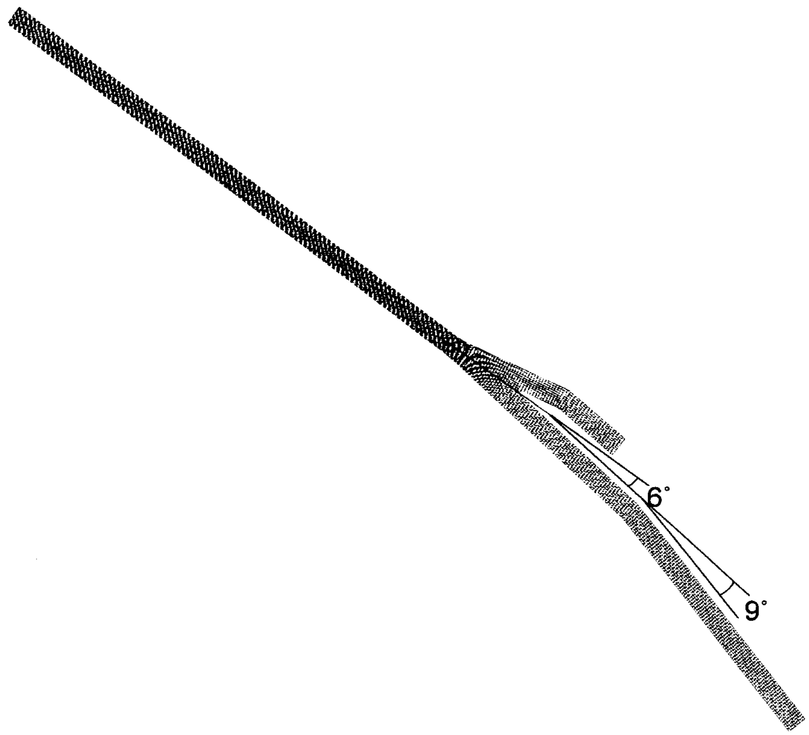


Figure 5.a Computational grid

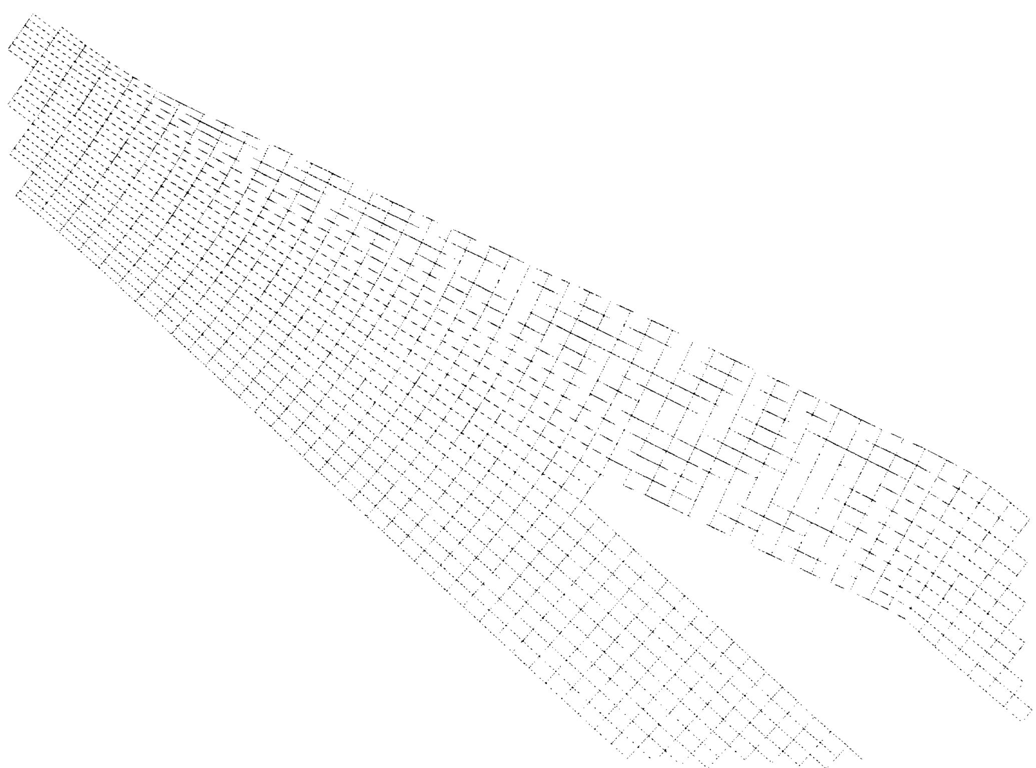


Figure 5.b Detail of the computational grid near the bifurcation

In vertical direction of the grid 10 layers have been chosen. The layer thickness is shown in next table as a percentage of the water depth (20 m); a decreasing thickness in the direction of the bottom has been applied. Notice that layer 1 is located just below the water surface, and layer 10 just above the bottom.

Layer	*% of the water depth*
1	26.44
2	19.85
3	14.90
4	11.18
5	8.39
6	6.30
7	4.73
8	3.55
9	2.66
10	2.00
total	100

The horizontal grid characteristics are summarized in next table.

quantity:	*value*
cell dimensions – upper section:	10 x 50 m^2
cell dimensions – lower branches:	22 x 35 m^2
grid size:	$n \times m \times k$ = 301 x 23 x 10
nr of active cells	5154 x 10 = 51540
channel width	220 m
non-orthogonality	< 0.014 (angle between the gridlines 89° - 91°)
non-smoothness	< 1.11

Other aspects of the hydraulic model

Besides the computational grid also bed topography, bottom roughness and boundary conditions are important modelling aspects.

A flat horizontal bed was assumed throughout the full model. The water depth of 20 m was imposed at the upstream boundary (left boundary in Figure 5.a). At the downstream boundaries (Post-Panamax Locks and Pedro Miguel Locks) the discontinuous water losses caused by lock operations was prescribed.

The bottom roughness was estimated with a Chézy-roughness of C = 50 $m^{1/2}/s$.

The outlet of the pumping station of the water recycling system was assumed just above the bottom and located 500 m away from the new Post-Panamax Locks. The outflow was directed perpendicular to the channel bank.

5.1.2 Computations

We have made various computations with different recycle quantities and different shipping intensities. In the case of 3-lift Post-Panamax Locks the recycle quantity at the Pacific side varies roughly between 1.15 m^3/s (locks with water saving basins, 1 Post-Panamax ship a day) and 43.4 m^3/s (locks without wsb's, 15 Post-Panamax ships a day). In the case of 2-lift locks the recycle quantity varies between 2.3 m^3/s (locks with water saving basins, 1 Post-Panamax ship a day) and 69.5 m^3/s (locks without wsb's, 15 Post-Panamax ships a day). Recycle quantities of single-lift locks are: minimum 2.3 m^3/s (locks with water saving basins, 1 Post-Panamax ship a day) and maximum 138.9 m^3/s (locks without wsb's, 15 Post-Panamax ships a day).

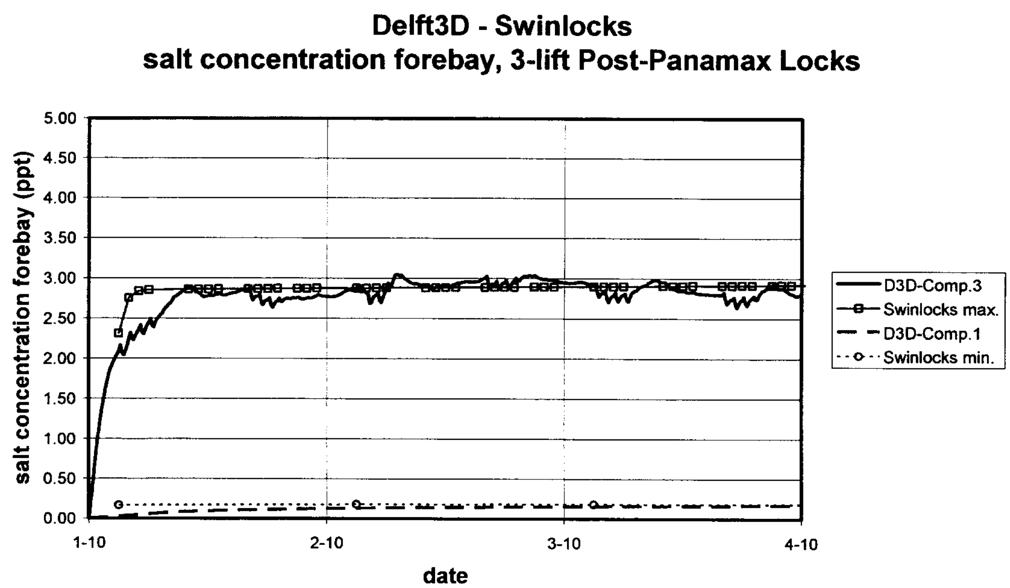
To get insight into salinity levels in the forebay of the Post-Panamax Locks we have made the following Delft3D-computations:

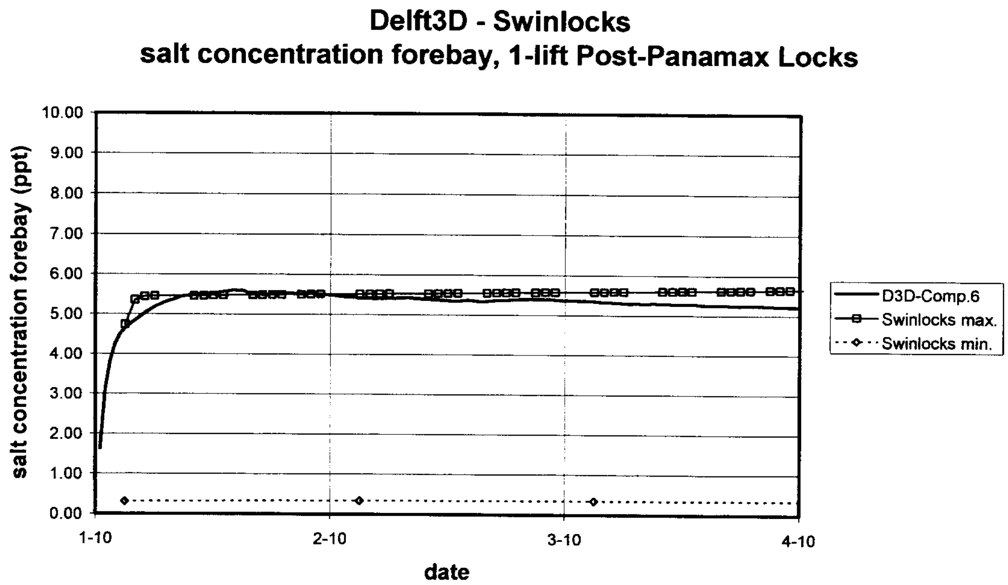
Computation no	Recycling of water			Ship intensity	
	quantity (m^3/s)	salt concentration (ppt)	continuously or intermittently	P-P Locks (ships/day)	P-M Locks (ships/day)
1	1.15	10	continuously	no ships	no ships
2	43.4	30	continuously	no ships	no ships
3	43.4	30	continuously	15	2 x 18
4	43.4	30	continuously	1	2 x 18
5	43.4	30	intermittently	15	2 x 18
6	138.9	30	continuously	no ships	no ships

The recycle quantity was varied between a minimum value of 1.15 m^3/s with salt concentration of 10 ppt and a maximum value of 138.9 m^3/s with salt concentration of 30 ppt. One computation (no 5) was done with an intermittent recycling discharge instead of a continuous discharge: the water loss (in Post-Panamax Locks) caused by an uplocking / downlocking ship was immediately recycled during a period of 10 minutes.
To check the effect of water losses at the locks and thus the effect of a water flow towards the locks, computations were done with and without uplocking / downlocking ships. In the case of ships the water losses caused by operation of Post-Panamax Locks and Pedro-Miguel Locks (water levelling, water displacement of ship) were effectuated as a concentrated outflow during a period of 10 minutes at the lock boundaries. In simulations without shipping no water losses were imposed at the lock boundaries. In the case of shipping the present ship traffic intensity of 18 ships a day in both west and east shipping lane was imposed at Pedro Miguel Locks; at the Post-Panamax Locks 1 ship transfer a day or 15 ship transfers a day were simulated.

Computations started with zero salinity in Gatun Lake and the forebays of locks. The simulation period covered three days. In all computations the recycled salt water propagated over the bottom (density flow) from the outlet of the pumping station into Gaillard Cut. An equilibrium salt concentration was reached in the forebay of the Post-Panamax Locks within one day (salt concentration averaged over the water volume of the forebay). The equilibrium salt concentration of the forebay appeared not very sensitive to water losses at the locks, but was mainly a function of the recycle discharge and the salt concentration of the recycled water. The intermittent recycling method (comp. no 5) caused strong variations of the salt concentration in the forebay, but the mean value was more or less the same as for continuous recycling.

Next figures present the computed volume-averaged salt concentration of the Post-Panamax Lock forebay as a function of time. Results of some Delft3D computations are compared with the salt concentration of the forebay simulated with Swinlocks (formulas of Sections 4.2.3 and 4.3.3 have been applied, describing the exchange of salt water between forebay and lake). The upper figure is valid for 3-lift Post-Panamax Locks, the lower figure for 1-lift Post-Panamax Locks.





The salt concentration values of Swinlocks are similar to those of Delft3D when the exchange coefficient e_{xfull} in:

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

(see Sections 4.2.3 and 4.3.3) is set to about 0.9. This choice implies that the water of the forebay has always a somewhat higher salt concentration in Swinlocks simulations than the water of the lake. The salt transfer from forebay to Gatun Lake is a little delayed, compared to the normally applied value e_{xfull} = 1.0 in simulations, but the final salt concentration is not effected.

In next sections the selection of other exchange coefficients used in Swinlocks is discussed.

5.2 Exchange coefficients Post-Panamax Locks with wsb's

Most exchange coefficients that are used in simulations for Post-Panamax Locks with wsb's, are not effected by recycling actions; these coefficients will remain as they are (they have been selected in previous studies, see Reports B, C and D). Exchange coefficients that are effected and additional exchange coefficients are further discussed.

In the case of direct water recycling, water is pumped from the tailbay to the forebay. For salt water intrusion simulations we assume that the pumped water has an equal salt concentration as the water of the tailbay (volume-averaged salt concentration). Consequently, the selected exchange coefficient has a value of 1.0, both for uplockage and downlockage of ships. However, the salt concentration in the tailbay (input for simulations, see Section 3.14) is corrected for the density effect of a lower water temperature in the dry season. Since this effect does not occur in direct pumping of water from tailbay to forebay, and recycling is mainly practised in the dry season, we reduce the recycle exchange coefficient with 10% from 1.0 till 0.9.

When a lower pond or a combination of a lower pond and upper pond form a part of the recycling system, the water that normally would be spilled from the lower lock chamber into the tailbay, is spilled into the lower pond. Similarly, fill water for the upper lock chamber that normally would be drawn from the forebay, is drawn from the upper pond. When the salt concentration of the lower lock chamber is considered, spilling of water to the tailbay through the lock emptying system is equivalent to spilling of water to the lower pond. Both actions take place after the wsb's of the lower lock chamber have been filled, while also the quantity of spilled water is the same and originates from the same water layer in the lock chamber. Therefore, there is no need to select a different exchange coefficient for these spill actions. As a value for the exchange coefficient *lower lock chamber → lower pond* we thus select a value of 1.25 for uplockage and 1.2 for downlockage (equal to the exchange coefficient *lower lock chamber → tailbay*).
Contrary, when the upper lock chamber is filled, withdrawing of water from the upper pond instead of the forebay is a different process. The offtakes in upper pond and forebay have a different geometry and location, while also the salt distributions in upper pond and forebay are different. For the withdrawal of water from the upper pond we select an exchange coefficient 1.0, both for uplockage and downlockage (note: the exchange coefficient *forebay → upper lock chamber* equals 0.95 for uplockage and 0.85 for downlockage). This choice supposes that the water in the upper pond is well mixed up during filling and has a more or less uniform density and salt concentration.
In the case of recycling of water from lower pond to forebay or recycling of water from lower pond to upper pond, we select an exchange coefficient 1.0 for the upward transfer of water, both for uplockage and downlockage; this choice supposes that the water in the lower pond is fully mixed up during filling and has an uniform density and salt concenration.

An overview of selected exchange coefficients for the Post-Panamax Locks at the Pacific side is presented in next sections. The exchange coefficients for all other locks remain as they have been selected in earlier studies (see Reports A, B, C and D).

5.2.1 Exchange coefficients for 3-lift locks with wsb's

Low basin	*High basin*	*Operation (Remarks)*	*Exchange coefficient*
Tailbay Lock G	Lock G	Fill wsb's of lock G	1.35
Tailbay Lock G	Lock G	Equalize water levels	1.25
Tailbay Lock G	Lock G	Move ship	0.7*
Lock G	Lock H	Empty wsb's of lock G	1.0
Lock G	Lock H	Fill wsb's of lock H	1.35
Lock G	Lock H	Equalize water levels	1.25
Lock G	Lock H	Move ship	0.05*
Lock H	Lock J	Empty wsb's of lock H	1.0
Lock H	Lock J	Fill wsb's of lock J	1.35
Lock H	Lock J	Equalize water levels	1.25
Lock H	Lock J	Move ship	0.0*
Lock J	Forebay Lock J	Empty wsb's of lock J	1.0
Lock J	Forebay Lock J	Equalize water levels	0.95
Lock J	Forebay Lock J	Move ship	0.0*
Tailbay Lock G	Forebay Lock J	Recycle water	0.9
Forebay Lock J	Gatun Lake	(Density flows)	0.9**

Table 5.1 Uplockage. Pacific Ocean → Gatun Lake. New lane, three-lift locks with wsb. Direct water recycling.

High basin	*Low basin*	*Operation (Remarks)*	*Exchange coefficient*
Gatun Lake	Forebay Lock J	(Density flows)	0.9**
Forebay Lock J	Lock J	Empty wsb's of lock J	1.0
Forebay Lock J	Lock J	Equalize water levels	0.85
Forebay Lock J	Lock J	Move ship	0.05*
Lock J	Lock H	Fill wsb's of lock J	1.2
Lock J	Lock H	Empty wsb's of lock H	1.0
Lock J	Lock H	Equalize water levels	1.2
Lock J	Lock H	Move ship	0.1*
Lock H	Lock G	Fill wsb's of lock H	1.2
Lock H	Lock G	Empty wsb's of lock G	1.0
Lock H	Lock G	Equalize water levels	1.2
Lock H	Lock G	Move ship	0.15*
Lock G	Tailbay Lock G	Fill wsb's of lock G	1.2
Lock G	Tailbay Lock G	Equalize water levels	1.2
Lock G	Tailbay Lock G	Move ship	0.4*
Forebay Lock J	Tailbay Lock G	Recycle water	0.9

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

Table 5.2 Downlockage. Gatun Lake → Pacific Ocean. New lane, three-lift locks with wsb. Direct water recycling.

Low basin	*High basin*	*Operation (Remarks)*	*Exchange coefficient*
Tailbay Lock G	Lock G	Fill wsb's of lock G	1.35
Lower Pond / Tailbay G	Lock G	Equalize water levels	1.25
Tailbay Lock G	Lock G	Move ship	0.7*
Lock G	Lock H	Empty wsb's of lock G	1.0
Lock G	Lock H	Fill wsb's of lock H	1.35
Lock G	Lock H	Equalize water levels	1.25
Lock G	Lock H	Move ship	0.05*
Lock H	Lock J	Empty wsb's of lock H	1.0
Lock H	Lock J	Fill wsb's of lock J	1.35
Lock H	Lock J	Equalize water levels	1.25
Lock H	Lock J	Move ship	0.0*
Lock J	Forebay Lock J	Empty wsb's of lock J	1.0
Lock J	Forebay Lock J	Equalize water levels	0.95
Lock J	Forebay Lock J	Move ship	0.0*
Lower Pond	Forebay Lock J	Recycle water	1.0
Forebay Lock J	Gatun Lake	(Density flows)	0.9**

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

Table 5.3 Uplockage. Pacific Ocean → Gatun Lake. New lane, three-lift locks with wsb. Recycling of water from LP to forebay.

High basin	*Low basin*	*Operation (Remarks)*	*Exchange coefficient*
Gatun Lake	Forebay Lock J	(Density flows)	0.9**
Forebay Lock J	Lock J	Empty wsb's of lock J	1.0
Forebay Lock J	Lock J	Equalize water levels	0.85
Forebay Lock J	Lock J	Move ship	0.05*
Lock J	Lock H	Fill wsb's of lock J	1.2
Lock J	Lock H	Empty wsb's of lock H	1.0
Lock J	Lock H	Equalize water levels	1.2
Lock J	Lock H	Move ship	0.1*
Lock H	Lock G	Fill wsb's of lock H	1.2
Lock H	Lock G	Empty wsb's of lock G	1.0
Lock H	Lock G	Equalize water levels	1.2
Lock H	Lock G	Move ship	0.15*
Lock G	Tailbay Lock G	Fill wsb's of lock G	1.2
Lock G	Lower Pond / Tailbay G	Equalize water levels	1.2
Lock G	Tailbay Lock G	Move ship	0.4*
Forebay Lock J	Lower Pond	Recycle water	1.0

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

Table 5.4 Downlockage. Gatun Lake → Pacific Ocean. New lane, three-lift locks with wsb. Recycling of water from LP to forebay.

Low basin	*High basin*	*Operation (Remarks)*	*Exchange coefficient*
Tailbay Lock G	Lock G	Fill wsb's of lock G	1.35
Lower Pond / Tailbay G	Lock G	Equalize water levels	1.25
Tailbay Lock G	Lock G	Move ship	0.7*
Lock G	Lock H	Empty wsb's of lock G	1.0
Lock G	Lock H	Fill wsb's of lock H	1.35
Lock G	Lock H	Equalize water levels	1.25
Lock G	Lock H	Move ship	0.05*
Lock H	Lock J	Empty wsb's of lock H	1.0
Lock H	Lock J	Fill wsb's of lock J	1.35
Lock H	Lock J	Equalize water levels	1.25
Lock H	Lock J	Move ship	0.0*
Lock J	Forebay Lock J	Empty wsb's of lock J	1.0
Lock J	Upper Pond / Forebay J	Equalize water levels	1.0
Lock J	Forebay Lock J	Move ship	0.0*
Lower Pond	Upper Pond	Recycle water	1.0
Forebay Lock J	Gatun Lake	(Density flows)	0.9**

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

Table 5.5 Uplockage. Pacific Ocean → Gatun Lake. New lane, three-lift locks with wsb. Recycling of water from LP to UP.

High basin	*Low basin*	*Operation (Remarks)*	*Exchange coefficient*
Gatun Lake	Forebay Lock J	(Density flows)	0.9**
Forebay Lock J	Lock J	Empty wsb's of lock J	1.0
Upper Pond / Forebay J	Lock J	Equalize water levels	1.0
Forebay Lock J	Lock J	Move ship	0.05*
Lock J	Lock H	Fill wsb's of lock J	1.2
Lock J	Lock H	Empty wsb's of lock H	1.0
Lock J	Lock H	Equalize water levels	1.2
Lock J	Lock H	Move ship	0.1*
Lock H	Lock G	Fill wsb's of lock H	1.2
Lock H	Lock G	Empty wsb's of lock G	1.0
Lock H	Lock G	Equalize water levels	1.2
Lock H	Lock G	Move ship	0.15*
Lock G	Tailbay Lock G	Fill wsb's of lock G	1.2
Lock G	Lower Pond / Tailbay G	Equalize water levels	1.2
Lock G	Tailbay Lock G	Move ship	0.4*
Upper Pond	Lower Pond	Recycle water	1.0

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

Table 5.6 Downlockage. Gatun Lake → Pacific Ocean. New lane, three-lift locks with wsb. Recycling of water from LP to UP.

5.2.2 Exchange coefficients for 2-lift locks with wsb's

Low basin	*High basin*	*Operation (Remarks)*	*Exchange coefficient*
Tailbay Lock P	Lock P	Fill wsb's of lock P	1.3
Lower Pond / Tailbay P	Lock P	Equalize water levels	1.15
Tailbay Lock P	Lock P	Move ship	0.7*
Lock P	Lock Q	Empty wsb's of lock P	1.0
Lock P	Lock Q	Fill wsb's of lock Q	1.3
Lock P	Lock Q	Equalize water levels	1.15
Lock P	Lock Q	Move ship	0.05*
Lock Q	Forebay Lock Q	Empty wsb's of lock Q	1.0
Lock Q	Upper Pond / Forebay Q	Equalize water levels	1.0
Lock Q	Forebay Lock Q	Move ship	0.0*
Lower Pond	Upper Pond	Recycle water	1.0
Forebay Lock Q	Gatun Lake	(Density flows)	0.9**

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

Table 5.7 Uplockage. Pacific Ocean → Gatun Lake. New lane, two-lift locks with wsb. Recycling of water from LP to UP.

High basin	*Low basin*	*Operation (Remarks)*	*Exchange coefficient*
Gatun Lake	Forebay Lock Q	(Density flows)	0.9**
Forebay Lock Q	Lock Q	Empty wsb's of lock Q	1.0
Upper Pond / Forebay Q	Lock Q	Equalize water levels	1.0
Forebay Lock Q	Lock Q	Move ship	0.10*
Lock Q	Lock P	Fill wsb's of lock Q	1.15
Lock Q	Lock P	Empty wsb's of lock P	1.0
Lock Q	Lock P	Equalize water levels	1.15
Lock Q	Lock P	Move ship	0.15*
Lock P	Tailbay Lock P	Fill wsb's of lock P	1.15
Lock P	Lower Pond / Tailbay P	Equalize water levels	1.15
Lock P	Tailbay Lock P	Move ship	0.4*
Upper Pond	Lower Pond	Recycle water	1.0

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

Table 5.8 Downlockage. Gatun Lake → Pacific Ocean. New lane, two-lift locks with wsb. Recycling of water from LP to UP.

5.2.3 Exchange coefficients for 1-lift locks with wsb's

Low basin	*High basin*	*Operation (Remarks)*	*Exchange coefficient*
Tailbay Lock N	Lock N	Fill wsb's of lock N	1.25
Lower Pond / Tailbay N	Lock N	Equalize water levels	1.05
Tailbay Lock N	Lock N	Move ship	0.7*
Lock N	Forebay Lock N	Empty wsb's of lock N	1.0
Lock N	Upper Pond / Forebay N	Equalize water levels	1.0
Lock N	Forebay Lock N	Move ship	0.05*
Lower Pond	Upper Pond	Recycle water	1.0
Forebay Lock N	Gatun Lake	(Density flows)	0.9**

*) 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 5.9 Uplockage. Pacific Ocean → Gatun Lake. New lane, single-lift locks with wsb. Recycling of water from LP to UP.

High basin	*Low basin*	*Operation (Remarks)*	*Exchange coefficient*
Gatun Lake	Forebay Lock N	(Density flows)	0.9**
Forebay Lock N	Lock N	Empty wsb's of lock N	1.0
Upper Pond / Forebay N	Lock N	Equalize water levels	1.0
Forebay Lock N	Lock N	Move ship	0.15*
Lock N	Tailbay Lock N	Fill wsb's of lock N	1.1
Lock N	Lower Pond / Tailbay N	Equalize water levels	1.1
Lock N	Tailbay Lock N	Move ship	0.4*
Upper Pond	Lower Pond	Recycle water	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 5.10 Downlockage. Gatun Lake → Pacific Ocean. New lane, single-lift locks with wsb. Recycling of water from LP to UP.

5.3 Exchange coefficients Post-Panamax Locks without wsb's

An overview of selected exchange coefficients for the locks at the Pacific side is presented in next tables.

5.3.1 Exchange coefficients for 3-lift locks without wsb's

Low basin	*High basin*	*Operation (Remarks)*	*Exchange coefficient*
Tailbay Lock G	Lock G	Equalize water levels	1.3
Tailbay Lock G	Lock G	Move ship	0.7*
Lock G	Lock H	Equalize water levels	1.3
Lock G	Lock H	Move ship	0.05*
Lock H	Lock J	Equalize water levels	1.3
Lock H	Lock J	Move ship	0.0*
Lock J	Forebay Lock J	Equalize water levels	0.95
Lock J	Forebay Lock J	Move ship	0.0*
Tailbay Lock G	Forebay Lock J	Recycle water	0.9
Forebay Lock J	Gatun Lake	(Density flows)	0.85**

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

Table 5.11 Uplockage. Pacific Ocean → Gatun Lake. New lane, three-lift locks without wsb. Direct water recycling.

High basin	*Low basin*	*Operation (Remarks)*	*Exchange coefficient*
Gatun Lake	Forebay Lock J	(Density flows)	0.85**
Forebay Lock J	Lock J	Equalize water levels	0.85
Forebay Lock J	Lock J	Move ship	0.05*
Lock J	Lock H	Equalize water levels	1.2
Lock J	Lock H	Move ship	0.1*
Lock H	Lock G	Equalize water levels	1.2
Lock H	Lock G	Move ship	0.15*
Lock G	Tailbay Lock G	Equalize water levels	1.2
Lock G	Tailbay Lock G	Move ship	0.4*
Forebay Lock J	Tailbay Lock G	Recycle water	0.9

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

Table 5.12 Downlockage. Gatun Lake → Pacific Ocean. New lane, three-lift locks without wsb. Direct water recycling.

Low basin	*High basin*	*Operation (Remarks)*	*Exchange coefficient*
Lower Pond / Tailbay G	Lock G	Equalize water levels	1.3
Tailbay Lock G	Lock G	Move ship	0.7*
Lock G	Lock H	Equalize water levels	1.3
Lock G	Lock H	Move ship	0.05*
Lock H	Lock J	Equalize water levels	1.3
Lock H	Lock J	Move ship	0.0*
Lock J	Forebay Lock J	Equalize water levels	0.95
Lock J	Forebay Lock J	Move ship	0.0*
Lower Pond	Forebay Lock J	Recycle water	1.0
Forebay Lock J	Gatun Lake	(Density flows)	0.85**

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

Table 5.13 Uplockage. Pacific Ocean → Gatun Lake. New lane, three-lift locks without wsb. Recycling of water from LP to forebay.

High basin	*Low basin*	*Operation (Remarks)*	*Exchange coefficient*
Gatun Lake	Forebay Lock J	(Density flows)	0.85**
Forebay Lock J	Lock J	Equalize water levels	0.85
Forebay Lock J	Lock J	Move ship	0.05*
Lock J	Lock H	Equalize water levels	1.2
Lock J	Lock H	Move ship	0.1*
Lock H	Lock G	Equalize water levels	1.2
Lock H	Lock G	Move ship	0.15*
Lock G	Lower Pond / Tailbay G	Equalize water levels	1.2
Lock G	Tailbay Lock G	Move ship	0.4*
Forebay Lock J	Lower Pond	Recycle water	1.0

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

Table 5.14 Downlockage. Gatun Lake → Pacific Ocean. New lane, three-lift locks without wsb. Recycling of water from LP to forebay.

Low basin	*High basin*	*Operation (Remarks)*	*Exchange coefficient*
Lower Pond / Tailbay G	Lock G	Equalize water levels	1.3
Tailbay Lock G	Lock G	Move ship	0.7*
Lock G	Lock H	Equalize water levels	1.3
Lock G	Lock H	Move ship	0.05*
Lock H	Lock J	Equalize water levels	1.3
Lock H	Lock J	Move ship	0.0*
Lock J	Upper Pond / Forebay J	Equalize water levels	1.0
Lock J	Forebay Lock J	Move ship	0.0*
Lower Pond	Upper Pond	Recycle water	1.0
Forebay Lock J	Gatun Lake	(Density flows)	0.85**

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

Table 5.15 Uplockage. Pacific Ocean → Gatun Lake. New lane, three-lift locks without wsb. Recycling of water from LP to UP.

High basin	*Low basin*	*Operation (Remarks)*	*Exchange coefficient*
Gatun Lake	Forebay Lock J	(Density flows)	0.85**
Upper Pond / Forebay J	Lock J	Equalize water levels	1.0
Forebay Lock J	Lock J	Move ship	0.05*
Lock J	Lock H	Equalize water levels	1.2
Lock J	Lock H	Move ship	0.1*
Lock H	Lock G	Equalize water levels	1.2
Lock H	Lock G	Move ship	0.15*
Lock G	Lower Pond / Tailbay G	Equalize water levels	1.2
Lock G	Tailbay Lock G	Move ship	0.4*
Upper Pond	Lower Pond	Recycle water	1.0

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

Table 5.16 Downlockage. Gatun Lake → Pacific Ocean. New lane, three-lift locks without wsb. Recycling of water from LP to UP.

5.3.2 Exchange coefficients for 2-lift locks without wsb's

Low basin	*High basin*	*Operation (Remarks)*	*Exchange coefficient*
Lower Pond / Tailbay P	Lock P	Equalize water levels	1.25
Tailbay Lock P	Lock P	Move ship	0.7*
Lock P	Lock Q	Equalize water levels	1.25
Lock P	Lock Q	Move ship	0.05*
Lock Q	Upper Pond / Forebay Q	Equalize water levels	1.0
Lock Q	Forebay Lock Q	Move ship	0.0*
Lower Pond	Upper Pond	Recycle water	1.0
Forebay Lock Q	Gatun Lake	(Density flows)	0.87**

*) 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 5.17 Uplockage. Pacific Ocean → Gatun Lake. New lane, two-lift locks without wsb. Recycling of water from LP to UP.

High basin	*Low basin*	*Operation (Remarks)*	*Exchange coefficient*
Gatun Lake	Forebay Lock Q	(Density flows)	0.87**
Upper Pond / Forebay Q	Lock Q	Equalize water levels	1.0
Forebay Lock Q	Lock Q	Move ship	0.1*
Lock Q	Lock P	Equalize water levels	1.15
Lock Q	Lock P	Move ship	0.15*
Lock P	Lower Pond / Tailbay P	Equalize water levels	1.15
Lock P	Tailbay Lock P	Move ship	0.4*
Upper Pond	Lower Pond	Recycle water	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 5.18 Downlockage. Gatun Lake → Pacific Ocean. New lane, two-lift locks without wsb. Recycling of water from LP to UP.

5.4 Other exchange coefficients

The exchange coefficients for the locks on the existing west and east shipping lanes do not change (for the values of the exchange coefficients reference is made to Report A). The same holds for the Post-Panamax Locks at the Atlantic side of the the new shipping lane (see Reports B, C and D for exchange coefficients).

We also assume that the exchange coefficients related to the release of water at Gatun Dam and Miraflores Dam are uneffected by the recycling of water at the Pacific side of the canal. The values of these exchange coefficients have been selected on the basis of validation runs for the existing situation (see report A).

6 Testing of simulation model

The three-lift Post-Panamax Locks in the salt-intrusion simulation model have been provided with three options for water recycling at the Pacific side of the canal. In addition, the two-lift and single-lift Post-Panamax Locks have been provided with a single option for water recycling. These extensions required the formulation of new expressions for water balance and salt balance, the definition of extra scenarios for ship movements and turn arounds, the definition of new nodes (Lower Pond and Upper Pond), and the extension of the input tables 'Initial Values' and 'Coefficient Set'. A check of the proper functioning of the extended simulation model was, therefore, necessary. The results of testing of the new elements in the simulation model is described in next sections for each Post-Panamax Lock configuration separately.

6.1 Three-lift Post-Panamax Locks with water recycling

Input data
Test cases were such designed that the functioning of in particular the new items (three options for water recycling) could be checked. Next Day Patterns and Coefficient Set were used in the test runs:

Day Pattern	*Scenarios in Day Pattern*	*Locks / recycling option*
d1	ship movement Pac.→GL, Turn around N→S, ship movement GL→Pac., Turn around S→N; ship type VIII	3-lift locks, water recycling option: tailbay→forebay
d1a	ship movement Pac.→GL, Turn around N→S, ship movement GL→Pac., Turn around S→N; ship type VIII	3-lift locks, no water recycling
d1a-r	ship movement Atl.→GL, Turn around S→N, ship movement GL→Atl., Turn around N→S; ship type VIII	3-lift locks, no water recycling
d2	ship movement Pac.→GL, Turn around N→S, ship movement GL→Pac., Turn around S→N; ship type VIII	3-lift locks, water recycling option: LP→forebay
d3	ship movement Pac.→GL, Turn around N→S, ship movement GL→Pac., Turn around S→N; ship type VIII	3-lift locks, water recycling option: LP→UP
d4	ship movement Pac.→GL, Turn around N→S, ship movement GL→Pac., Turn around S→N; ship type VIII	3-lift locks + wsb's, water recycling option: tailbay→forebay
d5	ship movement Pac.→GL, Turn around N→S, ship movement GL→Pac., Turn around S→N; ship type VIII	3-lift locks + wsb's, water recycling option: LP→forebay
d6	ship movement Pac.→GL, Turn around N→S, ship movement GL→Pac., Turn around S→N; ship type VIII	3-lift locks + wsb's, water recycling option: LP→UP
d6a	ship movement Pac.→GL, Turn around N→S, ship movement GL→Pac., Turn around S→N; ship type VIII	3-lift locks + wsb's, no water recycling

Table 6.1 Overview of Day Patterns used in test cases, three-lift locks

Basins involved in exchange	*up fill wsb*	*up empty wsb*	*down fill wsb*	*down empty wsb*
Lock G ⇔ G-wsb	0.111	0.211	0.311	0.411
Lock H ⇔ H-wsb	0.122	0.222	0.322	0.422
Lock J ⇔ J-wsb	0.133	0.233	0.333	0.433
Lock K ⇔ K-wsb	0.177	0.277	0.377	0.477
Lock L ⇔ L-wsb	0.166	0.266	0.366	0.466
Lock M ⇔ M-wsb	0.155	0.255	0.355	0.455
	up equalize	*up move ship*	*down equalize*	*down move ship*
tailbay G ⇔ Lock G	0.11	0.21	0.31	0.41
Lock G ⇔ Lock H	0.12	0.22	0.32	0.42
Lock H ⇔ Lock J	0.13	0.23	0.33	0.43
Lock J ⇔ forebay J	0.14	0.24	0.34	0.44
Lock M ⇔ forebay M	0.18	0.28	0.38	0.48
Lock L ⇔ Lock M	0.17	0.27	0.37	0.47
Lock K ⇔ Lock L	0.16	0.26	0.36	0.46
tailbay K ⇔ Lock K	0.15	0.25	0.35	0.45
	up recycling		*down recycling*	
tailbay G ⇔ forebay J	0.1111	-	0.3111	-
Lower Pond ⇔ Lock G	0.1222	-	0.3222	-
Lower Pond ⇔ forebay J	0.1333	-	0.3333	-
Lower Pond ⇔ Upper Pond	0.1444	-	0.3444	-
Lock J ⇔ Upper Pond	0.1555	-	0.3555	-
	up forebay-lake exchange		*down forebay-lake exchange*	
forebay J ⇔ Gatun Lake	1.0	-	1.0	-
forebay M ⇔ Gatun Lake	1.0	-	1.0	-

Table 6.2 Overview of salt exchange coefficients in Coefficient Set c1, used in test cases, three-lift locks

The exchange coefficients in the above Coefficient Set c1 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 exchange coefficients in the salt balance computations.

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 3.49 were selected). Water levels of Miraflores Lake and Gatun Lake, tidal movements in the tailbays, dimensions of locks, water saving basins, lower pond and upper pond were all prescribed (default values, see extensive discussion in Chapter 3).
The purpose of the tests was to check the set up of water balance and salt balance in relation to the new water recycling options in the simulation model. The results of the water-balance and salt-balance computations have been checked by computations 'by hand'. Test Case 7 was set up to check the execution of daypatterns which are prescribed for a few, specific days in the simulation period.

An overwiew of test cases is presented in Table 6.3.

Test Case	*Coefficient Set*	*Day Pattern*	*Period*	*Output interval*	*Remarks*
1	c1	d1	Jan 1 – Jan 5, 1970	scenario	single ship, S = 285000
1a	c1	d1a	Jan 1 – Jan 5, 1970	scenario	single ship, S = 285000
1a-r	c1	d1a-r	Jan 1 – Jan 5, 1970	scenario	single ship, S = 285000
2	c1	d2	Jan 1 – Jan 5, 1970	scenario	single ship, S = 285000
3	c1	d3	Jan 1 – Jan 5, 1970	scenario	single ship, S = 285000
4	c1	d4	Jan 1 – Jan 5, 1970	scenario	single ship, S = 285000
5	c1	d5	Jan 1 – Jan 5, 1970	scenario	single ship, S = 285000
6	c1	d6	Jan 1 – Jan 5, 1970	scenario	single ship, S = 285000
6a	c1	d6a	Jan 1 – Jan 5, 1970	scenario	single ship, S = 285000
7	c1	d1*	Jan 1 – Jan 30, 1970	scenario	single ship, S = 285000

*) daypattern only prescribed for day 2, 3, 5, 6, 19 and 20

Table 6.3 Test Cases for recycling options of three-lift locks

Conclusions

The water balance and salt balance are well computed within the extended simulation model for all three options of water recycling at the Pacific side of the canal: salt water migrates properly from the tailbays in the sea entrances to all higher basins, to wsb's and to lower and upper pond, the time-dependent exchange of salt water between forebays and lakes is correct. As an example some results of Test Case 6 are shown in Figures TC6, 1-6 in Figures Simulations 3-lift locks. Test Case 7 demonstrates that daypatterns are only executed at prescribed days in the simulation period.

As an extra test the validation case for the existing situation (Case VAL1, see Report A) has been run with the extended simulation model as Case A-1. It appeared that the extended model produced fully identical results, see Figures A-1, 1 and A-1, 2. Also the earlier case B1-50 (future situation, 3-lift locks, no recycling, see Report C) has been run with the extended model; results are shown in Figures B1-50, 1 and B1-50, 2.

6.2 Two-lift Post-Panamax Locks with water recycling

Input data

Test cases were such designed that in particular the single option for water recycling (Lower Pond → Upper Pond) could be checked. Next Day Patterns and Coefficient Set were used in the test runs:

Day Pattern	*Scenarios in Day Pattern*	*Locks / recycling option*
d3	ship movement Pac.→GL, Turn around N→S, ship movement GL→Pac., Turn around S→N; ship type VIII	2-lift locks, water recycling option: LP→UP
d3a	ship movement Pac.→GL, Turn around N→S, ship movement GL→Pac., Turn around S→N; ship type VIII	2-lift locks, no water recycling
d3a-r	ship movement Atl.→GL, Turn around S→N, ship movement GL→Atl., Turn around N→S; ship type VIII	2-lift locks, no water recycling
d6	ship movement Pac.→GL, Turn around N→S, ship movement GL→Pac., Turn around S→N; ship type VIII	2-lift locks + wsb's, water recycling option: LP→UP
d6a	ship movement Pac.→GL, Turn around N→S, ship movement GL→Pac., Turn around S→N; ship type VIII	2-lift locks + wsb's, no water recycling

Table 6.4 Overview of Day Patterns used in test cases, two-lift locks

Basins involved in exchange	*up fill wsb*	*up empty wsb*	*down fill wsb*	*down empty wsb*
Lock P ⇔ P-wsb	0.111	0.211	0.311	0.411
Lock Q ⇔ Q-wsb	0.122	0.222	0.322	0.422
Lock R ⇔ R-wsb	0.166	0.266	0.366	0.466
Lock S ⇔ S-wsb	0.155	0.255	0.355	0.455
	up equalize	*up move ship*	*down equalize*	*down move ship*
tailbay P ⇔ Lock P	0.11	0.21	0.31	0.41
Lock P ⇔ Lock Q	0.12	0.22	0.32	0.42
Lock Q ⇔ forebay Q	0.13	0.23	0.33	0.43
Lock S ⇔ forebay S	0.17	0.27	0.37	0.47
Lock R ⇔ Lock S	0.16	0.26	0.36	0.46
tailbay R ⇔ Lock R	0.15	0.25	0.35	0.45
	up recycling		*down recycling*	
Lower Pond ⇔ Lock P	0.1111	-	0.3111	-
Lower Pond ⇔ Upper Pond	0.1222	-	0.3222	-
Lock Q ⇔ Upper Pond	0.1333	-	0.3333	-
	up forebay-lake exchange		*down forebay-lake exchange*	
forebay Q ⇔ Gatun Lake	1.0	-	1.0	-
forebay S ⇔ Gatun Lake	1.0	-	1.0	-

Table 6.5 Overview of salt exchange coefficients in Coefficient Set c1, used in test cases, two-lift locks

For the purpose of a fast check of the use of the various exchange coefficients in the salt balance computations the coefficients in the above Coefficient Set c1 have all different values; these values are not realistic.

Test cases

Similar as for the three-lift locks 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 as well as water levels of Miraflores Lake and Gatun Lake, tidal movements in the tailbays, dimensions of locks, water saving basins, lower pond and upper pond (default values, see extensive discussion in Chapter 3).

The purpose of the tests was to check the set up of water balance and salt balance in relation to the new water recycling option in the simulation model. The results of the water-balance and salt-balance computations have been checked by computations 'by hand'.

An overwiew of test cases is presented in Table 6.6.

Test Case	*Coefficient Set*	*Day Pattern*	*Period*	*Output interval*	*Remarks*
3	c1	d3	Jan 1 – Jan 5, 1970	scenario	single ship, S = 285000
3a	c1	d3a	Jan 1 – Jan 5, 1970	scenario	single ship, S = 285000
3a-r	c1	d3a-r	Jan 1 – Jan 5, 1970	scenario	single ship, S = 285000
6	c1	d6	Jan 1 – Jan 5, 1970	scenario	single ship, S = 285000
6a	c1	d6a	Jan 1 – Jan 5, 1970	scenario	single ship, S = 285000

Table 6.6 Test Cases for recycling option of two-lift locks

Conclusions

The water balance and salt balance are well computed within the extended simulation model for the single option of water recycling at the Pacific side of the canal: salt water migrates properly from the tailbays in the sea entrances to all higher basins, to wsb's and to lower and upper pond, the time-dependent exchange of salt water between forebays and lakes is correct.

As an extra test the validation case for the existing situation (Case VAL1, see Report A) has been run with the extended simulation model as Case A-1. It appeared that the extended model produced fully identical results, see Figures A-1, 1 and A-1, 2. Also the earlier case C1-50 (future situation, 2-lift locks, no recycling, see Report D) has been run with the extended model; results are shown in Figures C1-50, 1 and C1-50, 2.

6.3 Single-lift Post-Panamax Locks with water recycling

Input data

Next Day Patterns and Coefficient Set were used in test cases which were designed to check in particular the single option for water recycling (Lower Pond → Upper Pond) in the extended model:

Day Pattern	*Scenarios in Day Pattern*	*Locks / recycling option*
d3	ship movement Pac.→GL, Turn around N→S, ship movement GL→Pac., Turn around S→N; ship type VIII	1-lift locks, water recycling option: LP→UP
d6	ship movement Pac.→GL, Turn around N→S, ship movement GL→Pac., Turn around S→N; ship type VIII	1-lift locks + wsb's, water recycling option: LP→UP
d6a	ship movement Pac.→GL, Turn around N→S, ship movement GL→Pac., Turn around S→N; ship type VIII	1-lift locks + wsb's, no water recycling

Table 6.7 Overview of Day Patterns used in test cases, single-lift locks

Basins involved in exchange	*up fill wsb*	*up empty wsb*	*down fill wsb*	*down empty wsb*
Lock N ⇔ N-wsb	0.111	0.211	0.311	0.411
Lock O ⇔ O-wsb	0.155	0.255	0.355	0.455
	up equalize	*up move ship*	*down equalize*	*down move ship*
tailbay N ⇔ Lock N	0.11	0.21	0.31	0.41
Lock N ⇔ forebay N	0.12	0.22	0.32	0.42
Lock O ⇔ forebay O	0.16	0.26	0.36	0.46
tailbay O ⇔ Lock O	0.15	0.25	0.35	0.45
	up recycling		*down recycling*	
Lower Pond ⇔ Lock N	0.1111	-	0.3111	-
Lower Pond ⇔ Upper Pond	0.1222	-	0.3222	-
Lock N ⇔ Upper Pond	0.1333	-	0.3333	-
	up forebay-lake exchange		*down forebay-lake exchange*	
forebay N ⇔ Gatun Lake	1.0	-	1.0	-
forebay O ⇔ Gatun Lake	1.0	-	1.0	-

Table 6.8 Overview of salt exchange coefficients in Coefficient Set c1, used in test cases, single-lift locks

For the purpose of a fast check of the use of the various exchange coefficients in the salt balance computations the coefficients in the above Coefficient Set c1 have all different values; these values are not realistic.

Test cases

Similar as for the three-lift locks and two-lift locks 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 as well as water levels of Miraflores Lake and Gatun Lake, tidal movements in the tailbays, dimensions of locks, water saving basins, lower pond and upper pond (default values, see extensive discussion in Chapter 3).

The purpose of the tests was to check the set up of water balance and salt balance in relation to the new water recycling option in the simulation model. The results of the water-balance and salt-balance computations have been checked by computations 'by hand'.

An overwiew of test cases is presented in Table 6.9.

Test Case	*Coefficient Set*	*Day Pattern*	*Period*	*Output interval*	*Remarks*
3	c1	d3	Jan 1 – Jan 5, 1970	scenario	single ship, S = 285000
6	c1	d6	Jan 1 – Jan 5, 1970	scenario	single ship, S = 285000
6a	c1	d6a	Jan 1 – Jan 5, 1970	scenario	single ship, S = 285000

Table 6.9 Test Cases for recycling option of single-lift locks

Conclusions

The water balance and salt balance are well computed within the extended simulation model for the single option of water recycling at the Pacific side of the canal: salt water migrates properly from the tailbays in the sea entrances to all higher basins, to wsb's and to lower and upper pond, the time-dependent exchange of salt water between forebays and lakes is correct.

As an extra test the validation case for the existing situation (Case VAL1, see Report A) has been run with the extended simulation model as Case A-1. It appeared that the extended model produced fully identical results, see Figures A-1, 1 and A-1, 2. Also the earlier case D1-50 (future situation, 1-lift locks, no recycling, see Report B) has been run with the extended model; results are shown in Figures D1-50, 1 and D1-50, 2.

7 Effect of water recycling on salinity levels

In this chapter we present the results of the salt-water intrusion analysis for the case that water is recycled. Post-Panamax Locks are built at both ends of the new, third shipping lane. These locks may be provided with water saving basins (wsb's). In dry periods, when there is a shortage of fresh water, the water that is lost by operation of the Post-Panamax Locks at the Pacific side of the canal, is recycled. The effect of water recycling on salt concentration levels of Gatun Lake and Miraflores Lake is analysed for three-lift, two-lift and single-lift configurations of Post-Panamax Locks for various recycling options.

7.1 Ship traffic intensities in simulations

The salt water intrusion in the future situation with Post-Panamax Locks and water recycling, is analysed for a period of 2 years with 1 Post-Panamax ship a day, a period of 3 years with 5 Post-Panamax ships a day, a period of 5 years with 10 Post-Panamax ships a day and finally a period of 5 years with 15 Post-Panamax ships a day. The latter ship-traffic intensity is expected for year 50 after opening of the third lane (we assume that the new lane will come in operation at January 1, 2011). The number of ship transits in west - and east shipping lane is maintained in the simulations at the present 18 ships a day in each lane.

The number of transiting ships a day and the type of ships are presented in next table for the considered periods. Panamax vessels are represented by ship type III, regular ships by ship types I and II, Post-Panamax vessels by ship type VIII (see Section 3.11).

Period	*Jan 1, 2011 – Dec 31, 2012*	*Jan 1, 2013 – Dec 31, 2015*	*Jan 1, 2026 – Dec 31, 2030*	*Jan 1, 2056 – Dec 31, 2060*
Vessel type	*Number of ships*			
Existing shipping lane West				
Type I	8	8	8	8
Type II	4	4	4	4
Type III	6	6	6	6
Total	**18**	**18**	**18**	**18**
Existing shipping lane East				
Type I	8	8	8	8
Type II	4	4	4	4
Type III	6	6	6	6
Total	**18**	**18**	**18**	**18**
Future, third shipping lane				
Type VIII	1	5	10	15
Total	**1**	**5**	**10**	**15**

Table 7.1 Ship transits in simulation model in existing and new shipping lanes

7.2 Effect of water recycling, 3-lift locks

7.2.1 Water control scenarios Gatun Lake and set up of cases

The water control scenarios for Gatun Lake as discussed in Section 3.13, form the starting point in the set up of cases. These scenarios are summarized in next table. Simulation cases have been built up for ship traffic intensities of 1, 5, 10 and 15 Post-Panamax ships a day in the new shipping lane, in addition to 18 ship transits a day in both west and east shipping lane. The various cases are shown in Table 7.2. The table presents also the total number of recycling days a year for each scenario considered. The number of recycling days is computed from the water balance of Gatun Lake: water is recycled at the Pacific side of the canal when the loss of water caused by operation of the Post-Panamax Locks at both sides of the canal exceeds the quantity of water that can be saved by reducing the water releases (spilled and used for hydropower) at Gatun Dam.

Water-Control scenario Gatun Lake	*Description*	*Case*	*Number of recycling days a year*
5	• Post-Panamax Locks with wsb's	B5-1ship	17
	• water releases at Gatun Dam are *reduced*	B5-5ships	92
	• if needed, recycling of water; lower pond > upper pond	B5-10ships	120
	• if needed, extra fresh water supply to Gatun Lake	B5-15ships	120
6	• Post-Panamax Locks without wsb's	B6-1ship	61
	• water releases at Gatun Dam are *reduced*	B6-5ships	120
	• if needed, recycling of water; lower pond > upper pond	B6-10ships	147
	• if needed, extra fresh water supply to Gatun Lake	B6-15ships	205
7	• Post-Panamax Locks with wsb's	B7-1ship	17
	• water releases at Gatun Dam are *reduced*	B7-5ships	92
	• if needed, recycling of water; lower pond > forebay	B7-10ships	120
	• if needed, extra fresh water supply to Gatun Lake	B7-15ships	120
8	• Post-Panamax Locks without wsb's	B8-1ship	61
	• water releases at Gatun Dam are *reduced*	B8-5ships	120
	• if needed, recycling of water; lower pond > forebay	B8-10ships	147
	• if needed, extra fresh water supply to Gatun Lake	B8-15ships	205
9	• Post-Panamax Locks with wsb's	B9-1ship	17
	• water releases at Gatun Dam are *reduced*	B9-5ships	92
	• if needed, recycling of water; tailbay > forebay	B9-10ships	120
	• if needed, extra fresh water supply to Gatun Lake	B9-15ships	120
10	• Post-Panamax Locks without wsb's	B10-1ship	61
	• water releases at Gatun Dam are *reduced*	B10-5ships	120
	• if needed, recycling of water; tailbay > forebay	B10-10ships	147
	• if needed, extra fresh water supply to Gatun Lake	B10-15ships	205

Table 7.2 Water control scenarios Gatun Lake and simulations for 3-lift locks

Next data is used in the numerical simulations:

- Dimensions of locks, forebays, tailbays, water saving basins, upper pond and lower pond: see Section 3.12
- Tidal movements and salt concentration of seaside tailbays: see Section 3.14
- Water levels, water volumes, water releases of Gatun Lake and Miraflores Lake (water releases depending on water control scenarios of Gatun Lake), water recycling quantities and number of recycling days: see Section 3.13
- Initial salt concentrations of Gatun Lake and Miraflores Lake: end values of corresponding simulations for 3-lift locks without water recycling are selected (values are taken from Report C).
- Exchange coefficients: see Section 5.2.

7.2.2 Results of simulations

The computed volume-averaged salt concentrations (ppt) of Miraflores Lake and Gatun Lake for a ship traffic intensity of 15 ships a day are shown in Figures B5-15s,1 through B10-15s,2 in 'Figures Simuations 3-lift Locks'. As can be seen the salt concentrations of Miraflores Lake and Gatun Lake fluctuate as a function of wet and dry season and the scenarios applied to control the water level of Gatun Lake.

The computed maximum and minimum value of the volume-averaged salt concentration of Miraflores Lake and Gatun Lake in the last year of the considered period are presented in Table 7.3. For reasons of comparison also the present salinity levels of the lakes are shown (case A).

Case and no of PP-ships a day	*Considered year*	*Salt conc. (ppt) Miraflores Lake*		*Salt conc. (ppt) Gatun Lake*	
		minimum	*maximum*	*minimum*	*maximum*
A, existing	-	0.64	1.42	0.010	0.027
B5-1ship	2	0.66	1.67	0.068	0.19
B5-5ships	5	0.69	1.75	0.084	0.32
B5-10ships	20	0.78	2.15	0.23	0.93
B5-15ships	50	0.89	2.71	0.50	1.63
B6-1ship	2	0.63	1.64	0.027	0.075
B6-5ships	5	0.66	1.59	0.044	0.22
B6-10ships	20	0.83	2.21	0.31	1.00
B6-15ships	50	1.22	3.17	1.08	2.20
B7-1ship	2	0.66	1.68	0.069	0.20
B7-5ships	5	0.69	1.87	0.095	0.46
B7-10ships	20	0.80	2.36	0.26	1.24
B7-15ships	50	0.93	3.10	0.56	2.09
B8-1ship	2	0.63	1.68	0.030	0.12
B8-5ships	5	0.69	1.88	0.088	0.61
B8-10ships	20	0.96	2.82	0.52	1.87

B8-15ships	50	1.64	4.44	1.79	3.92
B9-1ship	2	0.66	1.68	0.069	0.20
B9-5ships	5	0.70	1.93	0.10	0.54
B9-10ships	20	0.81	2.40	0.26	1.30
B9-15ships	50	0.93	3.17	0.57	2.17
B10-1ship	2	0.64	1.73	0.035	0.19
B10-5ships	5	0.73	2.26	0.15	1.17
B10-10ships	20	1.07	3.45	0.72	2.67
B10-15ships	50	1.92	5.35	2.28	5.08

Table 7.3 Maximum and minimum values of volume-averaged salt concentration of Miraflores Lake and Gatun Lake, 3-lift locks

The above maximum and minimum values have been plotted in Figures 7.1 (Miraflores Lake) and 7.2 (Gatun Lake). From Figure 7.1 it appears that the salt concentration of Miraflores Lake rises for all ship traffic intensities and all scenarios, compared to the present situation. Since Miraflores Lake is by-passed by the new shipping lane the effect of the new shipping lane and recycling is an indirect effect. Contrary, Gatun Lake is directly effected by the new shipping lane; the salt concentration of Gatun Lake (Figure 7.2) increases considerably for all ship traffic intensities and scenarios. As may be expected, direct water recycling from tailbay to forebay (scenarios B9 and B10) is the most unfavourable recycling option, recycling of water from lower storage pond to upper storage pond (scenarios B5 and B6) is the least unfavourable option. In general, the use of water saving basins is favourable when water is recycled (scenarios B5, B7 and B9), since the quantity of salt water that is recycled and intrudes the lakes is smaller. When water recycling is not practised water saving basins cause a stronger salt water intrusion, because a lesser quantity of fresh water is involved in the lockage process.

The results of the present and former simulations (all scenarios B1 – B10, see Table 3.47) are collected in Figure 7.3. Volume-averaged salt concentrations of Gatun Lake and Miraflores Lake are shown for a ship-traffic intensity of 15 Post-Panamax ships a day, which corresponds to the traffic level of year 50 after opening of the new shipping lane (see Table 2.2). From the view point of salt water intrusion prevention, Figure 7.3 clearly demonstrates that scenarios with water recycling in dry periods of the year (B5 – B10) are a bad alternative for scenarios (B1 – B4) where fresh water is supplied from new water sources to compensate for the water losses of the Post-Panamax Locks. In all water recycling scenarios the volume-averaged salt concentration of Gatun Lake rises in year 50 above the fresh-water limit. (Note: A value of 200 mg/l chloridity is used in the Netherlands as a fresh-water limit value; this corresponds to about 400 mg/l or 0.4 ppt salinity. In the USA a value of 250 mg/l cloridity (about 0.5 ppt salinity) is used as an upper limit for drinking water (Environmental Protection Agency standard)).

7.3 Effect of water recycling, 2-lift locks

7.3.1 Water control scenarios Gatun Lake and set up of cases

Similar as for the 3-lift locks the water control scenarios for Gatun Lake as discussed in Section 3.13, form the starting point in the set up of cases. These scenarios are summarized in next table. Simulation cases have been built up for ship traffic intensities of 1, 5, 10 and 15 Post-Panamax ships a day in the new shipping lane, in addition to 18 ship transits a day in both west and east shipping lane. The cases are shown in Table 7.4, together with the total number of recycling days a year for the scenarios considered.

Water-Control scenario Gatun Lake	*Description*	*Case*	*Number of recycling days a year*
5	• Post-Panamax Locks with wsb's	C5-1ship	61
	• water releases at Gatun Dam are *reduced*	C5-5ships	120
	• if needed, recycling of water; lower pond > upper pond	C5-10ships	126
	• if needed, extra fresh water supply to Gatun Lake	C5-15ships	164
6	• Post-Panamax Locks without wsb's	C6-1ship	75
	• water releases at Gatun Dam are *reduced*	C6-5ships	126
	• if needed, recycling of water; lower pond > upper pond	C6-10ships	208
	• if needed, extra fresh water supply to Gatun Lake	C6-15ships	281

Table 7.4 Water control scenarios Gatun Lake and simulations for 2-lift locks

Next data is used in the numerical simulations:

- Dimensions of locks, forebays, tailbays, water saving basins, upper pond and lower pond: see Section 3.12
- Tidal movements and salt concentration of seaside tailbays: see Section 3.14
- Water levels, water volumes, water releases of Gatun Lake and Miraflores Lake (water releases depending on water control scenarios of Gatun Lake), water recycling quantities and number of recycling days: see Section 3.13
- Initial salt concentrations of Gatun Lake and Miraflores Lake: end values of corresponding simulations for 2-lift locks without water recycling are selected (values are taken from Report D).
- Exchange coefficients: see Section 5.2.

7.3.2 Results of simulations

The computed volume-averaged salt concentrations (ppt) of Miraflores Lake and Gatun Lake for a ship traffic intensity of 15 ships a day are shown in Figures C5-15s,1 through C6-15s,2 in 'Figures Simuations 2-lift Locks'.

The computed maximum and minimum value of the volume-averaged salt concentration of Miraflores Lake and Gatun Lake in the last year of the considered period are presented in

Table 7.5. For reasons of comparison also the present salinity levels of the lakes are shown (case A).

Case and no of PP-ships a day	*Considered year*	*Salt conc. (ppt) Miraflores Lake*		*Salt conc. (ppt) Gatun Lake*	
		minimum	*maximum*	*minimum*	*maximum*
A, existing	-	0.64	1.42	0.010	0.027
C5-1ship	2	0.66	1.67	0.071	0.19
C5-5ships	5	0.73	1.82	0.16	0.53
C5-10ships	20	0.97	2.62	0.54	1.52
C5-15ships	50	1.40	3.78	1.38	2.98
C6-1ship	2	0.64	1.61	0.045	0.12
C6-5ships	5	0.72	1.76	0.14	0.45
C6-10ships	20	1.30	3.09	1.11	2.12
C6-15ships	50	2.19	4.67	2.80	3.66

Table 7.5 Maximum and minimum values of volume-averaged salt concentration of Miraflores Lake and Gatun Lake, 2-lift locks

The above maximum and minimum values have been plotted in Figures 7.4 (Miraflores Lake) and 7.5 (Gatun Lake). Similar as for the 3-lift locks, Figures 7.4 and 7.5 show that the salt concentration of Miraflores Lake and Gatun Lake rises for all ship traffic intensities and all scenarios, compared to the present situation.

The results of the present and former simulations (scenarios C1 – C6, see Table 3.47) are collected in Figure 7.6. Volume-averaged salt concentrations of Gatun Lake and Miraflores Lake are shown for a ship-traffic intensity of 15 Post-Panamax ships a day, which corresponds to the traffic level of year 50 after opening of the new shipping lane (see Table 2.2). Figure 7.6 shows that scenarios with water recycling in dry periods of the year (C5 – C6) are most unfavourable.

7.4 Effect of water recycling, 1-lift locks

7.4.1 Water control scenarios Gatun Lake and set up of cases

The water control scenarios for Gatun Lake as discussed in Section 3.13, form the starting point in the set up of cases. Simulation cases have been built up for ship traffic intensities of 1, 5, 10 and 15 Post-Panamax ships a day in the new shipping lane, in addition to 18 ship transits a day in both west and east shipping lane. The cases are shown in Table 7.6, together with the total number of recycling days a year for the single scenario considered.

Water-Control scenario Gatun Lake	*Description*	*Case*	*Number of recycling days a year*
5	• Post-Panamax Locks with wsb's	D5-1ship	61
	• water releases at Gatun Dam are *reduced*	D5-5ships	120
	• if needed, recycling of water; lower pond > upper pond	D5-10ships	129
	• if needed, extra fresh water supply to Gatun Lake	D5-15ships	171

Table 7.6 Water control scenario Gatun Lake and simulations for 1-lift locks

Next data is used in the numerical simulations:

- Dimensions of locks, forebays, tailbays, water saving basins, upper pond and lower pond: see Section 3.12
- Tidal movements and salt concentration of seaside tailbays: see Section 3.14
- Water levels, water volumes, water releases of Gatun Lake and Miraflores Lake (water releases depending on water control scenarios of Gatun Lake), water recycling quantities and number of recycling days : see Section 3.13
- Initial salt concentrations of Gatun Lake and Miraflores Lake: end values of corresponding simulations for 1-lift locks without water recycling are selected (values are taken from Report B).
- Exchange coefficients: see Section 5.2.

7.4.2 Results of simulations

The computed volume-averaged salt concentrations (ppt) of Miraflores Lake and Gatun Lake for a ship traffic intensity of 15 ships a day are shown in Figures D5-15s,1 and D5-15s,2 in 'Figures Simuations 1-lift Locks'.
The computed maximum and minimum value of the volume-averaged salt concentration of Miraflores Lake and Gatun Lake in the last year of the considered period are presented in Table 7.7. For reasons of comparison also the present salinity levels of the lakes are shown (case A).

Case and no of PP-ships a day	*Considered year*	*Salt conc. (ppt) Miraflores Lake*		*Salt conc. (ppt) Gatun Lake*	
		minimum	*maximum*	*minimum*	*maximum*
A, existing	-	0.64	1.42	0.010	0.027
D5-1ship	2	0.68	1.74	0.11	0.28
D5-5ships	5	0.91	2.40	0.48	1.26
D5-10ships	20	1.44	3.85	1.37	3.12
D5-15ships	50	2.30	5.81	2.97	5.41

Table 7.7 Maximum and minimum values of volume-averaged salt concentration of Miraflores Lake and Gatun Lake, 1-lift locks

The above maximum and minimum values have been plotted in Figures 7.7 (Miraflores Lake) and 7.8 (Gatun Lake). Similar as for the 3-lift locks and 2-lift locks, Figures 7.7 and 7.8 show that the salt concentration of Miraflores Lake and Gatun Lake rises for all ship traffic intensities and all scenarios, compared to the present situation.

The results of the present and former simulations (scenarios D1 – D5, see Table 3.47) are collected in Figure 7.9. Volume-averaged salt concentrations of Gatun Lake and Miraflores Lake are shown for a ship-traffic intensity of 15 Post-Panamax ships a day, which corresponds to the traffic level of year 50 after opening of the new shipping lane (see Table 2.2). Figure 7.9 shows that the scenario with water recycling in dry periods of the year (D5) is most unfavourable.

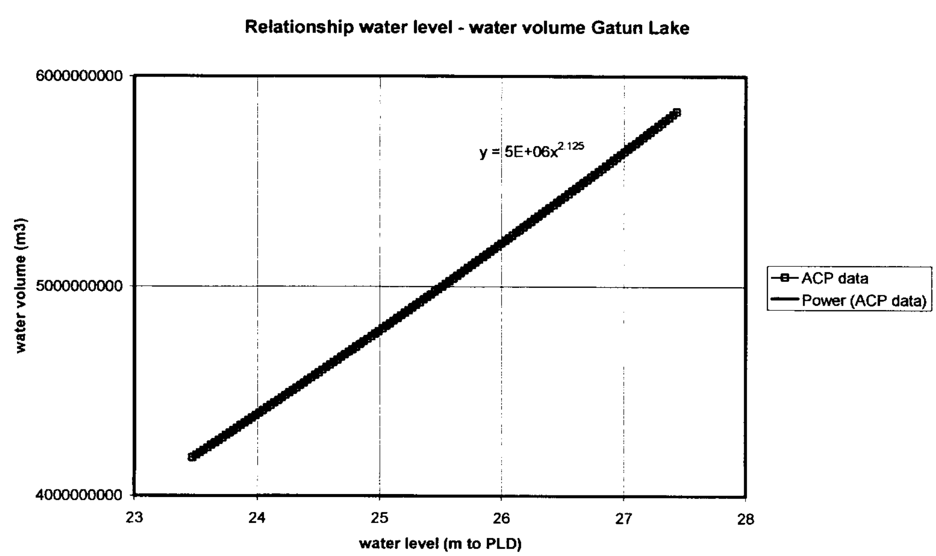
8 Simulations for 3-lift locks, hydraulic conditions as in period 1992 - 2001

The Swinlocks simulations reported in Chapter 7 are based on average values of monthly averages of water levels of Gatun Lake and Miraflores Lake and water releases in the period 1992 – 2001. This period includes the dry El Nino year 1997 and the wet year 1999. The extremes of the hydraulic conditions in this period do not show up in the results of the Swinlocks simulations, which have been done for the future situation with Post-Panamax Locks. After all, the future seasonal variations are not known and the best approach is than to use averaged seasonal variations of a sufficient long period in the past.
In order to get insight into the possible effects of the extremes in the hydraulic conditions on salt concentration levels of Gatun Lake and Miraflores Lake, we have re-run simulations for the future situation on the basis of the actual water levels and actual water releases in the 10-year period 1992-2001. These additional simulations have been done for the 3-lift Post-Panamax Locks with water saving basins, for different water control scenarios and different ship traffic intensities in the new shipping lane.

8.1 Water levels and water volumes of Gatun Lake and Miraflores Lake in period 1992-2001

8.1.1 Gatun Lake

The monthly averages of the actual water level and the corresponding water volume of Gatun Lake in the period 1992-2001 have been used in the additional Swinlocks simulations. The water volume of Gatun Lake was derived from the water level data using the relationship shown in next figure:



Next tables present the monthly averages of water level and water volume of Gatun Lake in the period 1992-2001:

Year / *Month*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*	*1999*	*2000*	*2001*
January	26.53	26.49	26.66	26.45	26.74	26.61	25.18	26.70	26.72	26.65
February	26.23	26.23	26.51	26.14	26.66	26.37	25.08	26.49	26.48	26.63
March	25.87	25.97	26.21	25.77	26.49	26.05	24.72	26.25	26.20	26.45
April	25.49	25.82	25.79	25.56	26.08	25.63	24.14	26.12	25.96	26.01
May	25.62	25.94	25.57	25.59	26.03	25.32	24.18	26.13	25.84	25.50
June	26.12	26.00	25.91	25.78	26.26	25.30	24.56	26.11	26.16	25.42
July	26.26	26.20	26.12	26.22	26.36	25.38	25.04	26.17	26.16	25.48
August	26.27	26.08	26.14	26.38	26.36	25.21	25.61	26.43	26.00	25.72
September	26.44	26.22	26.28	26.31	26.37	25.17	26.16	26.46	26.07	26.13
October	26.54	26.40	26.34	26.21	26.40	25.41	26.49	26.49	26.30	26.34
November	26.53	26.58	26.58	26.65	26.56	25.59	26.53	26.70	26.57	26.65
December	26.59	26.73	26.64	26.73	26.73	25.47	26.75	26.77	26.67	26.76

Table 8.1 Monthly averages of water level of Gatun Lake in period 1992-2001 (in m to PLD)

Year / *Month*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*	*1999*	*2000*	*2001*
January	5303	5283	5357	5266	5391	5337	4744	5373	5384	5354
February	5177	5173	5292	5139	5357	5234	4706	5287	5282	5342
March	5027	5065	5167	4986	5283	5101	4561	5185	5163	5267
April	4872	5007	4994	4896	5114	4925	4337	5130	5062	5083
May	4921	5055	4903	4912	5090	4801	4352	5133	5011	4874
June	5130	5077	5041	4987	5189	4792	4501	5126	5146	4842
July	5186	5162	5128	5169	5229	4824	4690	5151	5147	4867
August	5191	5113	5139	5236	5231	4757	4919	5257	5077	4963
September	5265	5173	5196	5208	5235	4741	5145	5272	5107	5132
October	5307	5246	5222	5168	5246	4836	5285	5284	5204	5221
November	5303	5323	5325	5351	5314	4910	5304	5374	5320	5354
December	5326	5387	5347	5385	5385	4863	5395	5405	5363	5401

Table 8.2 Monthly averages of water volume of Gatun Lake in period 1992-2001 (in 10^6 m^3)

The water level of Gatun Lake is also shown in Figure 8.1. This figure indicates that the year 1997 is a very dry year, which leads to an extreme low water level in the dry season of 1998.

8.1.2 Miraflores Lake

The monthly averages of the water level in the period 1992-2001 and the corresponding water volume of Miraflores Lake, which have been used in the additional Swinlocks simulations, are presented in next tables. The mean water level in the period 1992-2001 amounts to about PLD+16.58 m which corresponds to a water volume of $23.8*10^6$ m^3. The water volume was derived from the water level using the lineair relationship $y = (x/16.58)*23.8*10^6$, where y = volume, x = water level.

Year / *Month*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*	*1999*	*2000*	*2001*
January	16.55	16.57	16.54	16.56	16.58	16.58	16.58	16.52	16.57	16.61
February	16.56	16.57	16.55	16.56	16.56	16.56	16.57	16.60	16.11	16.63
March	16.58	16.56	16.54	16.58	16.56	16.56	16.40	16.55	16.46	16.60
April	16.56	16.56	16.56	16.56	16.57	16.55	16.24	16.57	16.61	16.71
May	16.54	16.57	16.56	16.56	16.52	16.55	14.99	16.57	16.61	16.39
June	16.54	16.56	16.55	16.56	16.60	16.54	15.92	16.61	16.61	16.50
July	16.56	16.55	16.56	16.59	16.61	16.48	16.48	16.57	16.62	16.56
August	16.57	16.56	16.57	16.58	16.61	16.61	16.57	16.60	16.62	16.59
September	16.58	16.57	16.57	16.61	16.63	16.50	16.54	16.61	16.64	16.58
October	16.58	16.57	16.57	16.63	16.63	16.61	16.63	16.61	16.68	16.61
November	16.58	16.58	16.57	16.62	16.61	16.53	16.62	16.61	16.61	16.59
December	16.56	16.56	16.57	16.59	16.58	16.50	16.61	16.63	16.60	16.58

Table 8.3 Monthly averages of water level of Miraflores Lake, 1992-2001 (in m to PLD)

Year / *Month*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*	*1999*	*2000*	*2001*
January	23.76	23.78	23.74	23.78	23.80	23.80	23.81	23.71	23.78	23.85
February	23.77	23.78	23.76	23.78	23.77	23.77	23.78	23.82	23.13	23.87
March	23.80	23.77	23.74	23.79	23.77	23.77	23.54	23.76	23.62	23.82
April	23.77	23.77	23.77	23.77	23.78	23.76	23.31	23.78	23.85	23.98
May	23.74	23.79	23.77	23.77	23.71	23.76	21.52	23.78	23.84	23.52
June	23.74	23.78	23.76	23.78	23.83	23.75	22.85	23.85	23.85	23.69
July	23.77	23.76	23.78	23.81	23.84	23.66	23.66	23.79	23.86	23.77
August	23.78	23.78	23.78	23.80	23.85	23.84	23.78	23.83	23.85	23.81
September	23.81	23.78	23.78	23.84	23.87	23.69	23.74	23.84	23.88	23.80
October	23.80	23.78	23.79	23.87	23.87	23.85	23.87	23.84	23.94	23.85
November	23.80	23.80	23.78	23.86	23.84	23.73	23.86	23.85	23.84	23.82
December	23.77	23.78	23.78	23.81	23.80	23.69	23.84	23.87	23.82	23.80

Table 8.4 Monthly averages of water volume of Miraflores Lake, 1992-2001 (in 10^6 m^3)

The water level of Miraflores Lake is also shown in Figure 8.2.

The water releases at Miraflores Dam (spilled water and water used for cooling) are not known in detail for the period 1992 – 2001. We have used the representative values of Table 3.45 as input for the additional simulations.

8.2 Water releases Gatun Lake and water recycling in simulations

The monthly averages of the water releases at Gatun Dam (the sum of spilled water and water used for hydropower generation) is shown in next table for the period 1992 – 2001. A graphical presentation of these data is shown in Figure 8.3.

Year / *Month*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*	*1999*	*2000*	*2001*
January	0.00	0.00	0.00	0.01	23.08	0.11	0.00	3.32	11.10	8.48
February	0.00	0.01	0.00	0.00	1.36	0.01	0.00	1.63	2.94	0.08
March	0.07	0.00	0.00	0.00	1.48	0.00	0.10	0.27	0.02	0.05
April	0.03	0.04	0.00	0.01	0.98	0.01	0.00	0.40	0.08	0.08
May	0.03	2.07	0.01	0.01	2.09	0.01	0.00	5.05	0.07	0.06
June	6.30	3.89	2.44	0.23	8.20	0.02	0.00	7.93	7.22	0.05
July	9.00	9.42	6.60	4.52	11.04	0.00	0.00	3.95	10.96	0.06
August	10.70	8.79	0.03	9.65	11.22	0.00	0.00	14.88	10.47	0.05
September	11.82	10.79	7.84	11.00	12.00	0.00	1.45	16.19	10.62	1.47
October	12.51	15.82	8.83	3.50	13.04	0.00	10.91	10.84	5.30	1.56
November	8.15	17.46	17.48	13.44	20.16	0.00	4.74	22.77	7.15	4.61
December	4.85	5.92	0.37	9.93	15.21	0.00	18.72	44.45	9.28	17.64

Table 8.5 Monthly averages of water release at Gatun Dam, period 1992-2001 (in 10^6 m^3/day)

In the additional Swinlocks simulations we have applied water control scenarios for Gatun Lake, in which these water releases are reduced. An overview of water level control scenarios, which have previously been used in simulations, is shown in Table 3.47. Simulations for the 3-lift locks are indicated with the capital letter B followed by the scenario number. Next table presents an overview of scenarios which have been applied in the additional simulations:

Scenario	*Description*	*3-lift locks*	*Ship traffic intensity*
3	wsb's water releases at Gatun Dam are *reduced* if needed, extra fresh water supply to Gatun Lake	*B3*	*5, 10, 15 Post-Panamax ships / day*
5	wsb's water releases at Gatun Dam are *reduced* if needed, recycling of water; lower pond > upper pond if needed, extra fresh water supply to Gatun Lake	B5	*5, 10, 15 Post-Panamax ships / day*
9	wsb's water releases at Gatun Dam are *reduced* if needed, recycling of water; tailbay > Gatun Lake if needed, extra fresh water supply to Gatun Lake	B9	*5 Post-Panamax ships / day*

Table 8.6 Scenarios for control of water level of Gatun Lake used in additional simulations for 3-lift Post-Panamax locks with water saving basins

In all three scenarios water saving basins are used to reduce the water losses (3 water saving basins for each lock, providing a water saving rate of 60% each lift). The losses at both sides of the canal caused by the operation of the 3-lift Post-Panamax Locks are compensated by a lesser water release at Gatun Dam.
If this is not sufficient, the remaining portion of the water losses is in scenario 3 compensated by an extra supply of fresh water to Gatun Lake from new water sources.
In scenarios 5 and 9 the remaining portion of the water losses is compensated by a recycling of the water lost by the operation of the Post-Panamax Locks at the Pacific side of the canal. When this is still not sufficient extra fresh water is supplied to Gatun Lake from new water sources. In scenario 5 water is recycled from lower storage pond to upper storage pond, in scenario 9 water is recycled from tailbay to forebay (direct recycling), see also description in Chapters 2 and 3.

The water losses caused by a single ship transfer in the new lane with 3-lift Post-Panamax Locks provided with 3 wsb's per lock amounts to $0.21*10^6$ m^3 (see Table 3.48). The water release quantities at Gatun Dam, the water recycling quantities at the Pacific side of the canal and the extra fresh water supplies to Gatun Lake are thus dependent on the ship traffic intensity. Simulations are executed for 5, 10 and 15 ship transfers per day (see Table 8.6).

As an example next table presents for the first year of the period 1992-2001 and for 5, 10 and 15 Post-Panamax ships a day the daily quantities of water that are relaesed at Gatun Dam, recycled at the Pacific side of the canal and supplied from fresh water sources. Note that the released water quantity is similar in scenarios 3, 5 and 9, while the supplied water quantity in scenario 3 (not shown in the tables) is equal to the sum of the recycled and the supplied water quantities in scenarios 5 and 9.

	5 ships / day					**10 ships / day**					**15 ships / day**				
Scenario	*3*	*5 and 9*				*3*	*5 and 9*				*3*	*5 and 9*			
	released	*released*	*recycled*	*supplied*	*number of rec. days*	*released*	*released*	*recycled*	*supplied*	*number of rec. days*	*released*	*released*	*recycled*	*supplied*	*number of rec. days*
January	0.00	0.00	0.53	0.53	31.00	0.00	0.00	1.06	1.06	31.00	0.00	0.00	1.58	1.58	31.00
February	0.00	0.00	0.53	0.53	28.00	0.00	0.00	1.06	1.06	28.00	0.00	0.00	1.58	1.58	28.00
March	0.00	0.00	0.53	0.46	31.00	0.00	0.00	1.06	0.99	31.00	0.00	0.00	1.58	1.51	31.00
April	0.00	0.00	0.53	0.49	30.00	0.00	0.00	1.06	1.02	30.00	0.00	0.00	1.58	1.55	30.00
May	0.00	0.00	0.53	0.50	31.00	0.00	0.00	1.06	1.02	31.00	0.00	0.00	1.58	1.55	31.00
June	5.24	5.24	0.00	0.00	0.00	4.19	4.19	0.00	0.00	0.00	3.13	3.13	0.00	0.00	0.00
July	7.94	7.94	0.00	0.00	0.00	6.88	6.88	0.00	0.00	0.00	5.83	5.83	0.00	0.00	0.00
August	9.65	9.65	0.00	0.00	0.00	8.59	8.59	0.00	0.00	0.00	7.54	7.54	0.00	0.00	0.00
September	10.76	10.76	0.00	0.00	0.00	9.71	9.71	0.00	0.00	0.00	8.65	8.65	0.00	0.00	0.00
October	11.45	11.45	0.00	0.00	0.00	10.40	10.40	0.00	0.00	0.00	9.34	9.34	0.00	0.00	0.00
November	7.09	7.09	0.00	0.00	0.00	6.04	6.04	0.00	0.00	0.00	4.98	4.98	0.00	0.00	0.00
December	3.79	3.79	0.00	0.00	0.00	2.73	2.73	0.00	0.00	0.00	1.68	1.68	0.00	0.00	0.00

Table 8.7 Hydraulic conditions 1992: released, recycled and supplied water quantities in 10^6 m^3/day and number of recycling days for 3-lift Post-Panamax Locks with wsb's.

Similar tables have been prepared for the years 1993 – 2001. The released water quantities at Gatun Dam and the number of recycling days form input for the simulations. They are shown in Figures 8.4 – 8.6 (water release) and Figures 8.7 – 8.9 (recycling days) for the period 1992-2001.

8.3 Set up of simulations

The salt water intrusion through the 3-lift Post-Panamax Locks with water saving basins is analysed for a period of ten years; starting point form the hydraulic conditions as in the period 1992-2001. The water control scenarios and the number of Post-Panamax ships as applied in the simulations, are shown in Table 8.6. The number of ships in the existing west and east shipping lanes was kept constant: 18 ships a day in each lane, see Table 7.1. Other used input data:

- Dimensions of locks, forebays, tailbays, water saving basins, upper pond and lower pond: see Section 3.12
- Tidal movements and salt concentration of seaside tailbays: see Section 3.14
- Water levels, water volumes, water releases of Gatun Lake and Miraflores Lake, and number of recycling days: see Sections 8.1 and 8.2
- Initial salt concentrations of Gatun Lake and Miraflores Lake: end values of corresponding simulations for 3-lift locks without water recycling are selected (values are taken from Report C).
- Exchange coefficients: see Section 5.2.1

8.4 Results of simulations and conclusions

8.4.1 Results of simulations

Results of the simulations are presented in Figures 8.10 – 8.14 and will separately be discussed for each water control scenario.

Scenario B3
(3-lift locks with wsb's; water releases at Gatun Dam are reduced; if needed, extra fresh water supply to Gatun Lake)

Figures 8.10 and 8.11 show the seasonal variation of the volume-averaged salt concentration of Gatun Lake and Miraflores Lake during a 10-year period with hydraulic conditions as in 1992-2001. Results are shown for 5, 10 and 15 Post-Panamax ships a day. The effects of the dry El Nino year 1997 and the extreme low water level of the lakes in the first half of 1998 are clearly visible in the results. The salt concentration of Gatun Lake strongly increases in this period. The salt concentration of Miraflores Lake is indirectly effected (the new shipping lane bypasses the lake), and increases as well. The next, wet year 1999 causes a strong reduction of the salt concentration in Gatun Lake; the salt concentration of Miraflores Lake follows.
For reasons of comparison the results of the former Case B3-15ships (see Report C) are also taken up in the charts (grey line). This simulation is done with average hydraulic conditions as input (average water level variation in lakes, average water release variation). As can be seen (compare blue line with grey line) the salt concentration of Gatun Lake is about twice

as high in 1998 when non-averaged hydraulic conditions are taken into account, and in the next wet year 1999 the salt concentration drops much farther than with average hydraulic conditions. The latter is caused by the heavy rainfall and spillage of large amounts of water at Gatun Dam in the second half of the wet year 1999.

Scenario B5
(3-lift locks with wsb's; water releases at Gatun Dam are reduced; if needed, recycling of water: lower pond > upper pond; if needed, extra fresh water supply to Gatun Lake)

The computed volume-averaged salt concentrations of Gatun Lake and Miraflores Lake are shown in Figures 8.12 and 8.13 for 5, 10 and 15 Post-Panamax ships a day. Salt concentration levels are higher in scenario 5 than in scenario 3, due to the recycling of water at the Pacific side. The results of Case B5-15ships (see Section 7.2) are included in the charts for reasons of comparison. The effects of non-averaged hydraulic conditions are similar as in scenario 3, but are intensified because of the water recycling.

Scenario B9
(3-lift locks with wsb's; water releases at Gatun Dam are reduced; if needed, recycling of water: tailbay >forebay; if needed, extra fresh water supply to Gatun Lake)

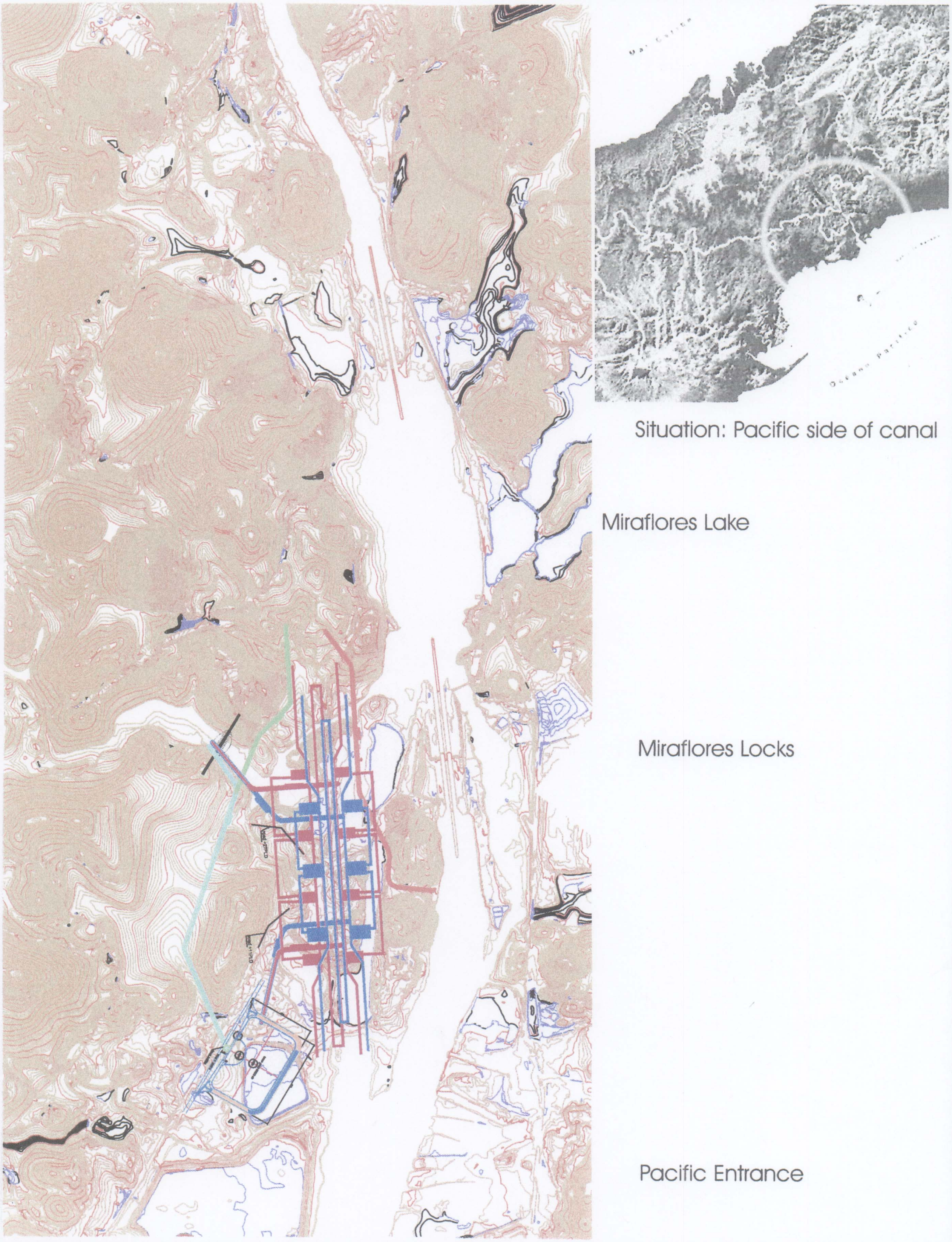
Figure 8.14 shows the volume-averaged salt concentration of Gatun Lake and Miraflores Lake for 5 Post-Panamax ships a day. Compared to the results for scenarios 3 and 5 salt concentration levels in scenario 9 are highest due to the direct water recycling method (from tailbay to forebay). The effects of non-averaged hydraulic conditions are similar as in scenarios 3 and 5.

8.4.2 Conclusions

A study has been conducted into the effects of the extremes in seasonal hydraulic variations such as dry El Nino years or very wet years, on salt concentration levels of Gatun Lake and Miraflores Lake. In dry years the water level of Gatun Lake drops to a minimum, water releases at Gatun Dam are stopped, and - as a future option - recycling of water is started. Heavy rainfall in wet years is the reason that much fresh water is supplied to Gatun Lake and to limit the rise of the water level a large amount of water is spilled at Gatun Dam.
The hydraulic conditions of the period 1992 – 2001, including the dry year 1997 and the wet year 1999, have been modelled in the salt water intrusion simulation model Swinlocks. Simulations have been executed for 3-lift Post-Panamax Locks with water saving basins for different water control scenarios of Gatun Lake and different ship traffic intensities in the new shipping lane.
The extremes in the hydraulic conditions clearly show up in the results of the salt water intrusion simulations. A dry year causes a sharp increase of the volume-averaged salt concentration of Gatun Lake, while the spillage of huge amounts of water in a wet year causes a strong drop of the salt concentration (the spilled water carries salt water). Miraflores Lake is not directly effected by navigation in the new shipping lane (the new shipping lane bypasses the lake), but the extremes in the seasonal hydraulic variations show up as well in the volume-averaged salt concentration of Miraflores Lake.
When instead of averaged seasonal variations real variations are appplied as input in the simulation model the maximum salt concentration of Gatun Lake and Miraflores Lake may be a factor up to about 2 higher in dry years, but may at the same time be much smaller in

wet years (hydraulic conditions as in the period 1992 – 2001 form the basis for this comparison). This holds for all simulated ship traffic intensities of 5, 10 and 15 Post-Panamax ships a day in the new shipping lane and 18 ships a day in both the existing west and east shipping lanes. It appears also that the effect of the extremes in hydraulic conditions is intensified when water is recycled.
For the prediction of future salt concentration levels of the lakes, which are aimed to be used in a mutual comparison of different lock configurations or an analysis of mitigation measures, the best approach is still to start from averaged seasonal hydraulic variations. For final design purposes also the effects of the extremes in hydraulic conditions should be taken into account.

Figures



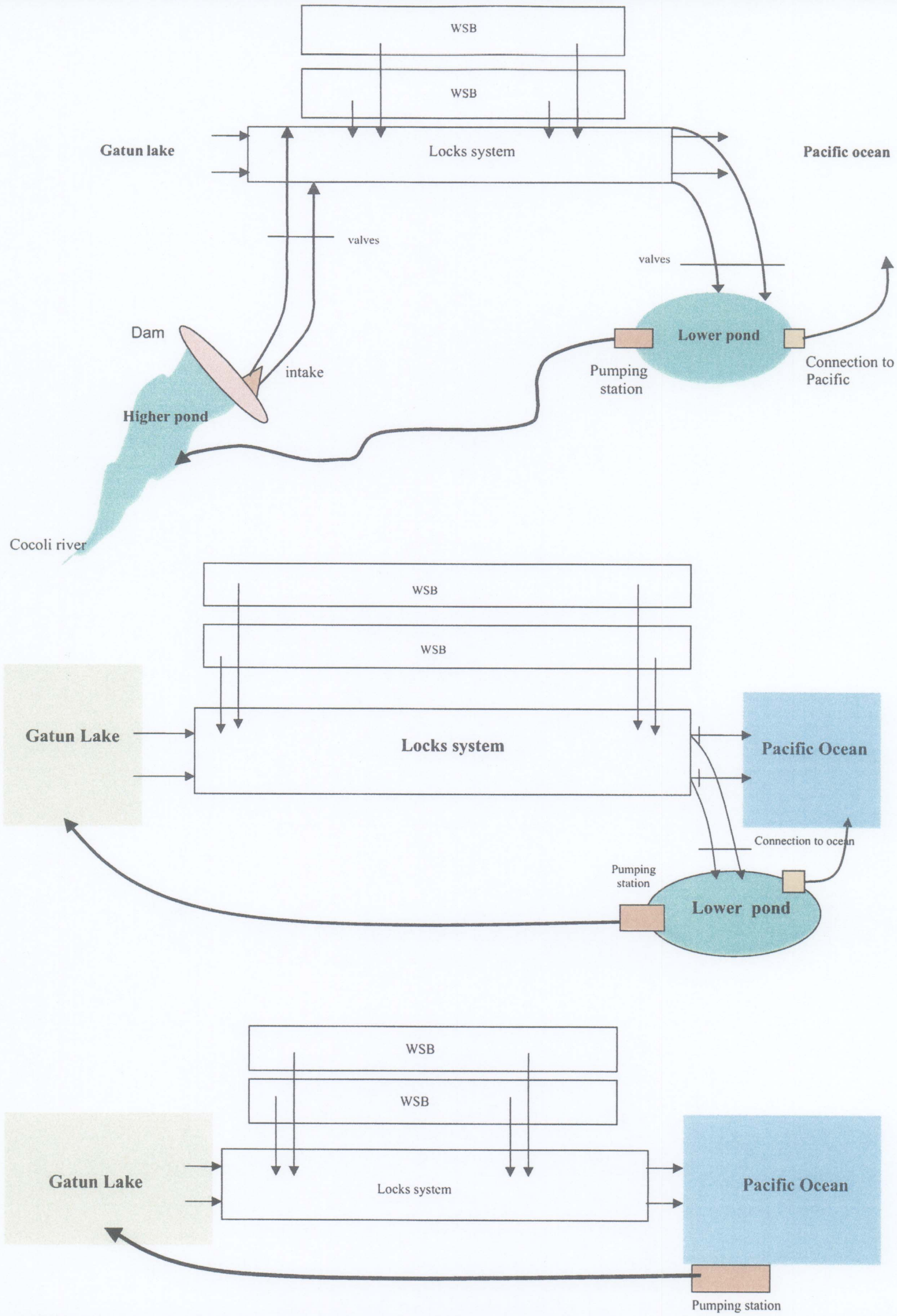
PLAN VIEW OF PROPOSED WATER RECYCLING SYSTEM
AT PACIFIC SIDE OF THE CANAL, VARIOUS DESIGNS

Source: CPP

WL | DELFT HYDRAULICS

Q 3476

Fig. 2.1

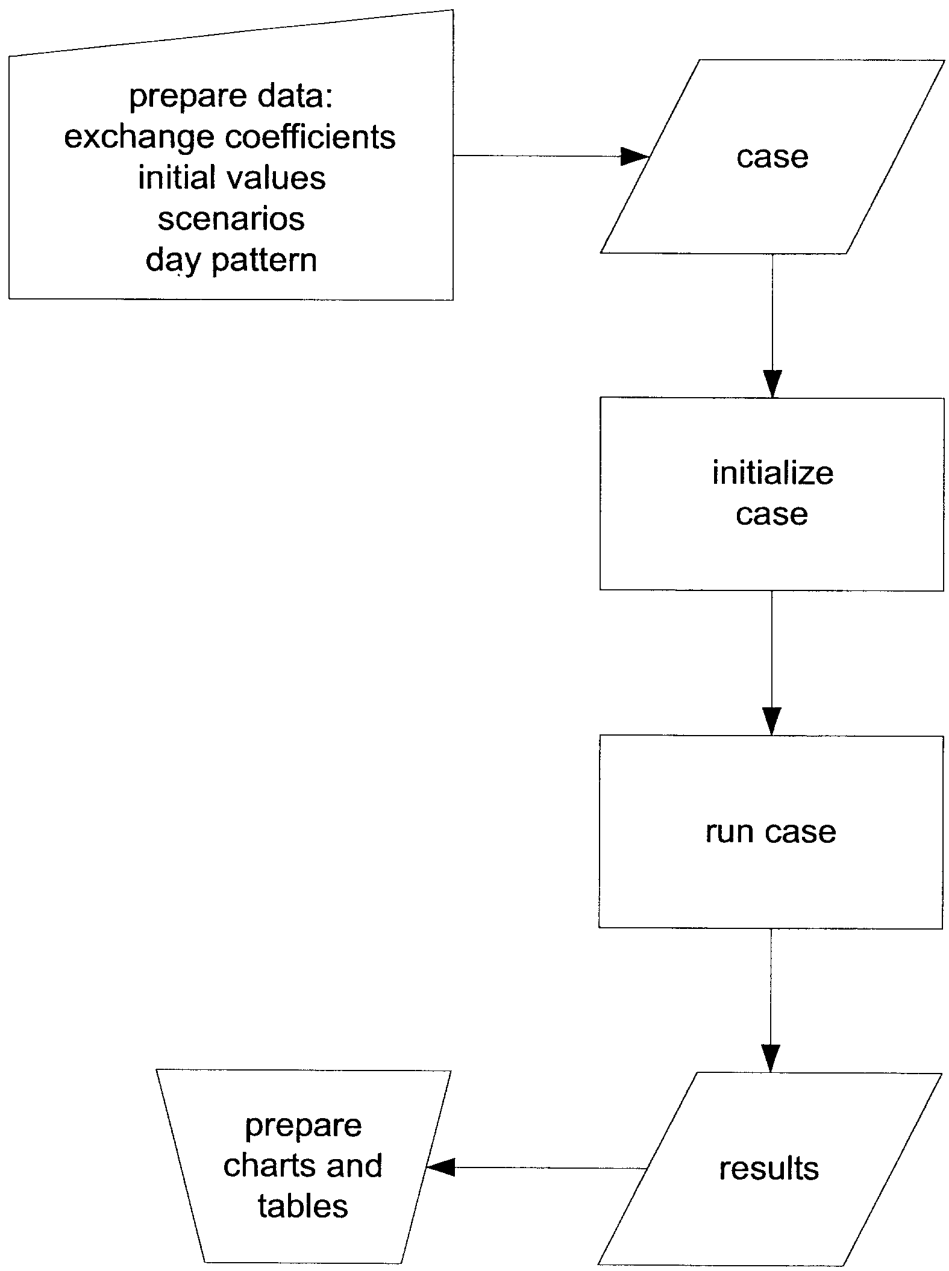


OPTIONS FOR WATER RECYCLING SYSTEM (source: CPP)
PACIFIC SIDE OF THE CANAL

WL | DELFT HYDRAULICS

Q 3476

Fig. 2.2

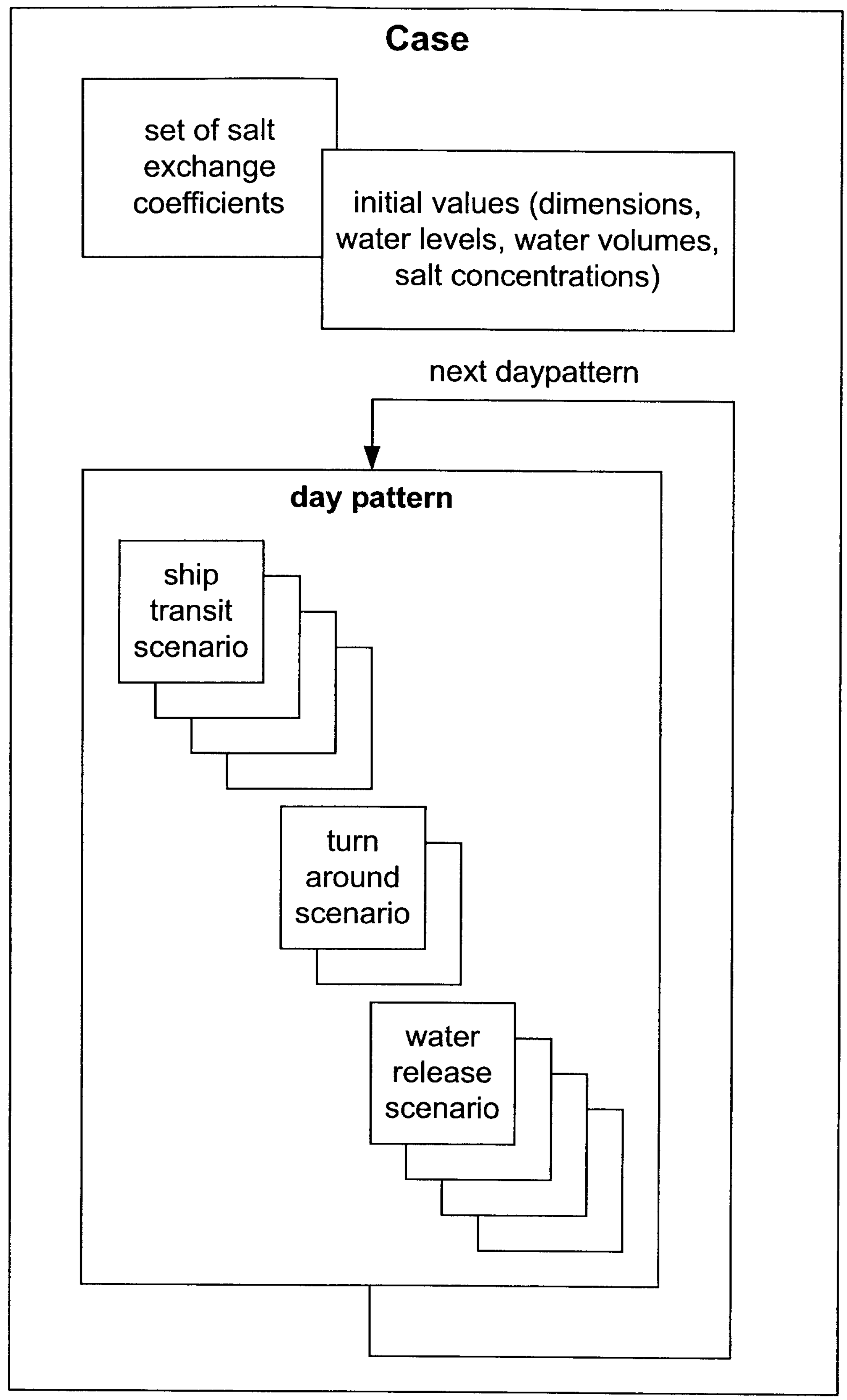


SIMULATION MODEL
FLOW CHART

WL | DELFT HYDRAULICS

Q 3476

Fig. 3.1

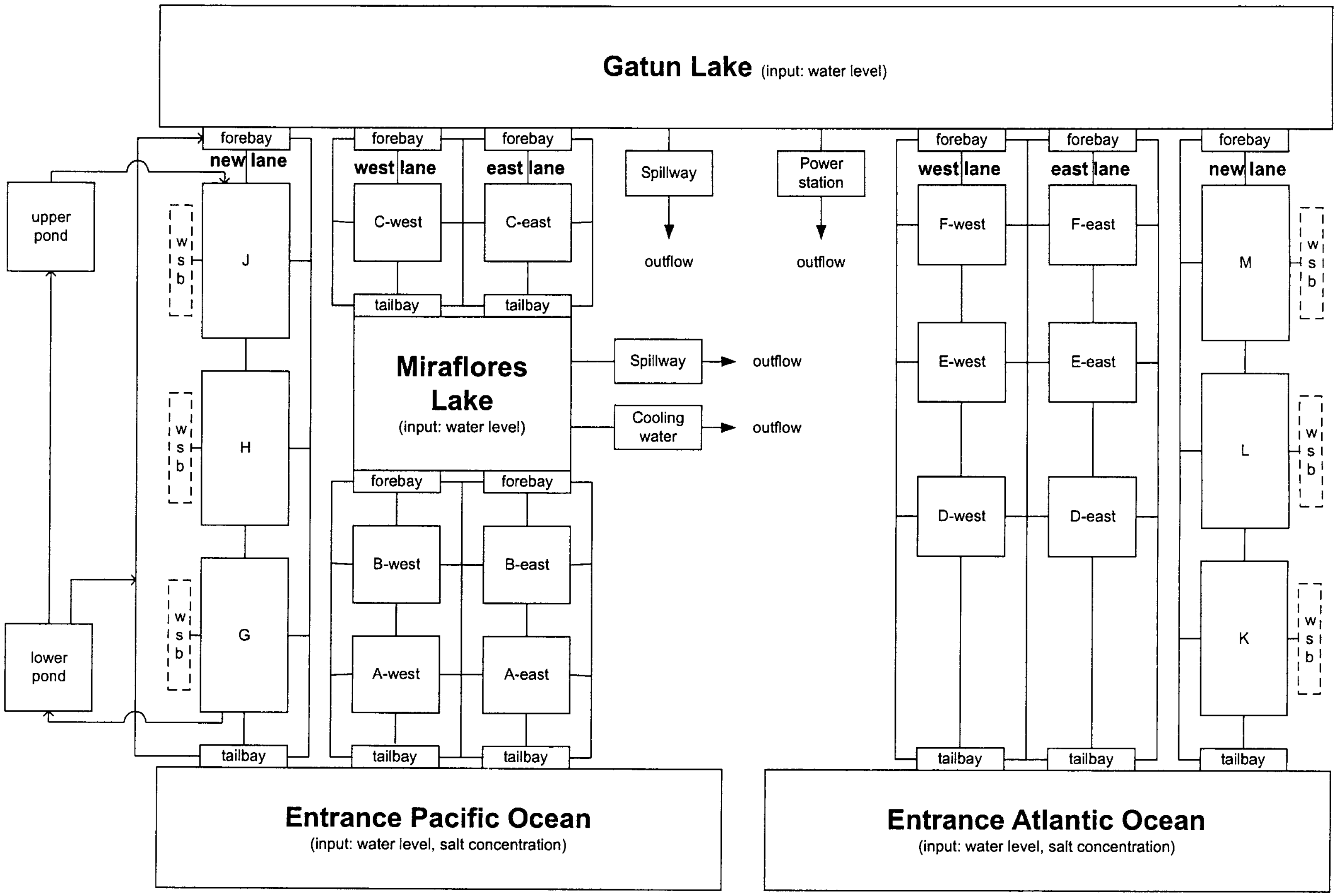


SIMULATION MODEL
COMPOSITION OF CASE

WL | DELFT HYDRAULICS

Q 3476

Fig. 3.2

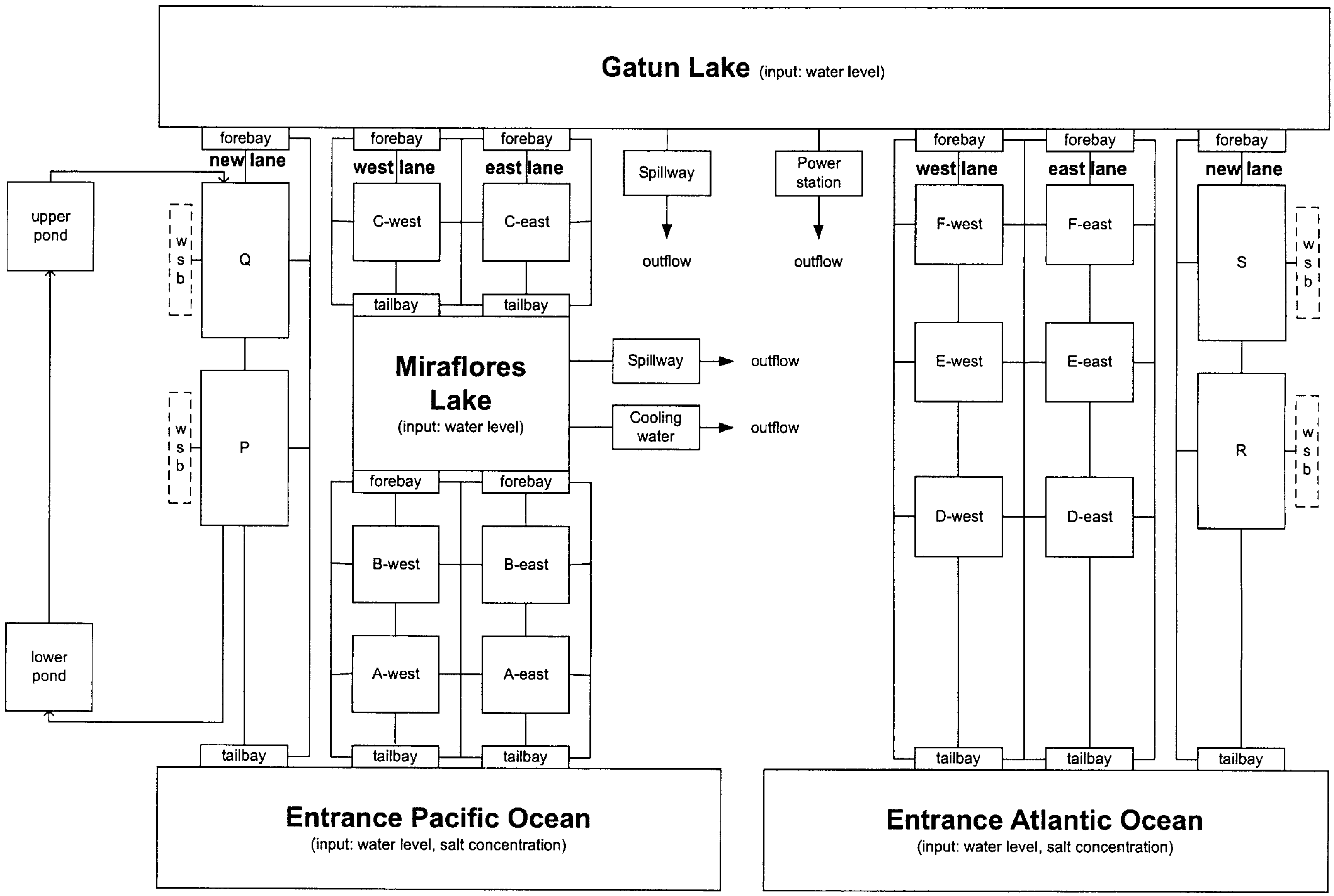


SIMULATION MODEL WITH NEW LANE AND 3-LIFT LOCKS.
THREE OPTIONS FOR WATER RECYCLING, PACIFIC SIDE.

WL | DELFT HYDRAULICS

Q 3476

Fig. 3.3

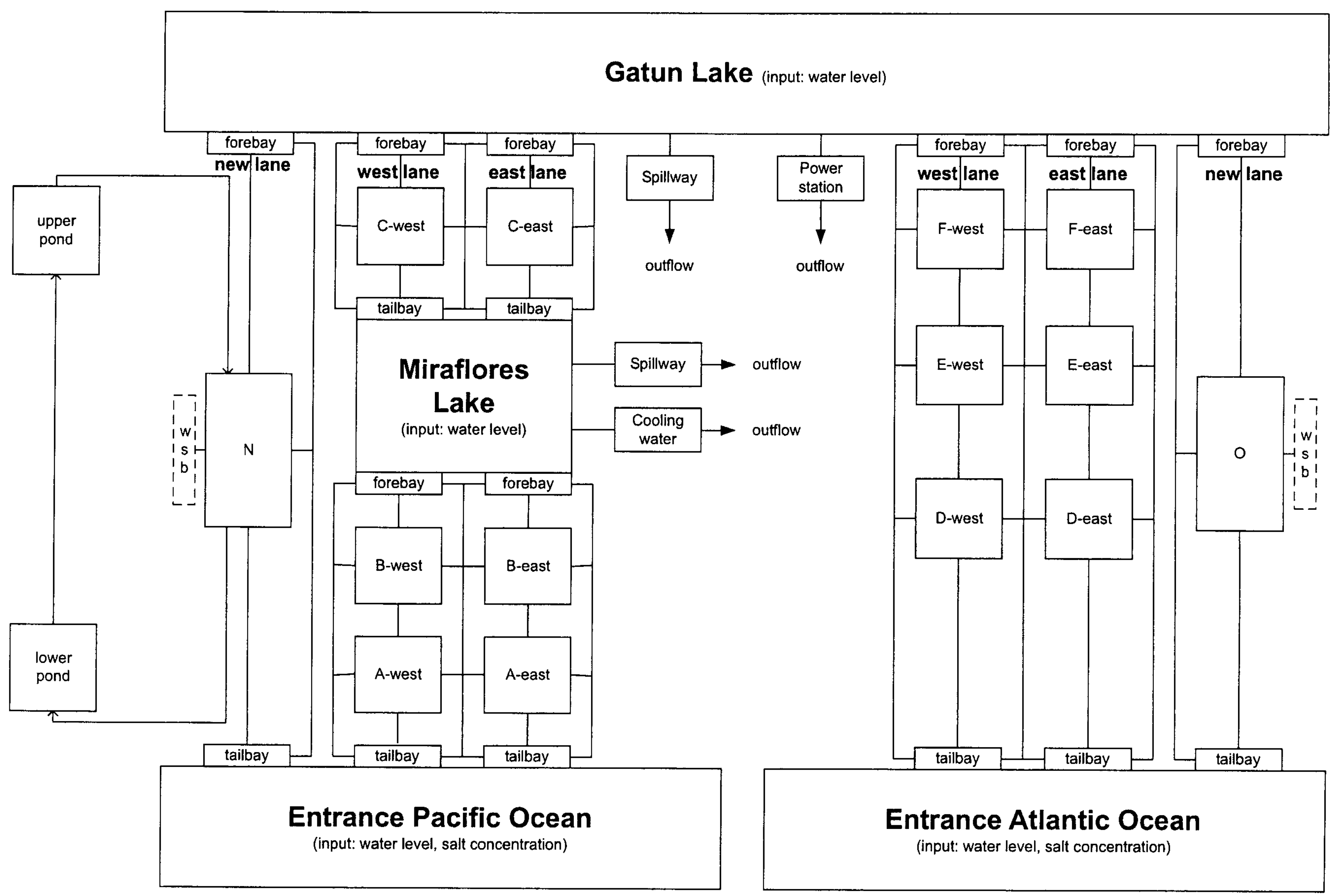


SIMULATION MODEL WITH NEW LANE AND 2-LIFT LOCKS.
ONE OPTION FOR WATER RECYCLING, PACIFIC SIDE.

WL | DELFT HYDRAULICS

Q 3476

Fig. 3.4

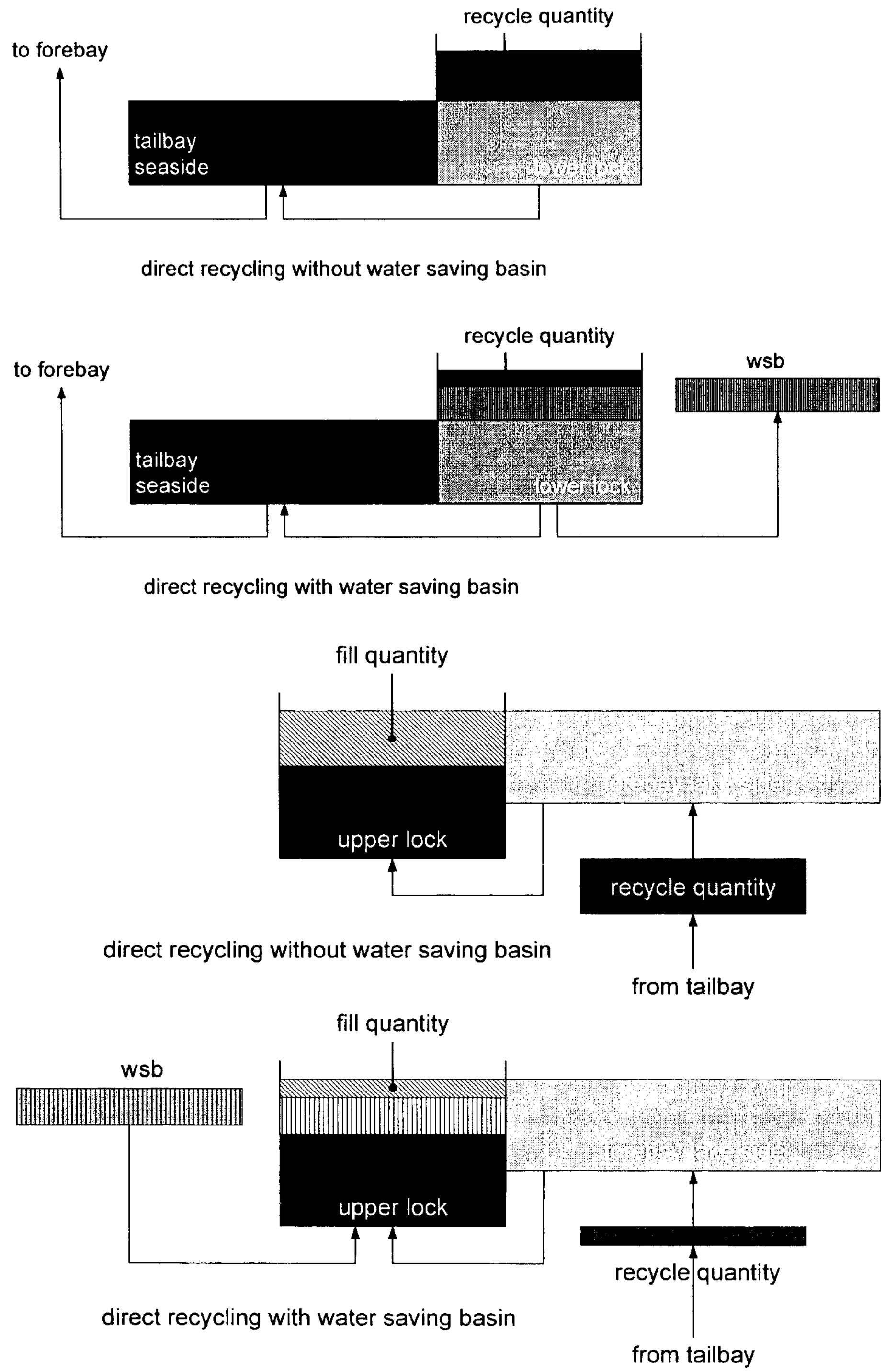


SIMULATION MODEL WITH NEW LANE AND 1-LIFT LOCKS.
ONE OPTION FOR WATER RECYCLING, PACIFIC SIDE.

WL | DELFT HYDRAULICS

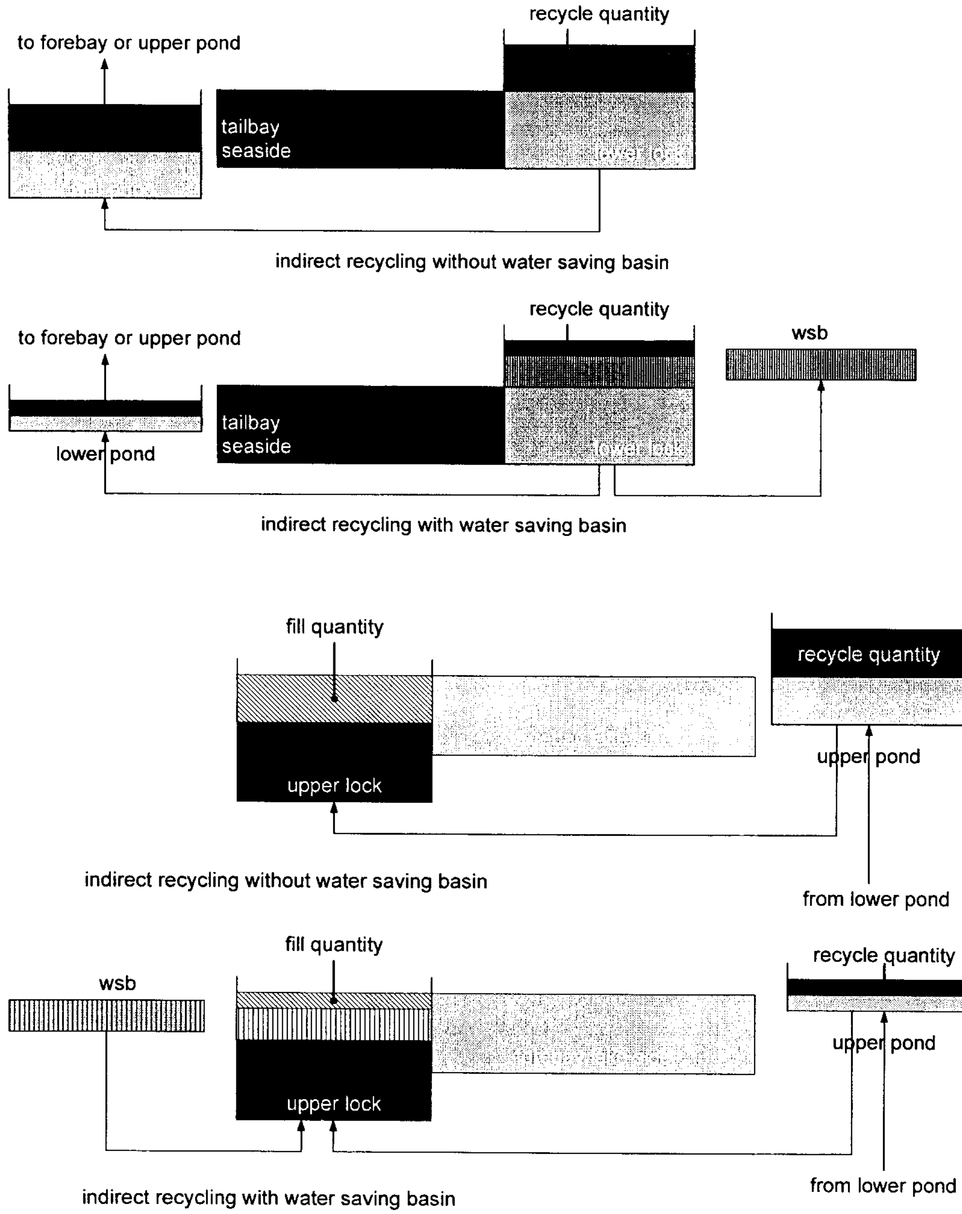
Q 3476

Fig. 3.5



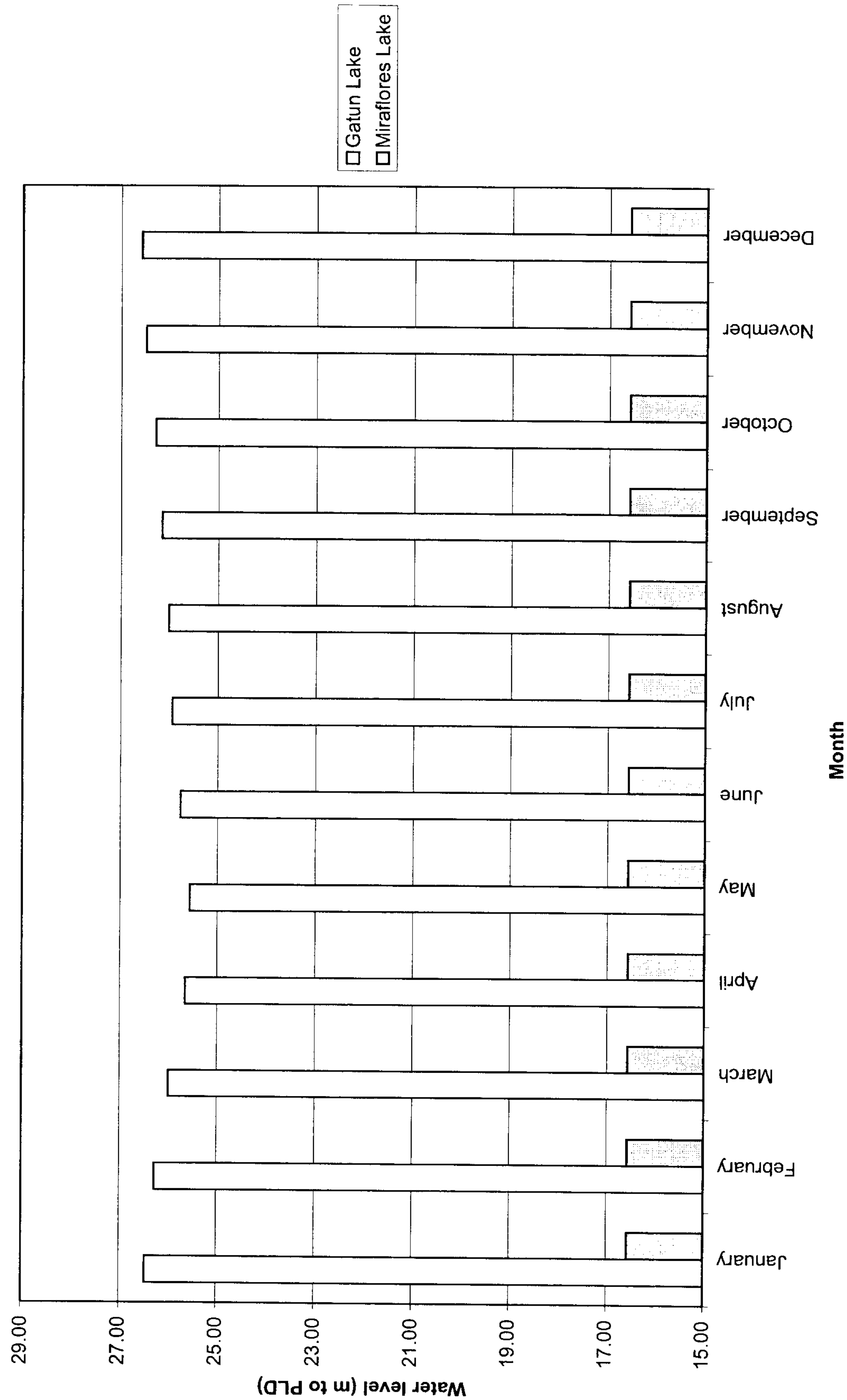
DIRECT WATER RECYCLING (TAILBAY > FOREBAY)
WATER EXCHANGE IN SIMULATION MODEL

WL | DELFT HYDRAULICS	Q 3476	Fig. 3.6a



INDIRECT WATER RECYCLING (LOWER POND > UPPER POND)
WATER EXCHANGE IN SIMULATION MODEL

WL | DELFT HYDRAULICS	Q 3476	Fig. 3.6b

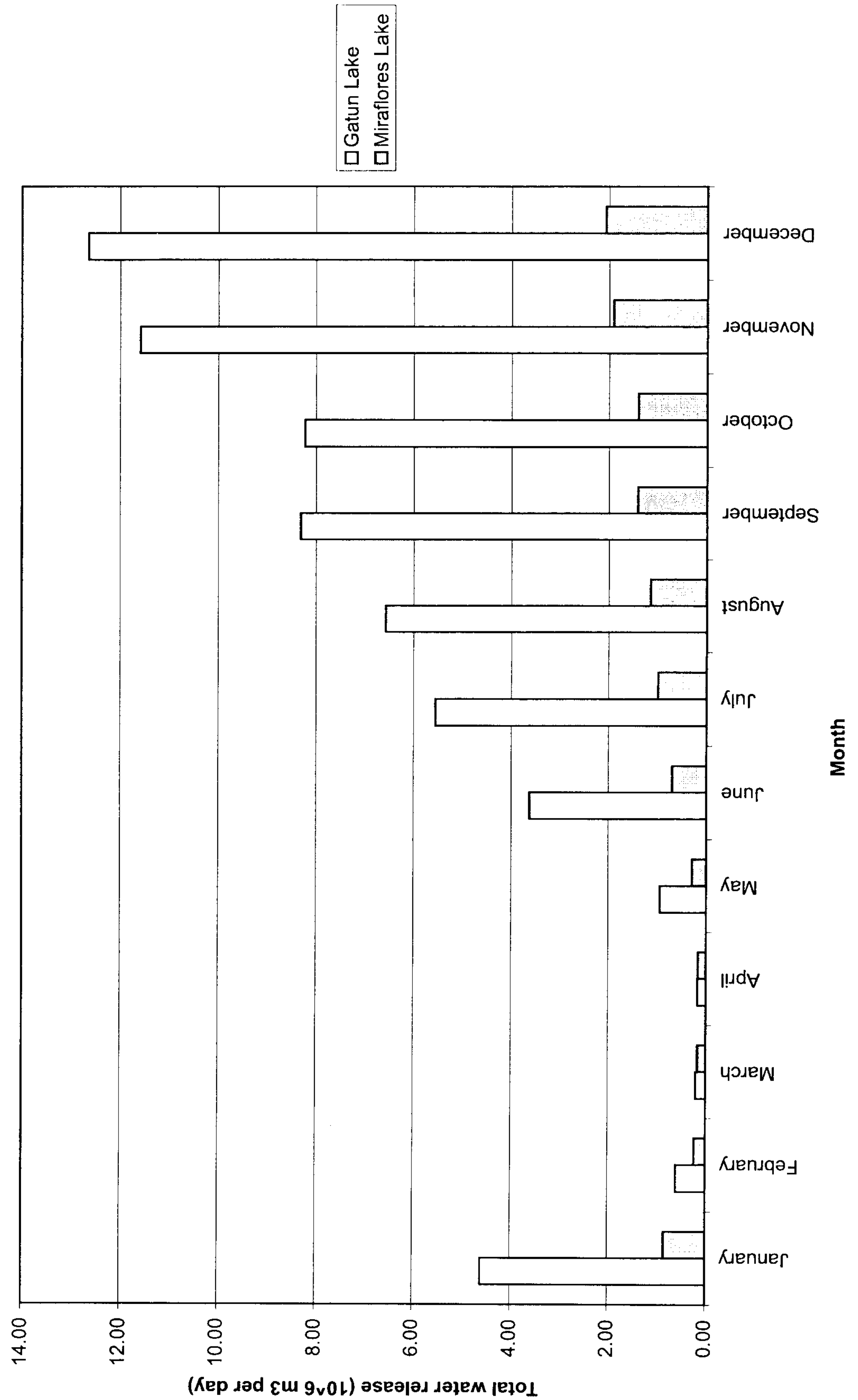


GATUN LAKE AND MIRAFLORES LAKE
REPRESENTATIVE WATER LEVELS

WL | DELFT HYDRAULICS

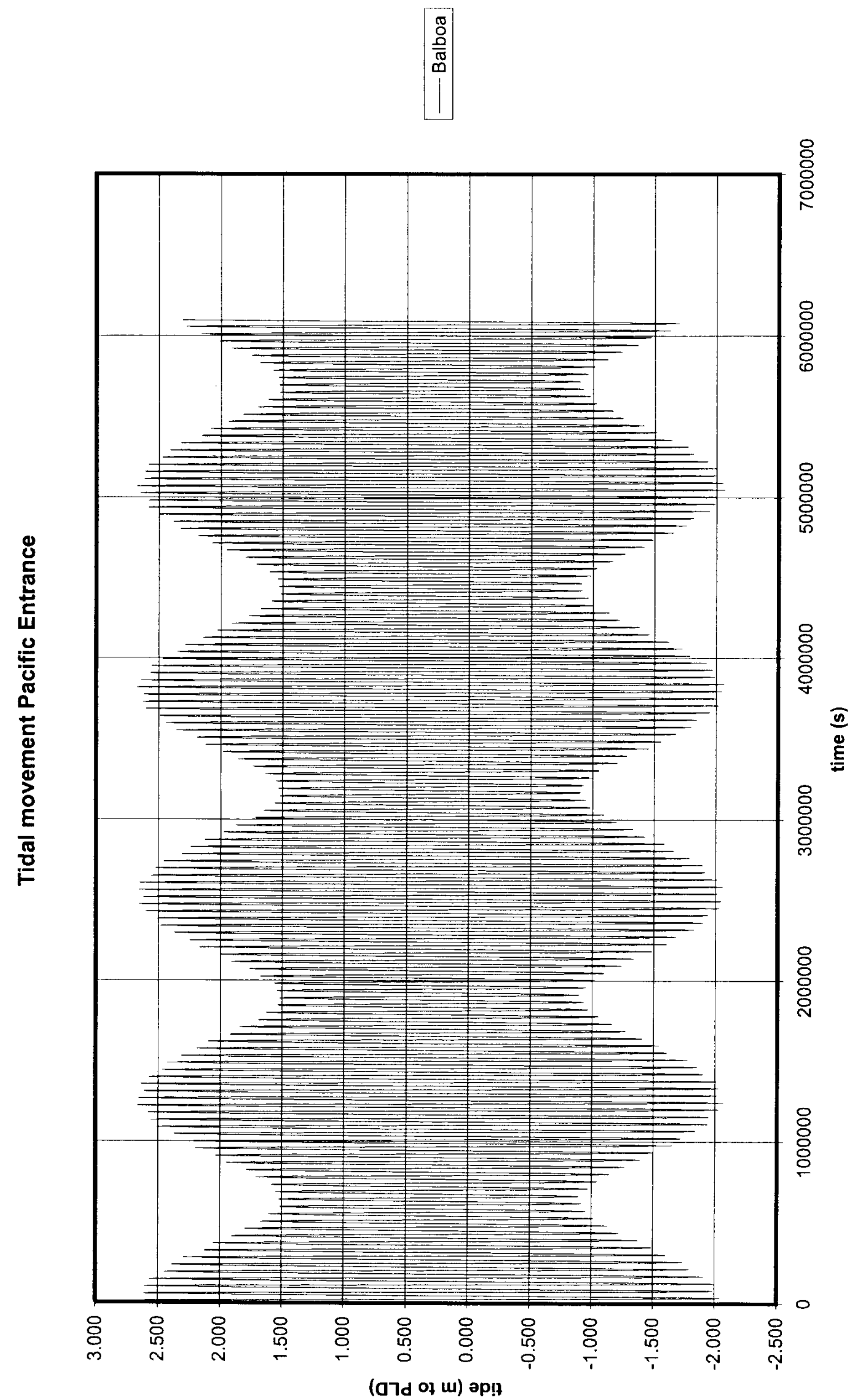
Q 3476

Fig. 3.7

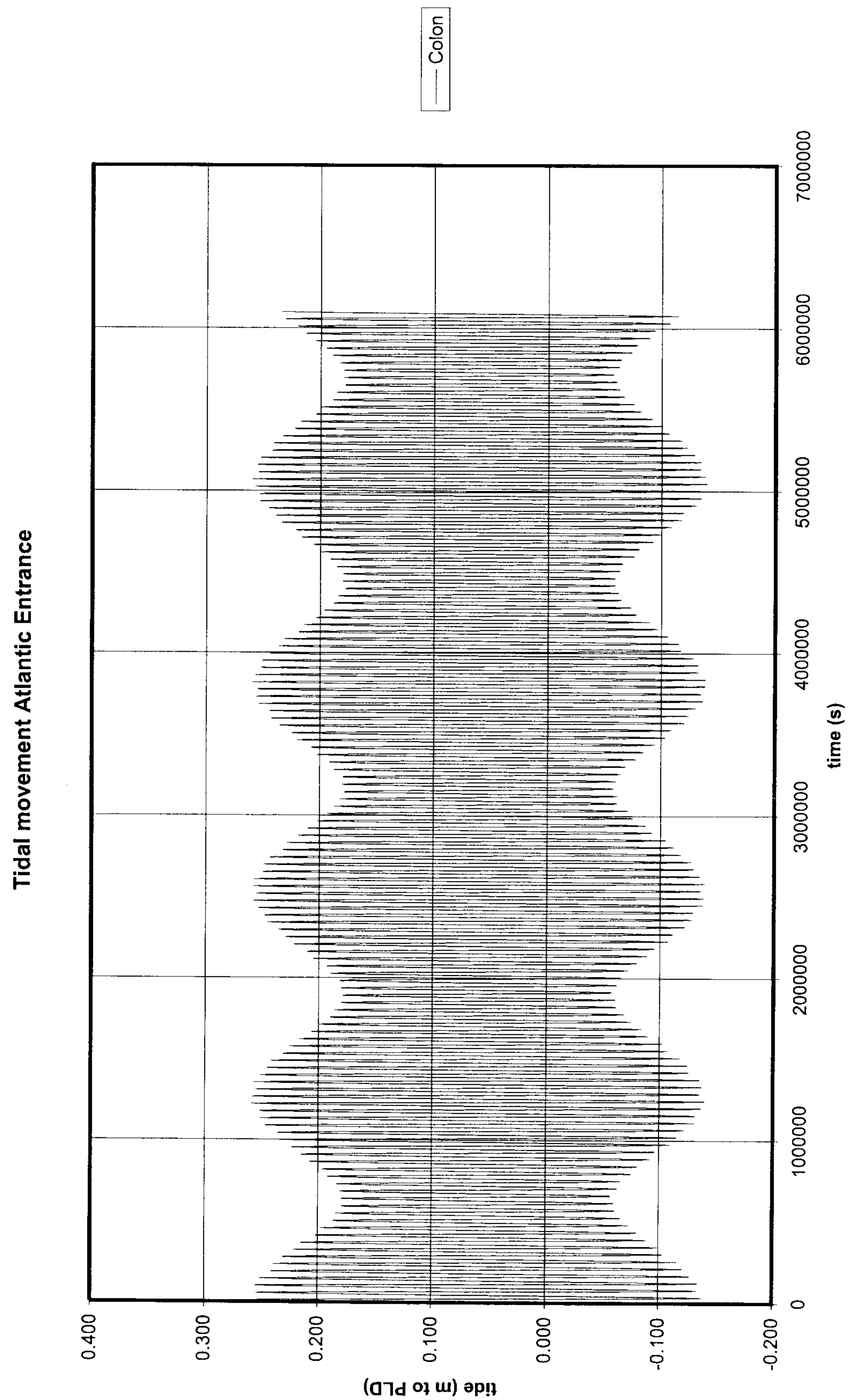


GATUN LAKE AND MIRAFLORES LAKE
WATER RELEASES (BASELINE SCENARIO)

WL | DELFT HYDRAULICS	Q 3476	Fig. 3.8



TAILBAYS PACIFIC SIDE PREDICTION OF TIDAL MOVEMENT		
WL | DELFT HYDRAULICS	Q 3476	Fig. 3.9a

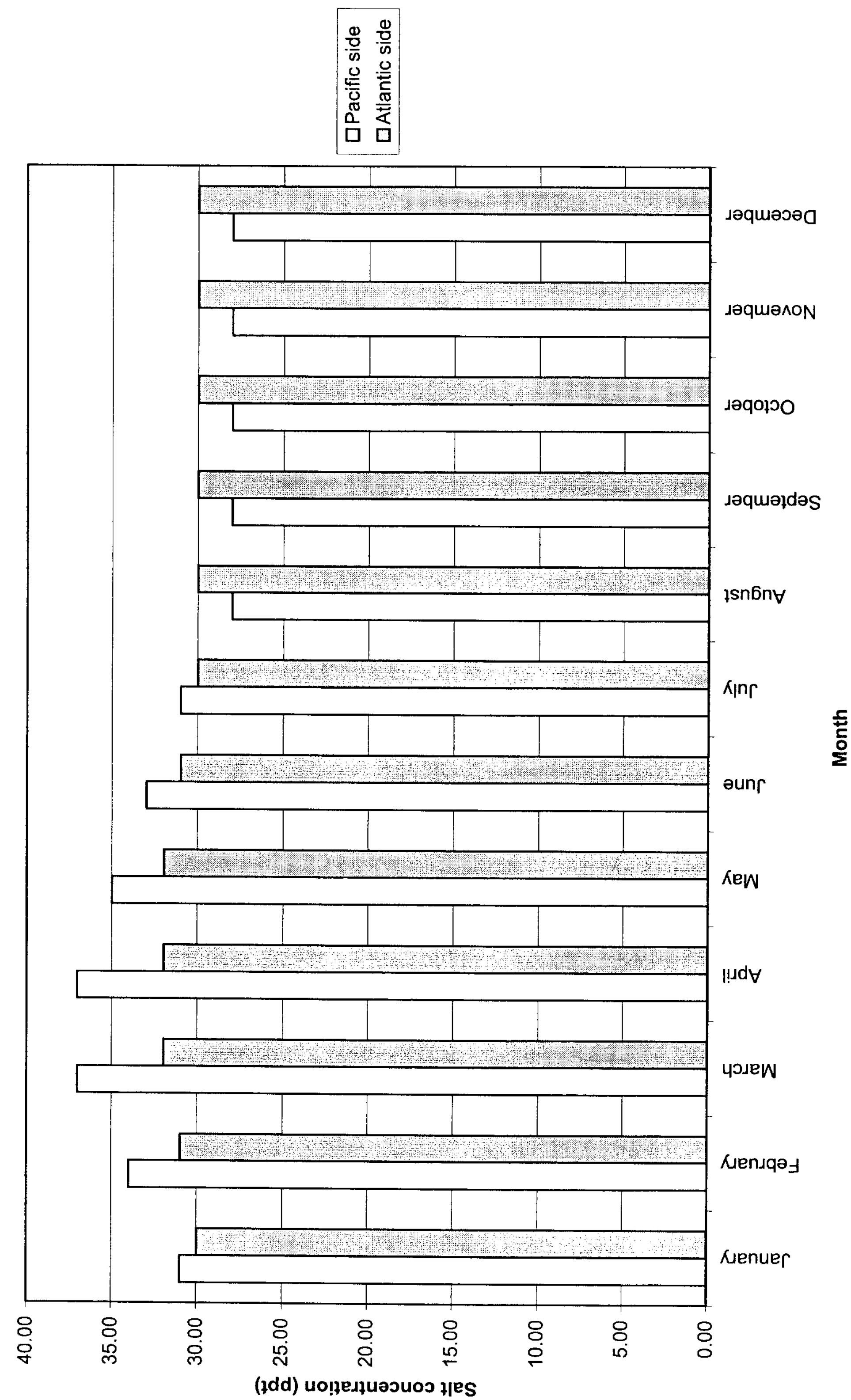


TAILBAYS ATLANTIC SIDE
PREDICTION OF TIDAL MOVEMENT

WL | DELFT HYDRAULICS

Q 3476

Fig. 3.9b

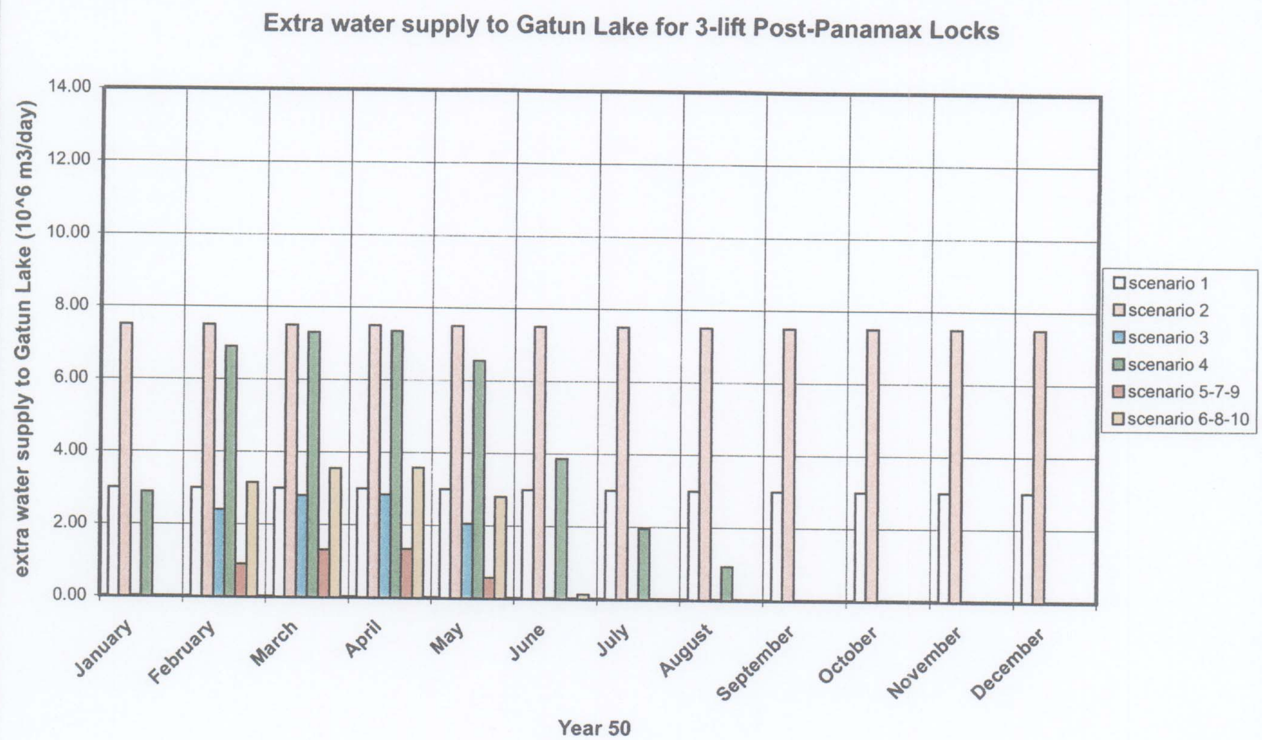


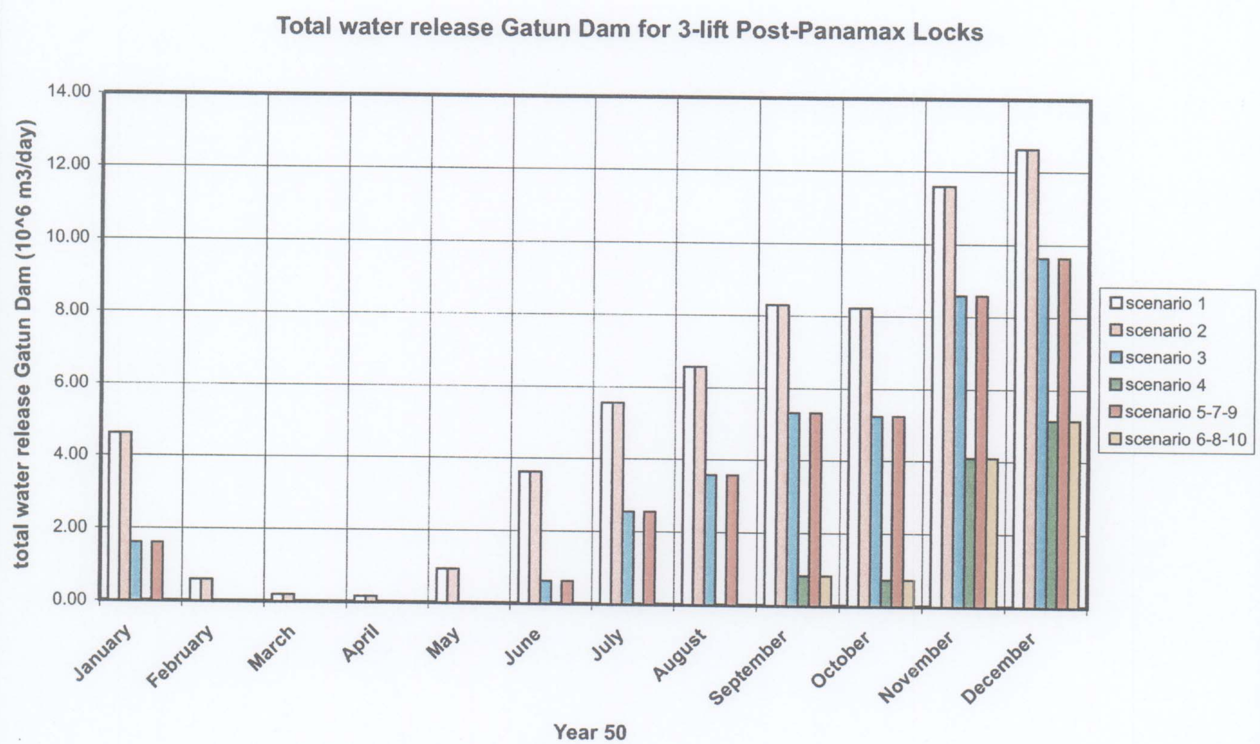
TEMPERATURE-COMPENSATED SALT CONCENTRATION OF PACIFIC AND ATLANTIC ENTRANCES

WL | DELFT HYDRAULICS

Q 3476

Fig. 3.10





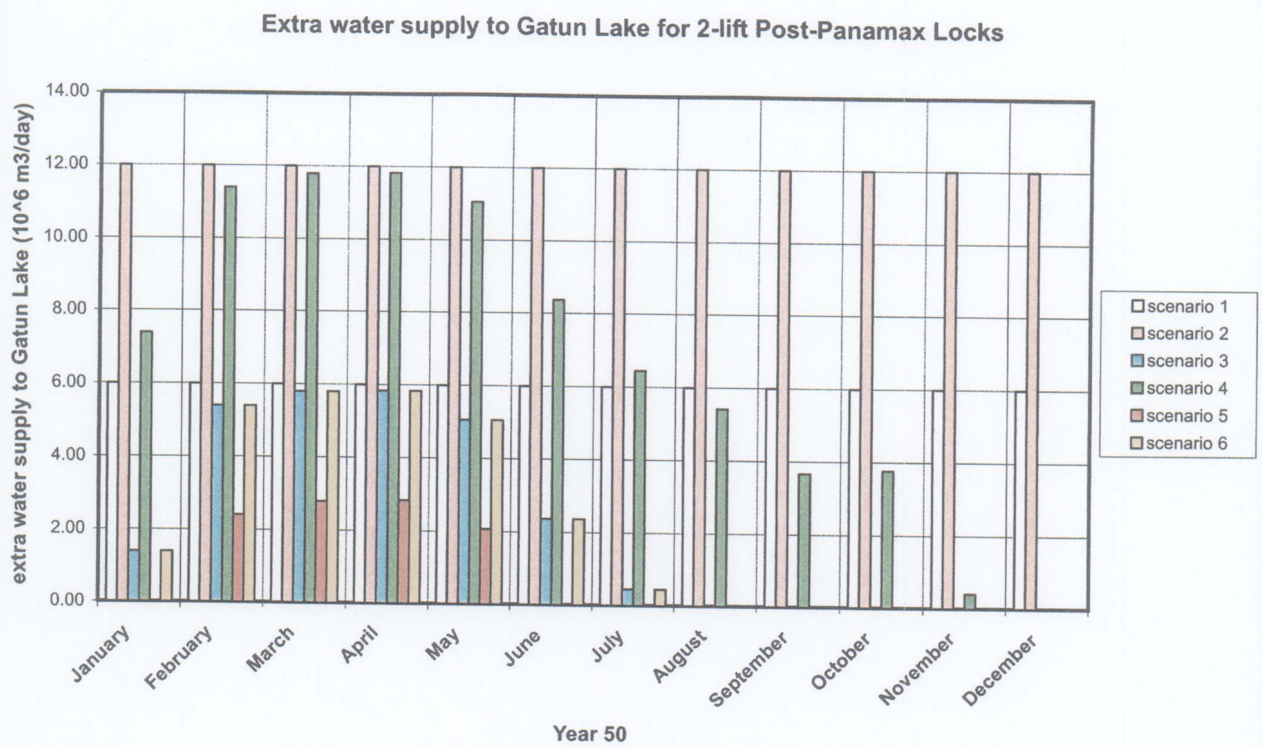
GATUN LAKE
FRESH WATER SUPPLY AND WATER RELEASE
Year 50 - 15 Post-Panamax ships/day - Various scenarios

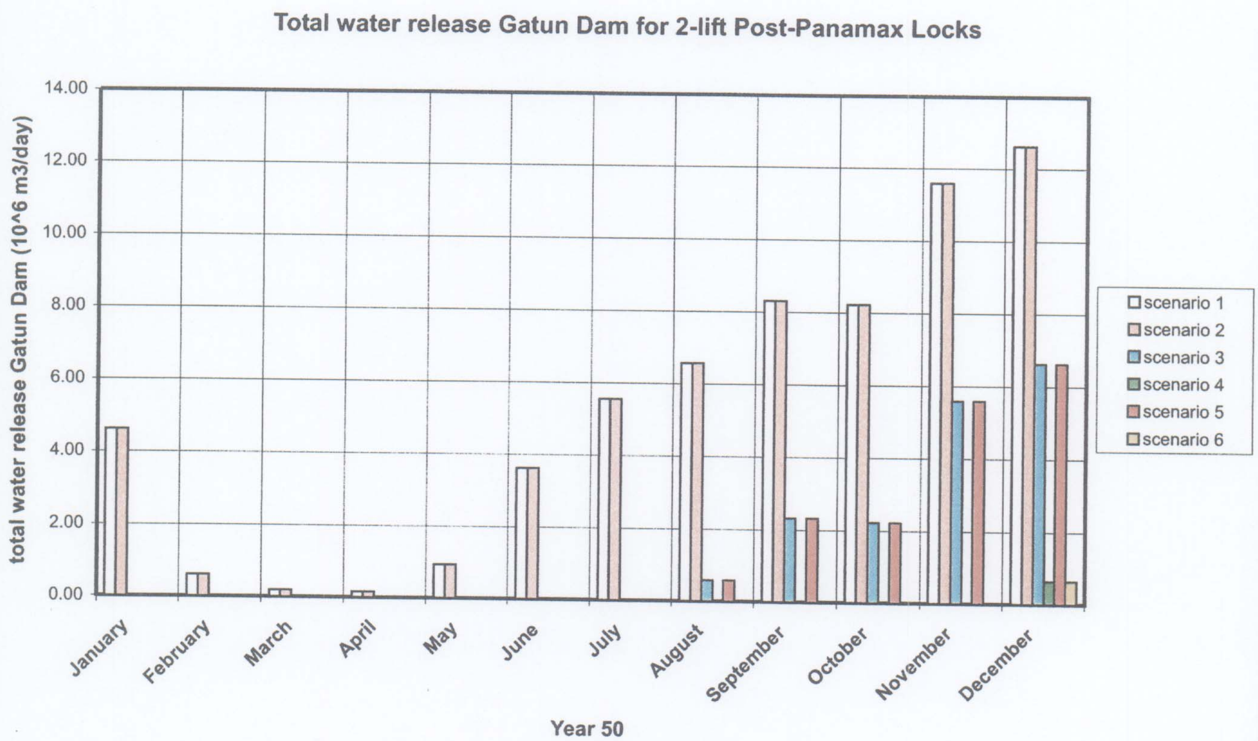
3-lift locks

WL | DELFT HYDRAULICS

Q 3476

Fig. 3.11





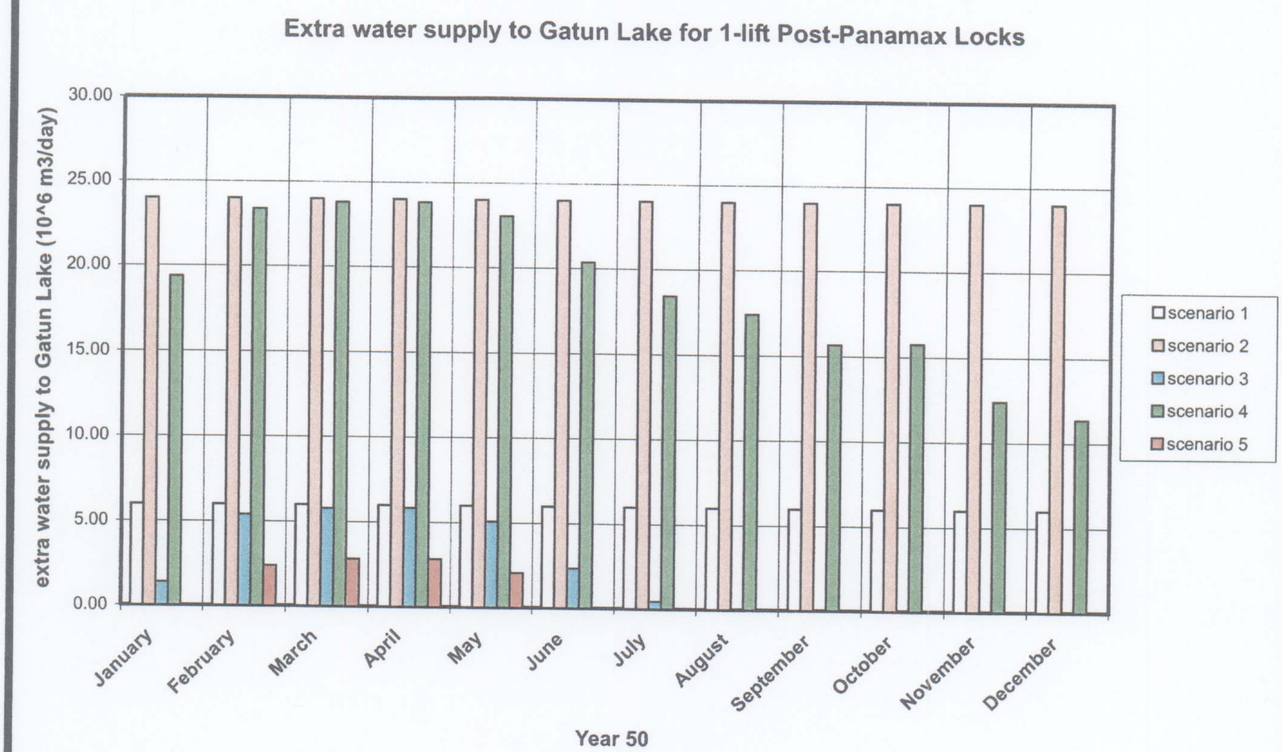
GATUN LAKE
FRESH WATER SUPPLY AND WATER RELEASE
Year 50 - 15 Post-Panamax ships/day - Various scenarios

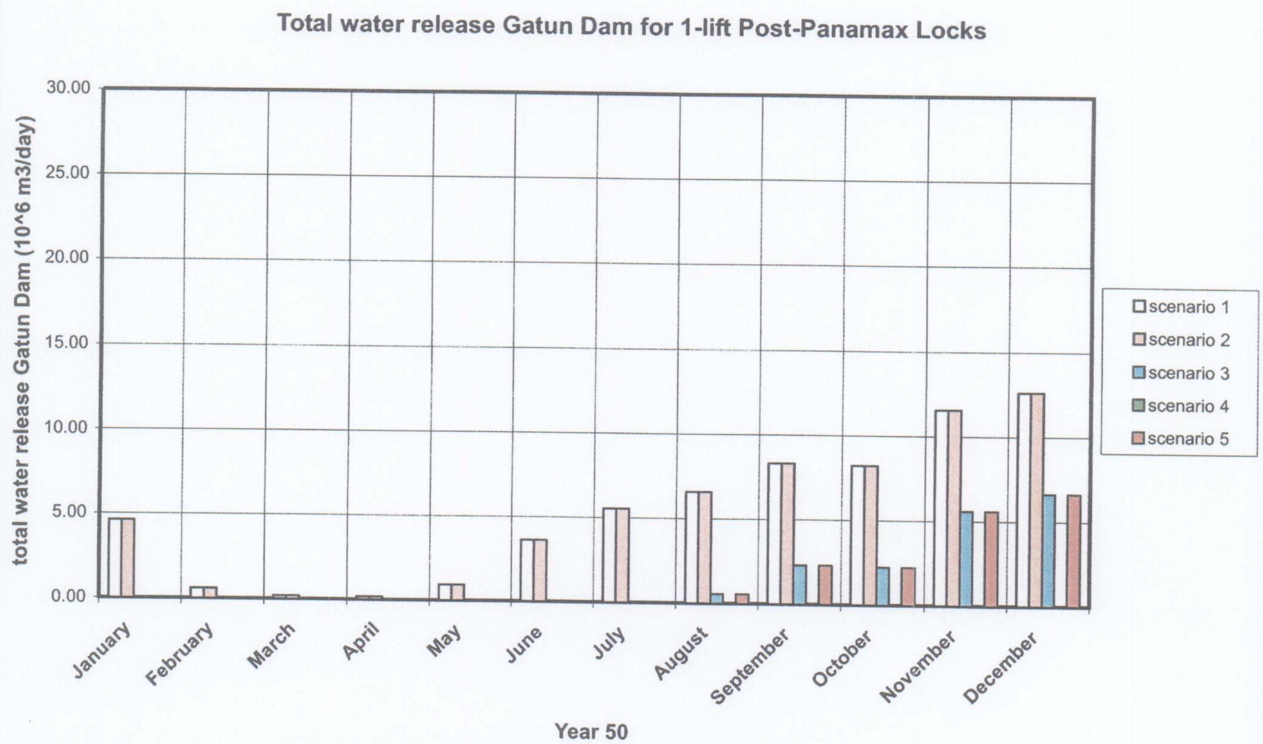
2-lift locks

WL | DELFT HYDRAULICS

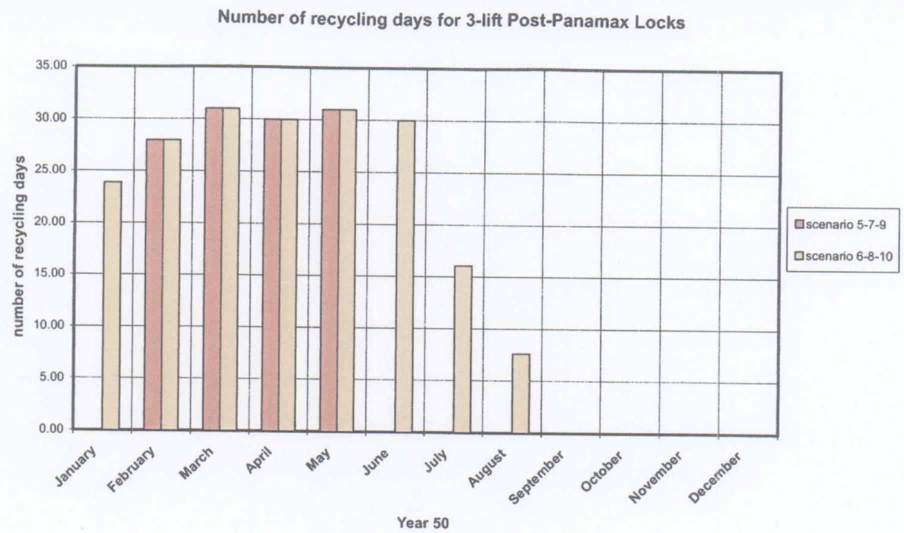
Q 3476

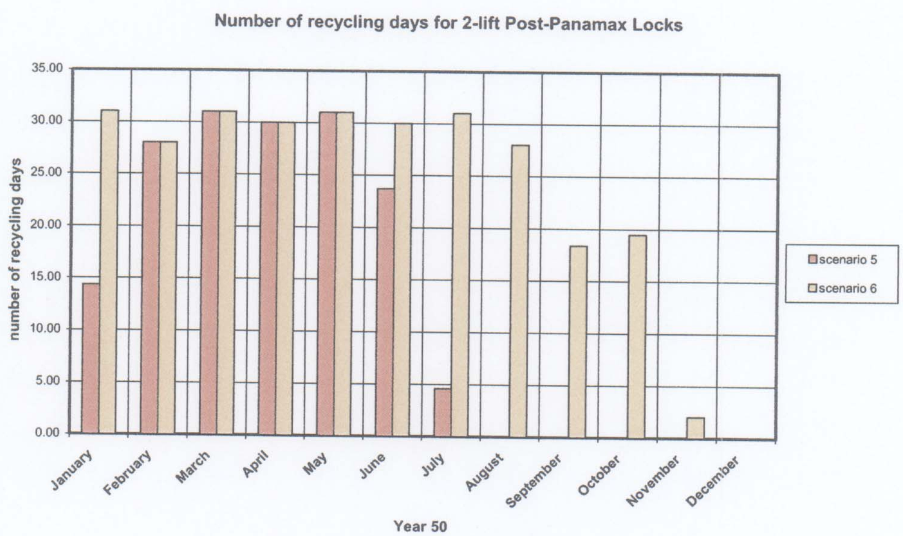
Fig. 3.12

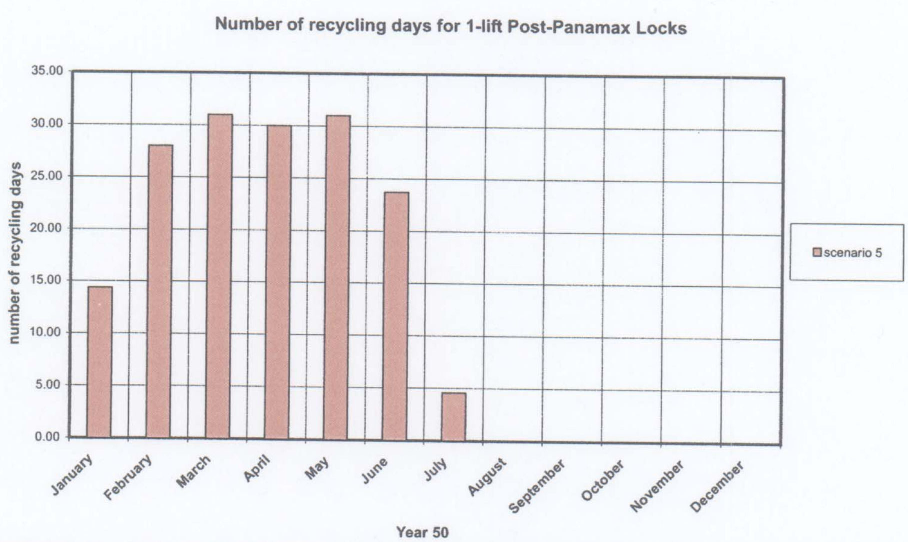




GATUN LAKE FRESH WATER SUPPLY AND WATER RELEASE Year 50 - 15 Post-Panamax ships/day - Various scenarios	1-lift locks	
WL | DELFT HYDRAULICS	Q 3476	Fig. 3.13







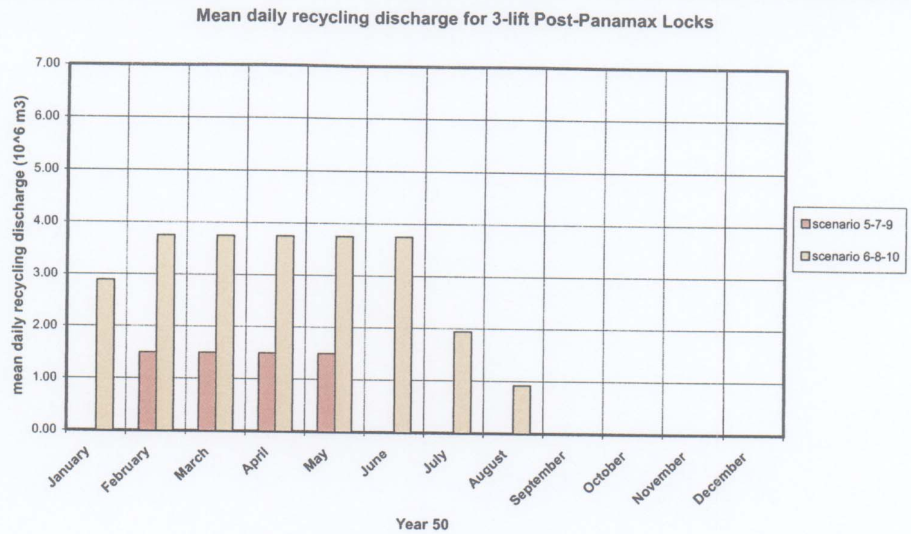
GATUN LAKE
NUMBER OF RECYCLING DAYS
Year 50 - 15 Post-Panamax ships/day - Various scenarios

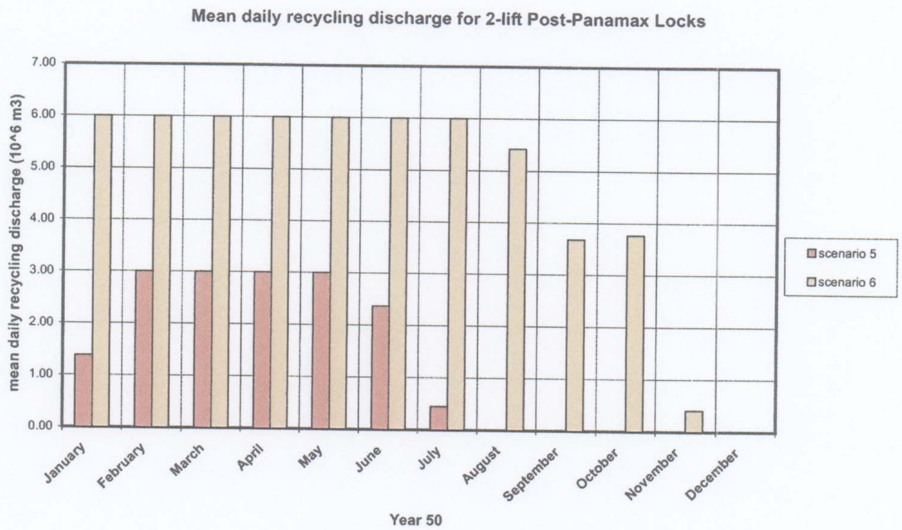
3-lift, 2-lift, 1-lift locks

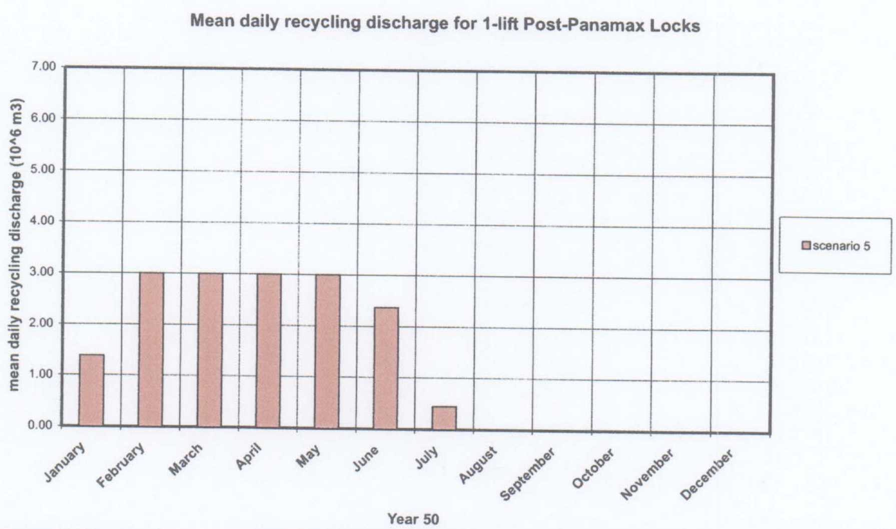
WL | DELFT HYDRAULICS

Q 3476

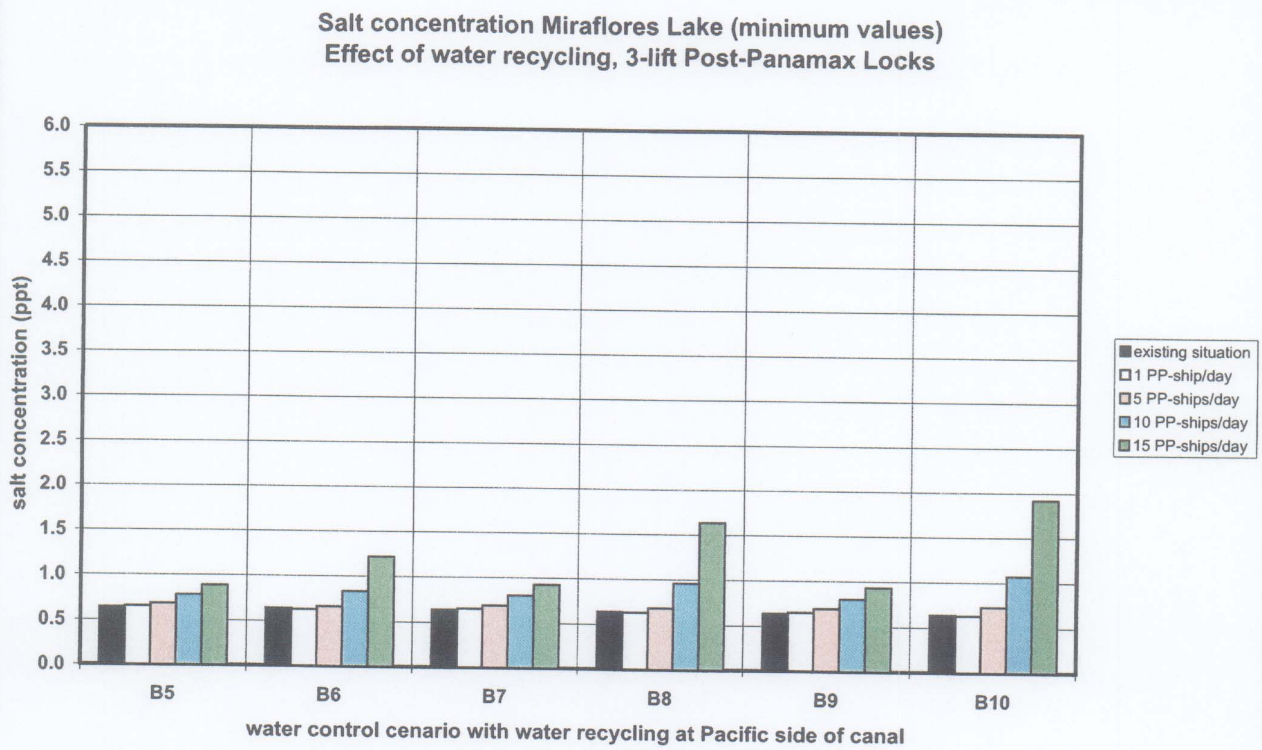
Fig. 3.14

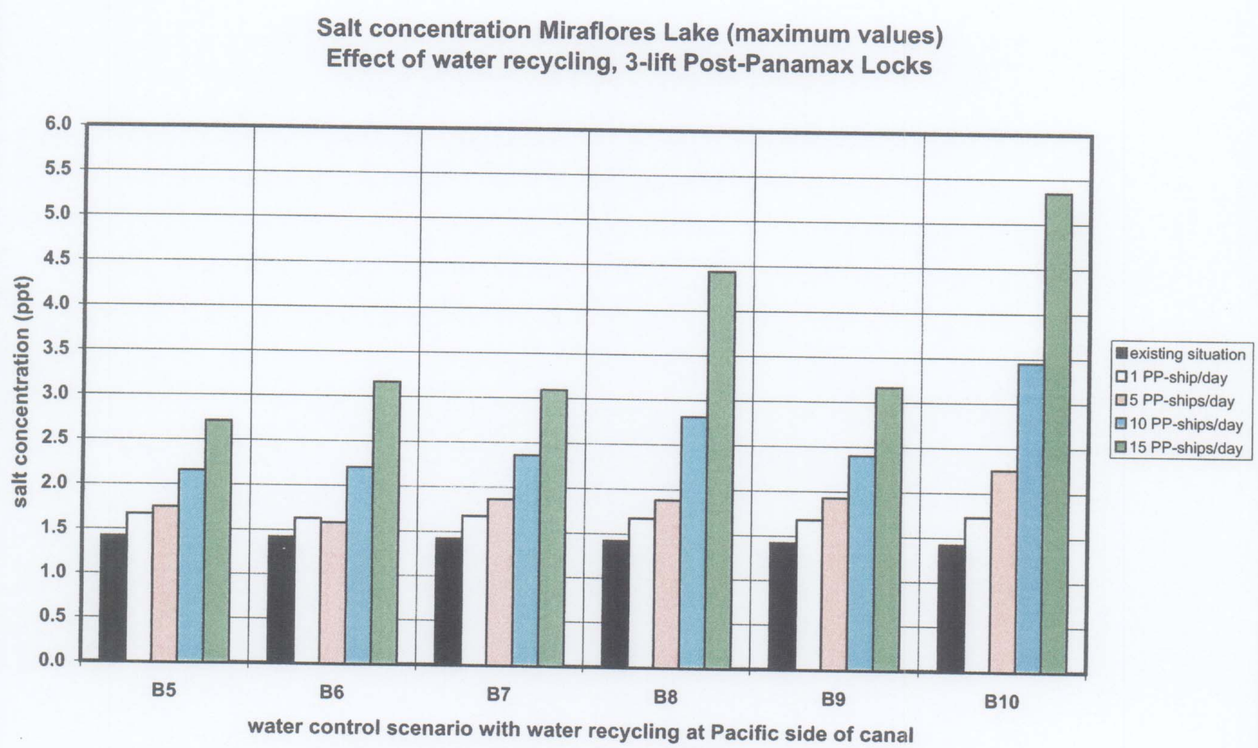






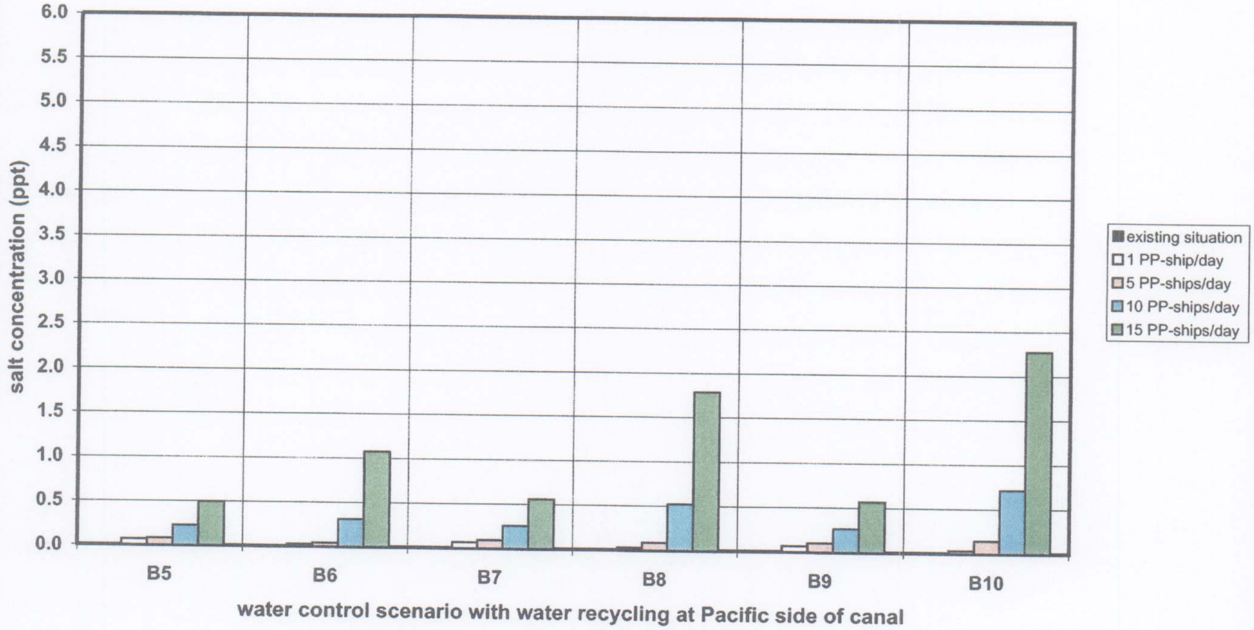
GATUN LAKE MEAN DAILY RECYCLING DISCHARGE Year 50 - 15 Post-Panamax ships/day - Various scenarios	3-lift, 2-lift, 1-lift locks	
WL | DELFT HYDRAULICS	Q 3476	Fig. 3.15



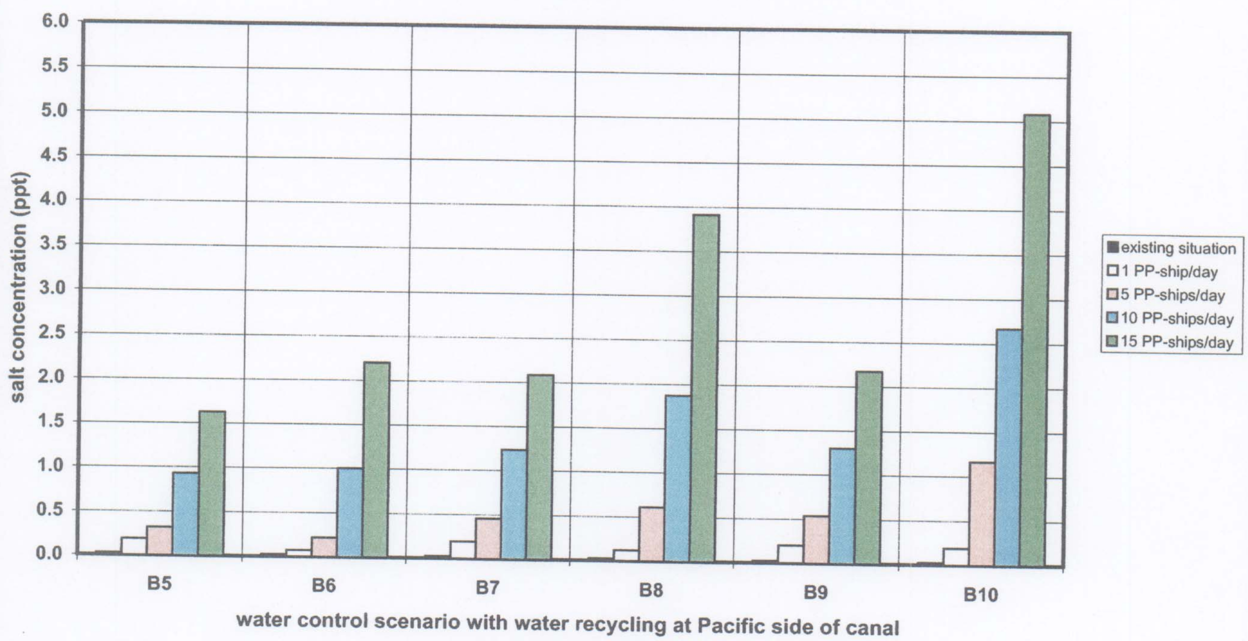


SALT CONCENTRATION MIRAFLORES LAKE effect of water recycling as function of PP-ship traffic intensity	3-lift locks	
WL | DELFT HYDRAULICS	Q 3476	Fig. 7.1

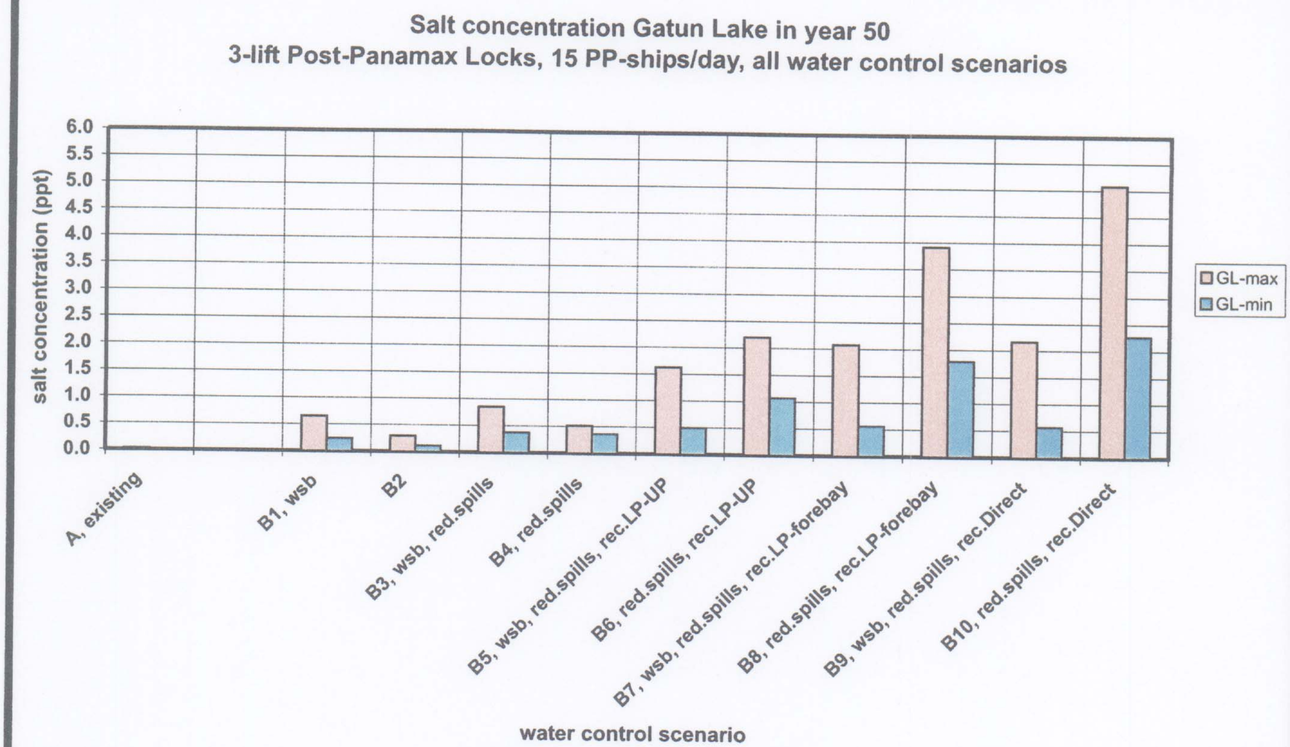
Salt concentration Gatun Lake (minimum values)
Effect of water recycling, 3-lift Post-Panamax Locks

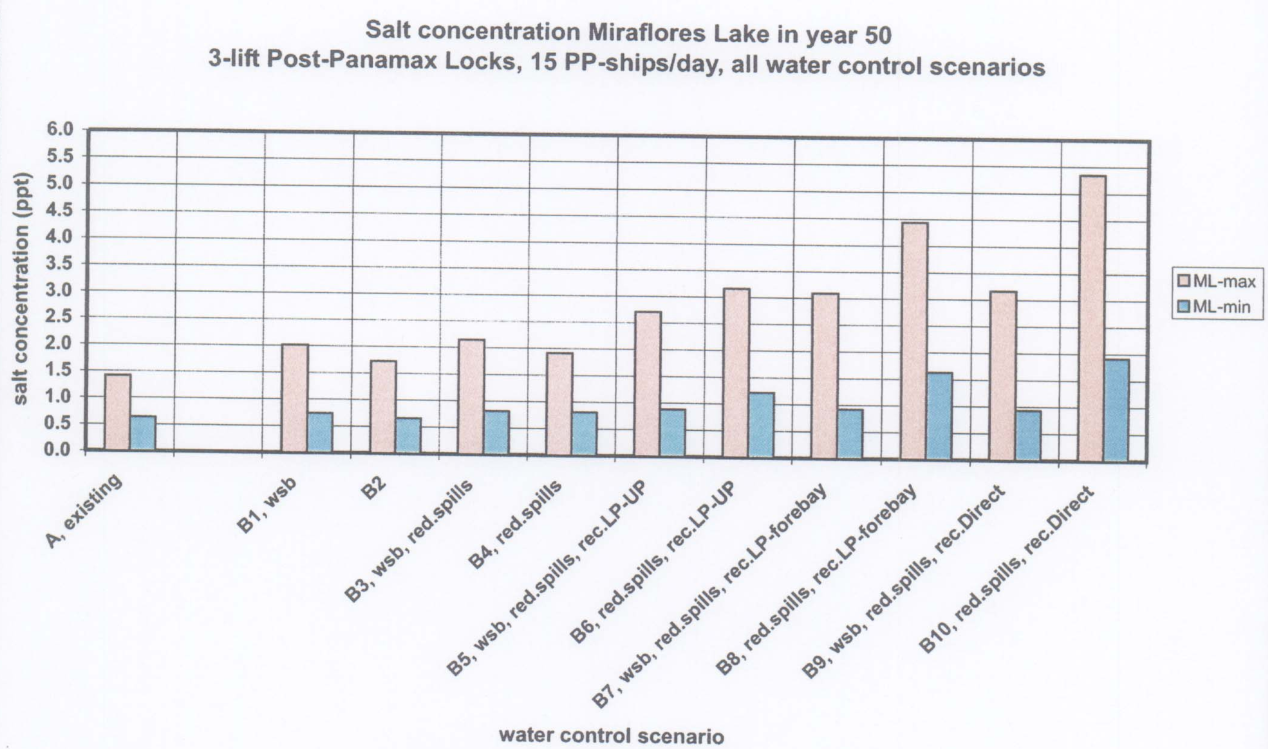


Salt concentration Gatun Lake (maximum values)
Effect of water recycling, 3-lift Post-Panamax Locks



SALT CONCENTRATION GATUN LAKE effect of water recycling as function of PP-ship traffic intensity	3-lift locks	
WL | DELFT HYDRAULICS	Q 3476	Fig. 7.2





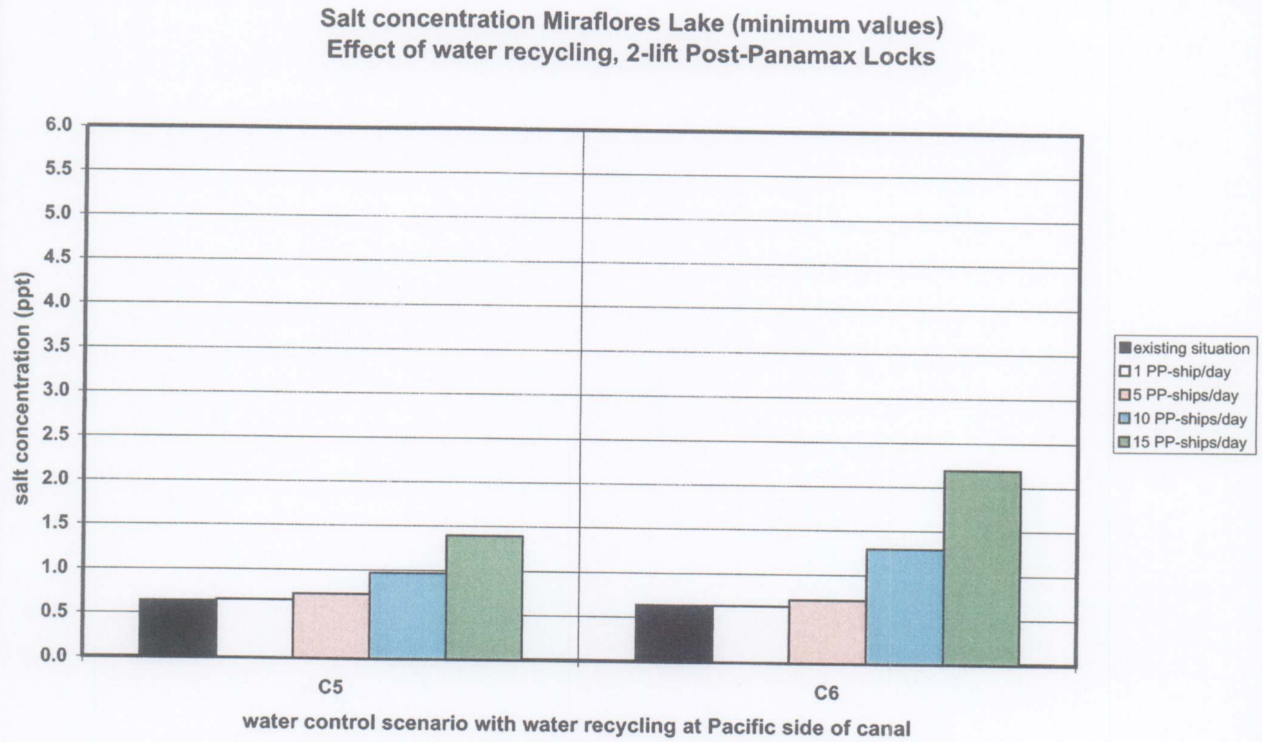
SALT CONCENTRATION GATUN LAKE and MIRAFLORES LAKE
Year 50 - 15 Post-Panamax ships/day - All scenarios

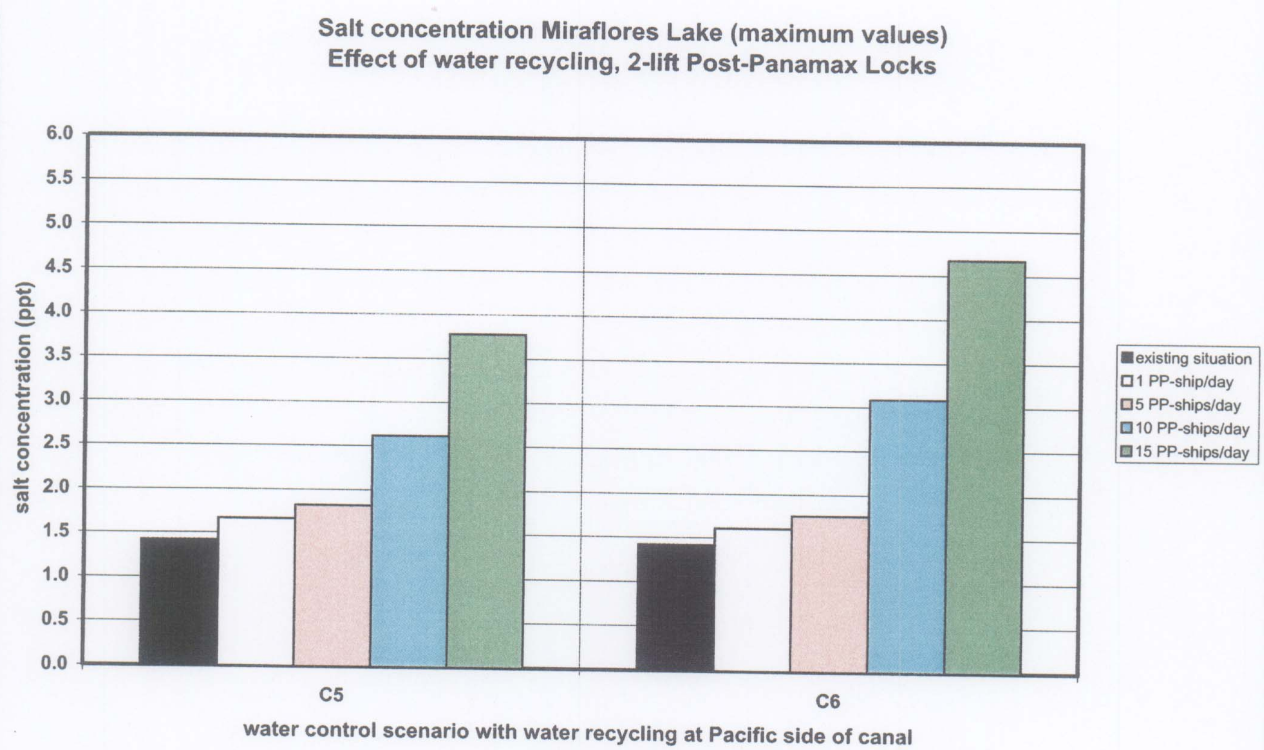
3-lift locks

WL | DELFT HYDRAULICS

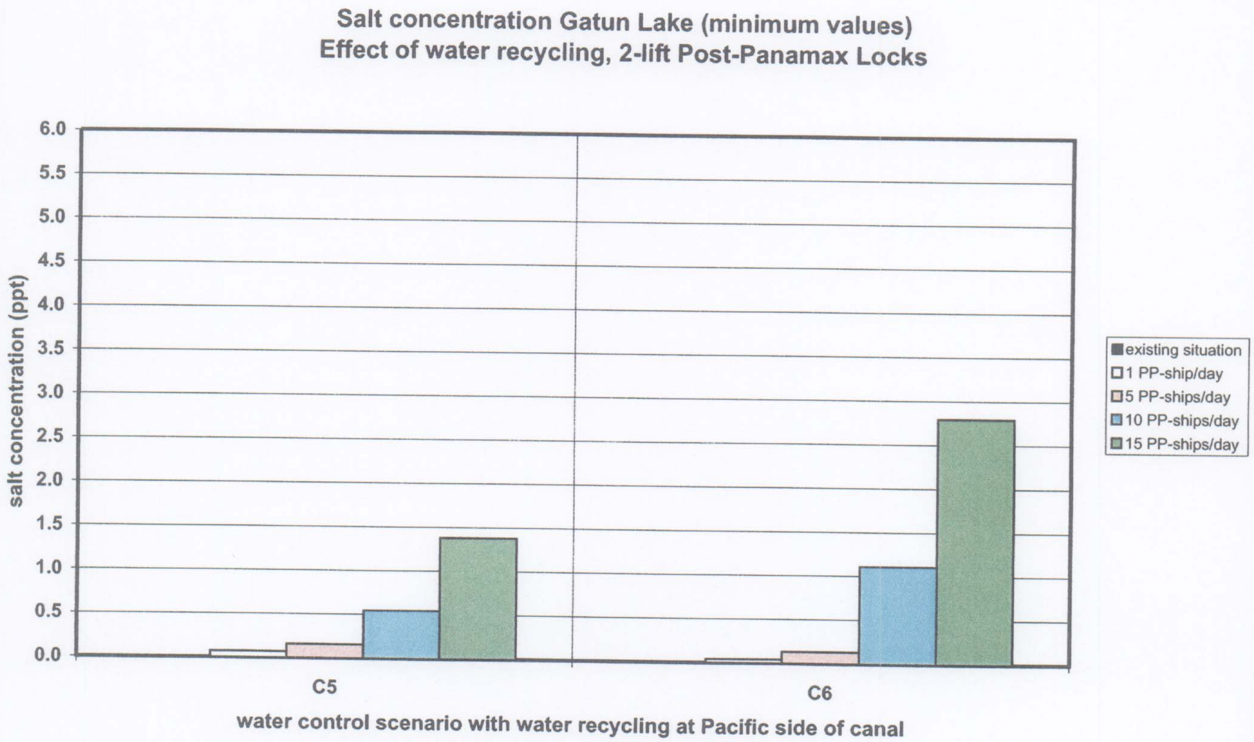
Q 3476

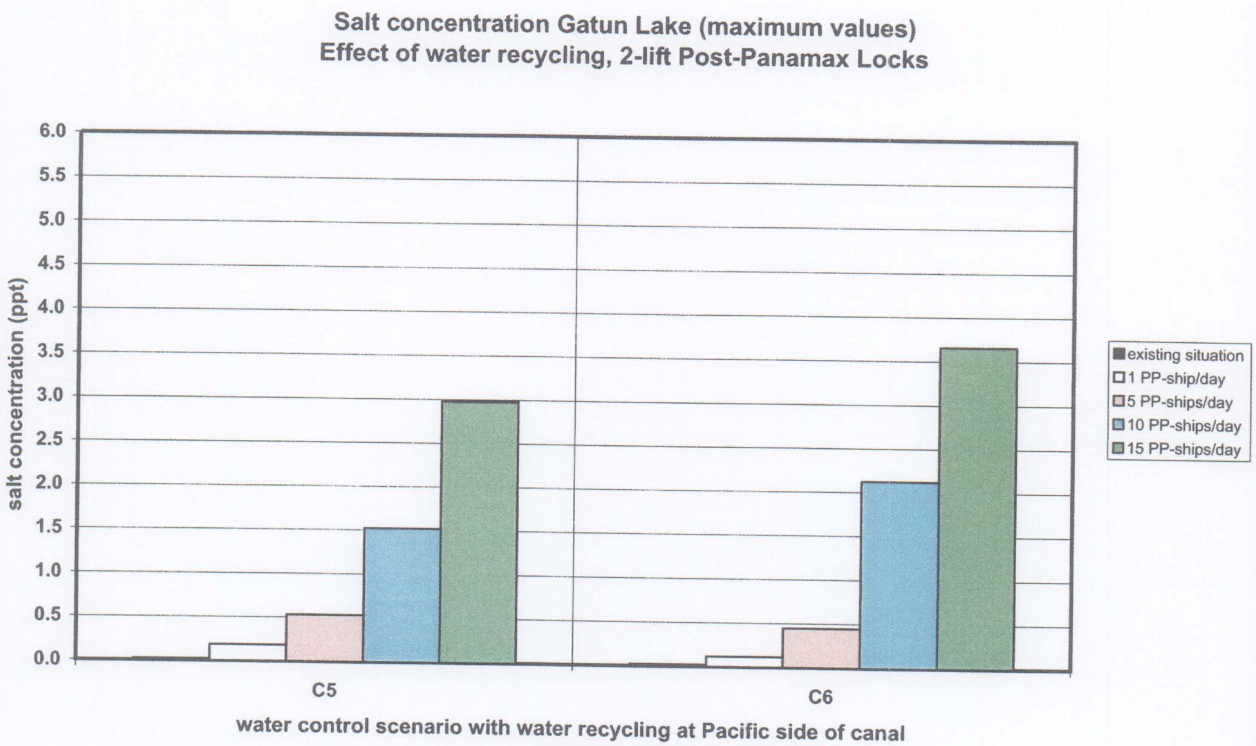
Fig. 7.3





SALT CONCENTRATION MIRAFLORES LAKE effect of water recycling as function of PP-ship traffic intensity	2-lift locks	
WL | DELFT HYDRAULICS	Q 3476	Fig. 7.4





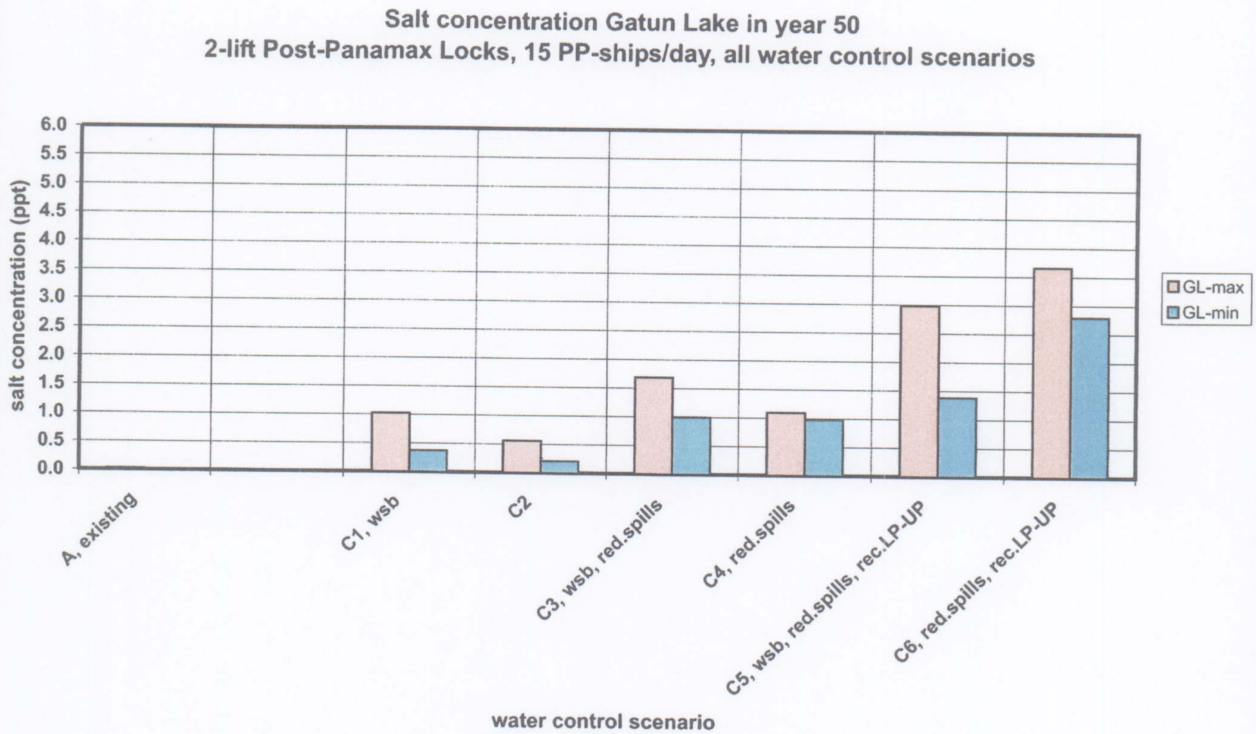
SALT CONCENTRATION GATUN LAKE
effect of water recycling as function of PP-ship traffic intensity

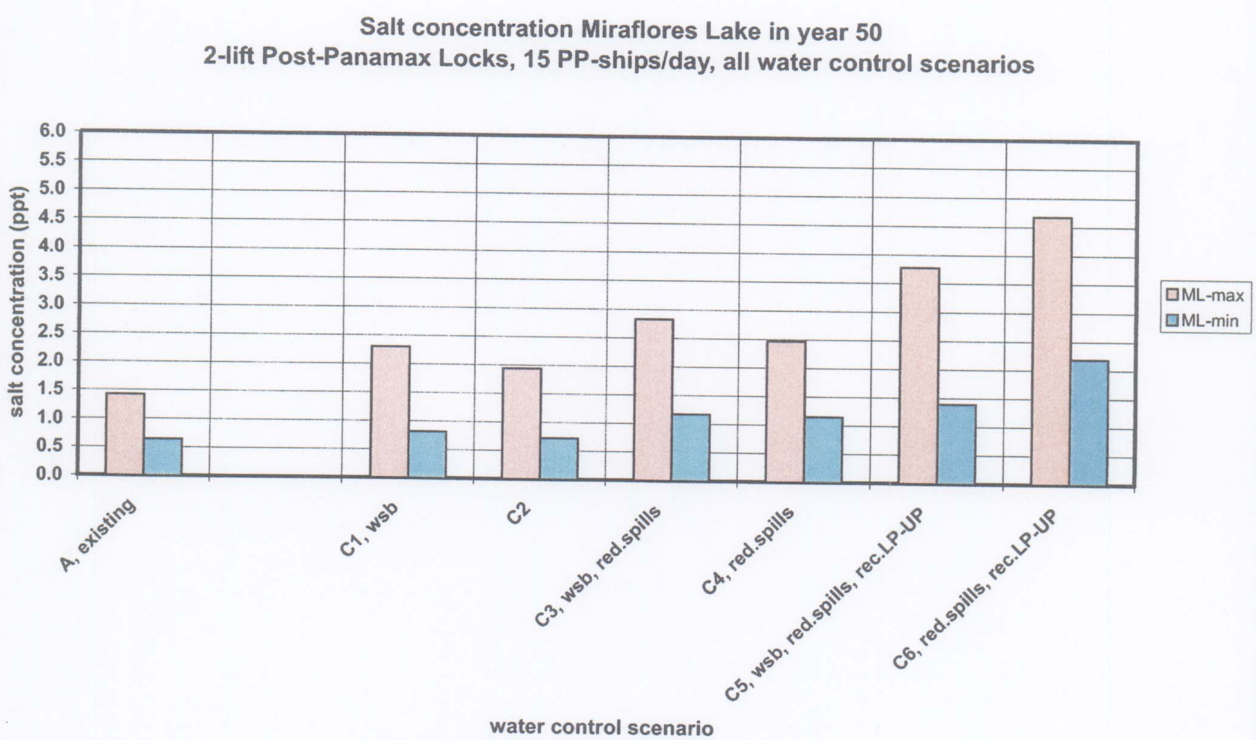
2-lift locks

WL | DELFT HYDRAULICS

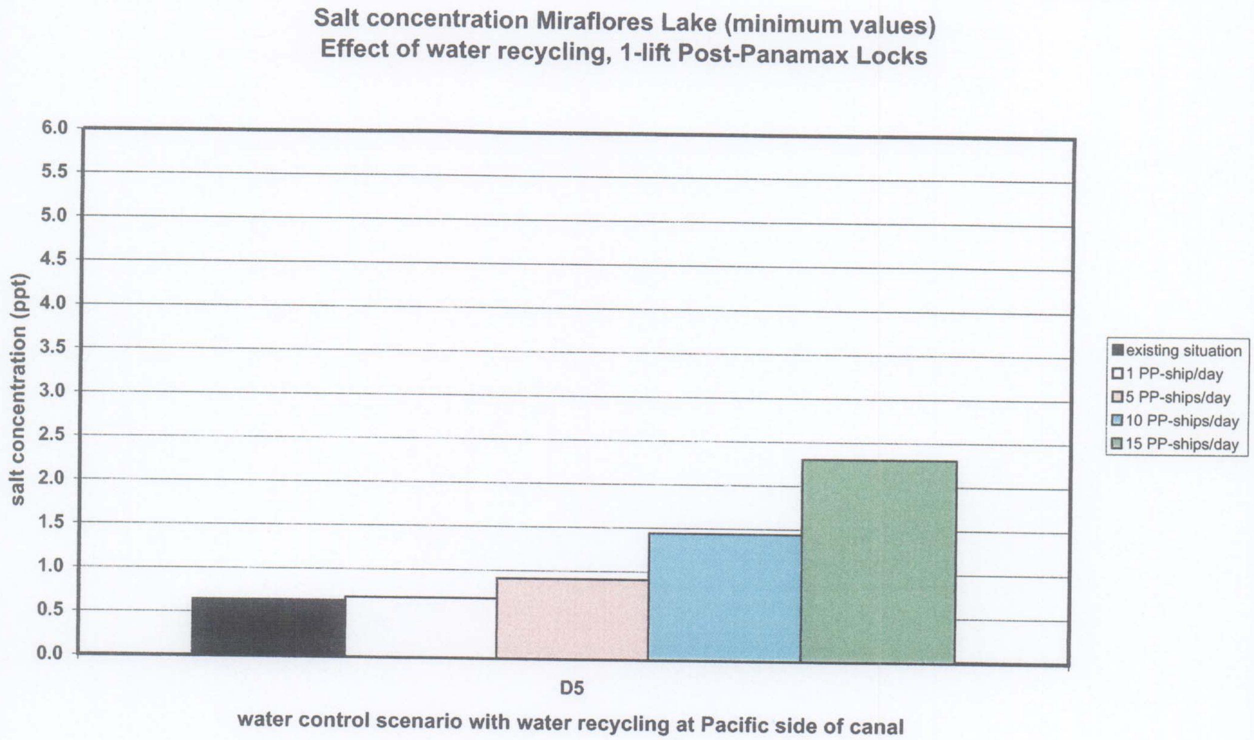
Q 3476

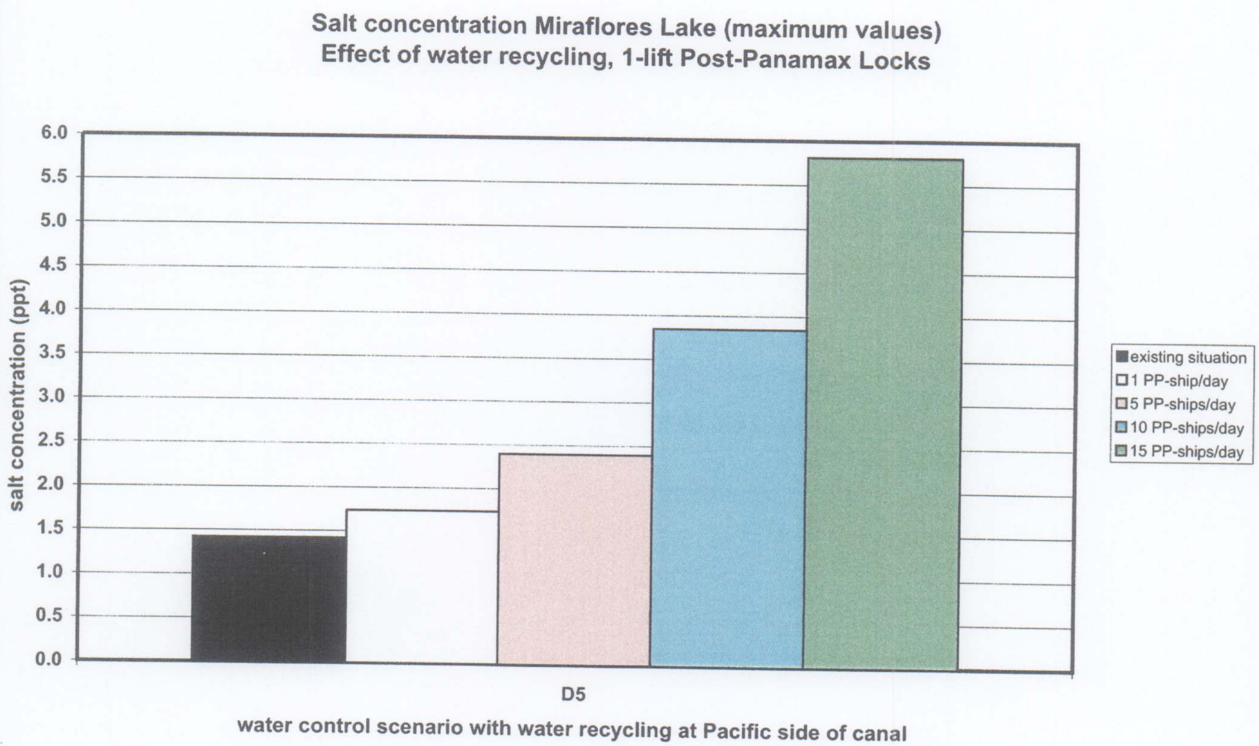
Fig. 7.5





SALT CONCENTRATION GATUN LAKE and MIRAFLORES LAKE Year 50 - 15 Post-Panamax ships/day - All scenarios	2-lift locks	
WL | DELFT HYDRAULICS	Q 3476	Fig. 7.6





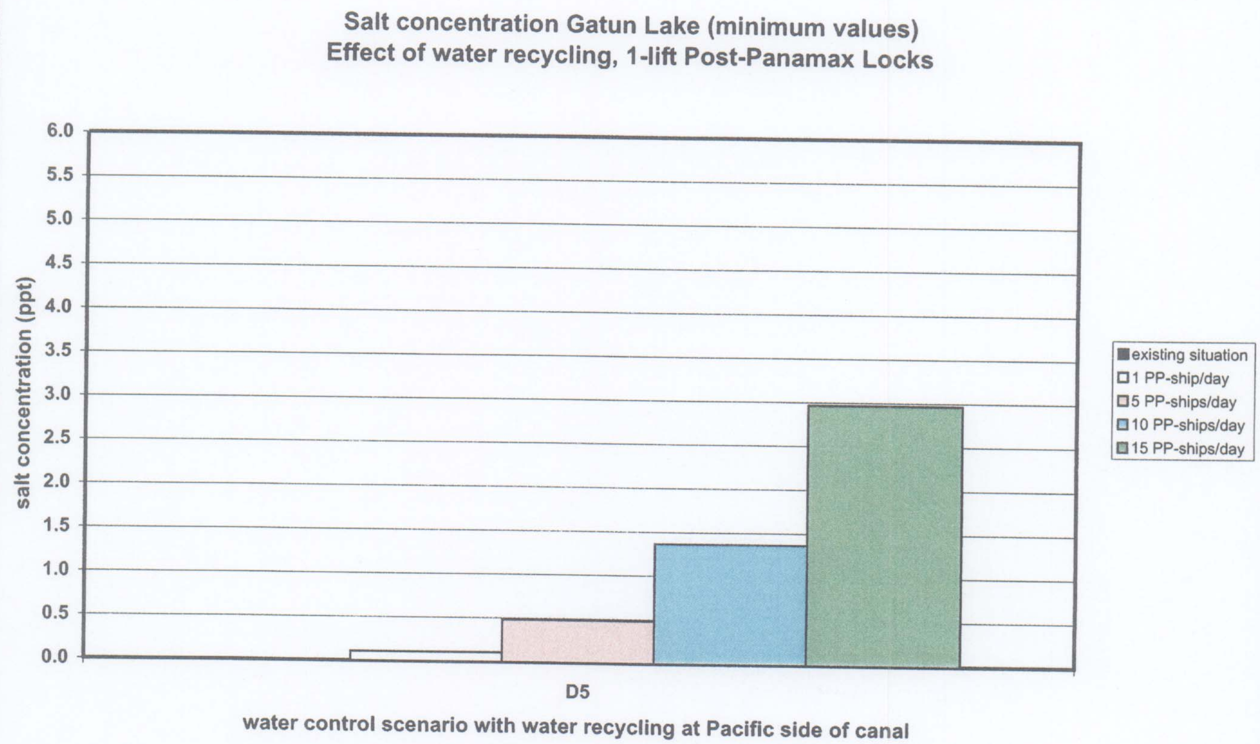
SALT CONCENTRATION MIRAFLORES LAKE
effect of water recycling as function of PP-ship traffic intensity

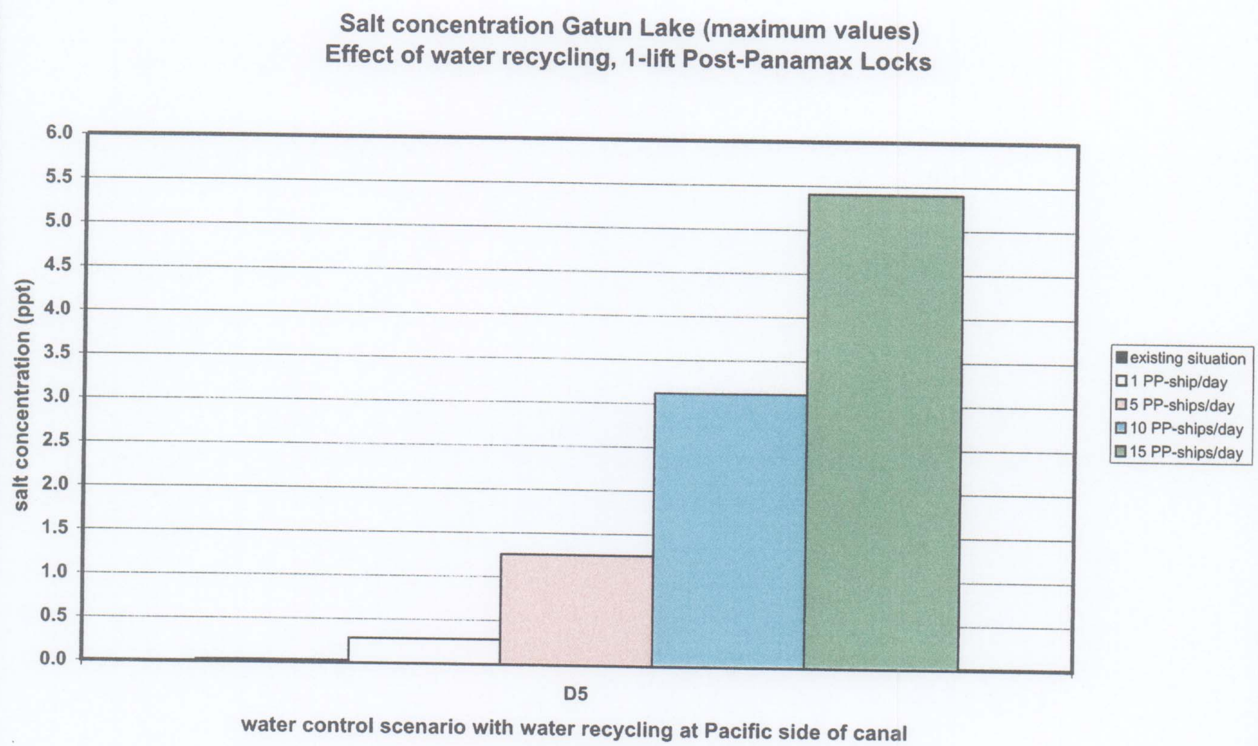
1-lift locks

WL | DELFT HYDRAULICS

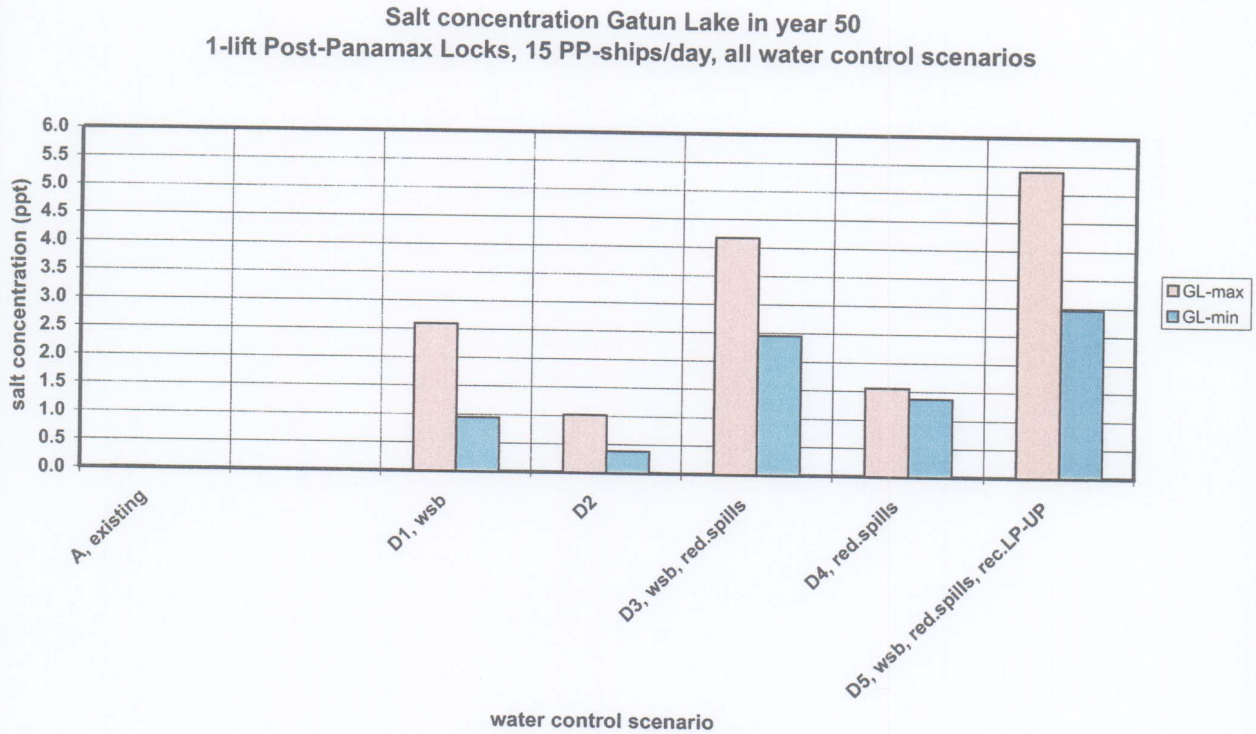
Q 3476

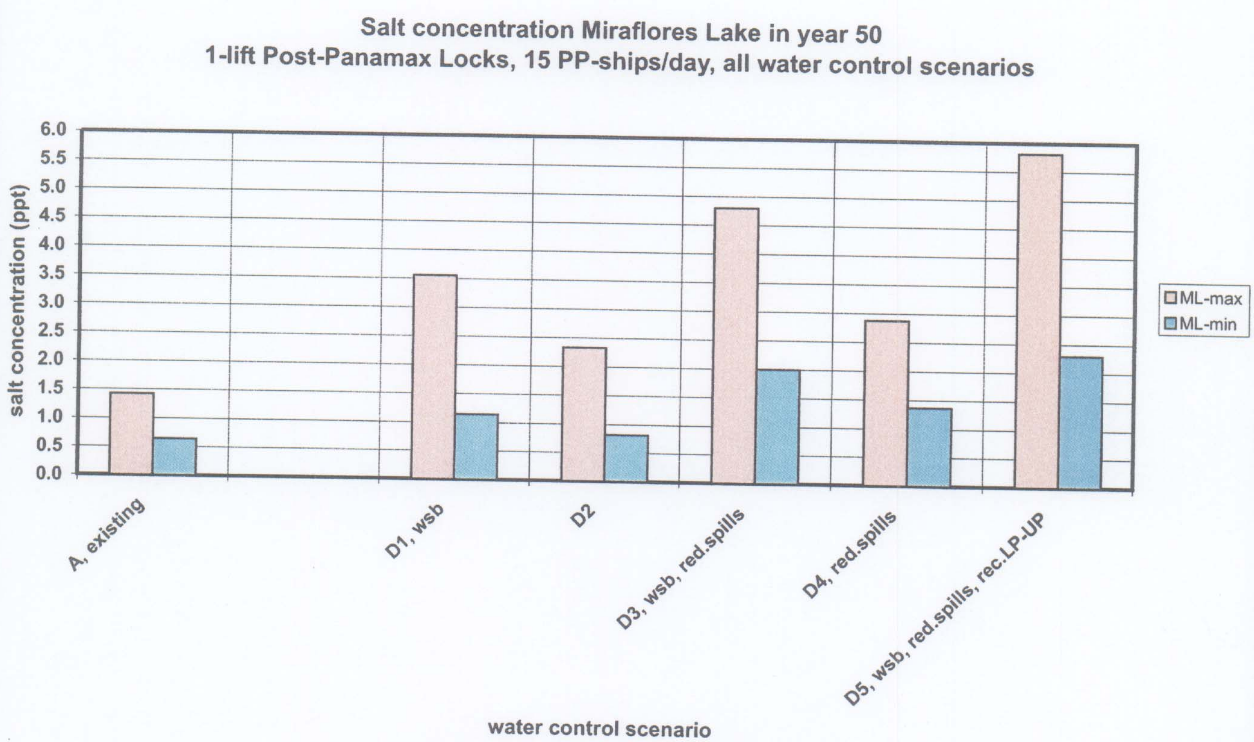
Fig. 7.7



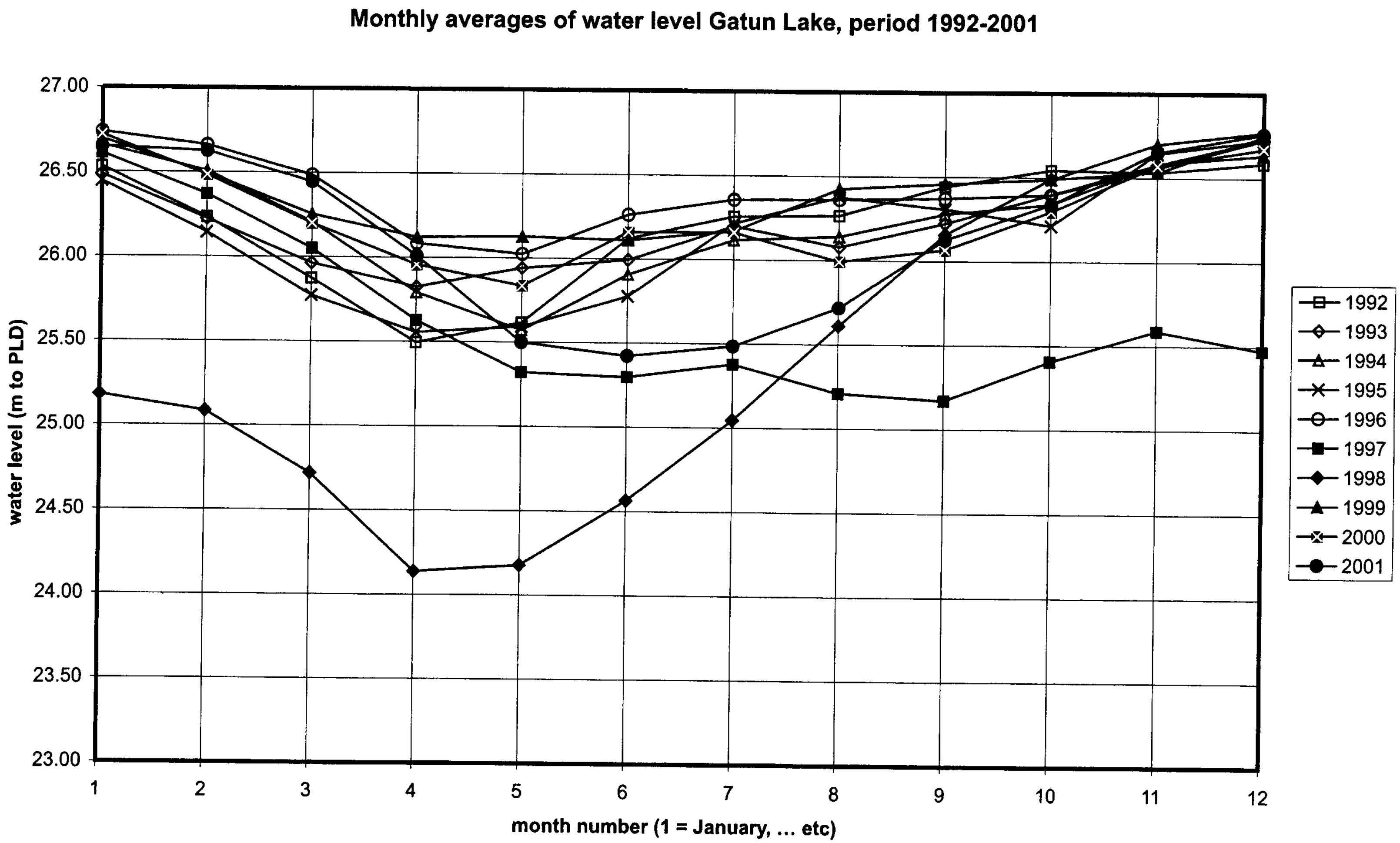


SALT CONCENTRATION GATUN LAKE effect of water recycling as function of PP-ship traffic intensity		
	1-lift locks	
WL | DELFT HYDRAULICS	Q 3476	Fig. 7.8





SALT CONCENTRATION GATUN LAKE and MIRAFLORES LAKE Year 50 - 15 Post-Panamax ships/day - All scenarios	1-lift locks	
WL | DELFT HYDRAULICS	Q 3476	Fig. 7.9

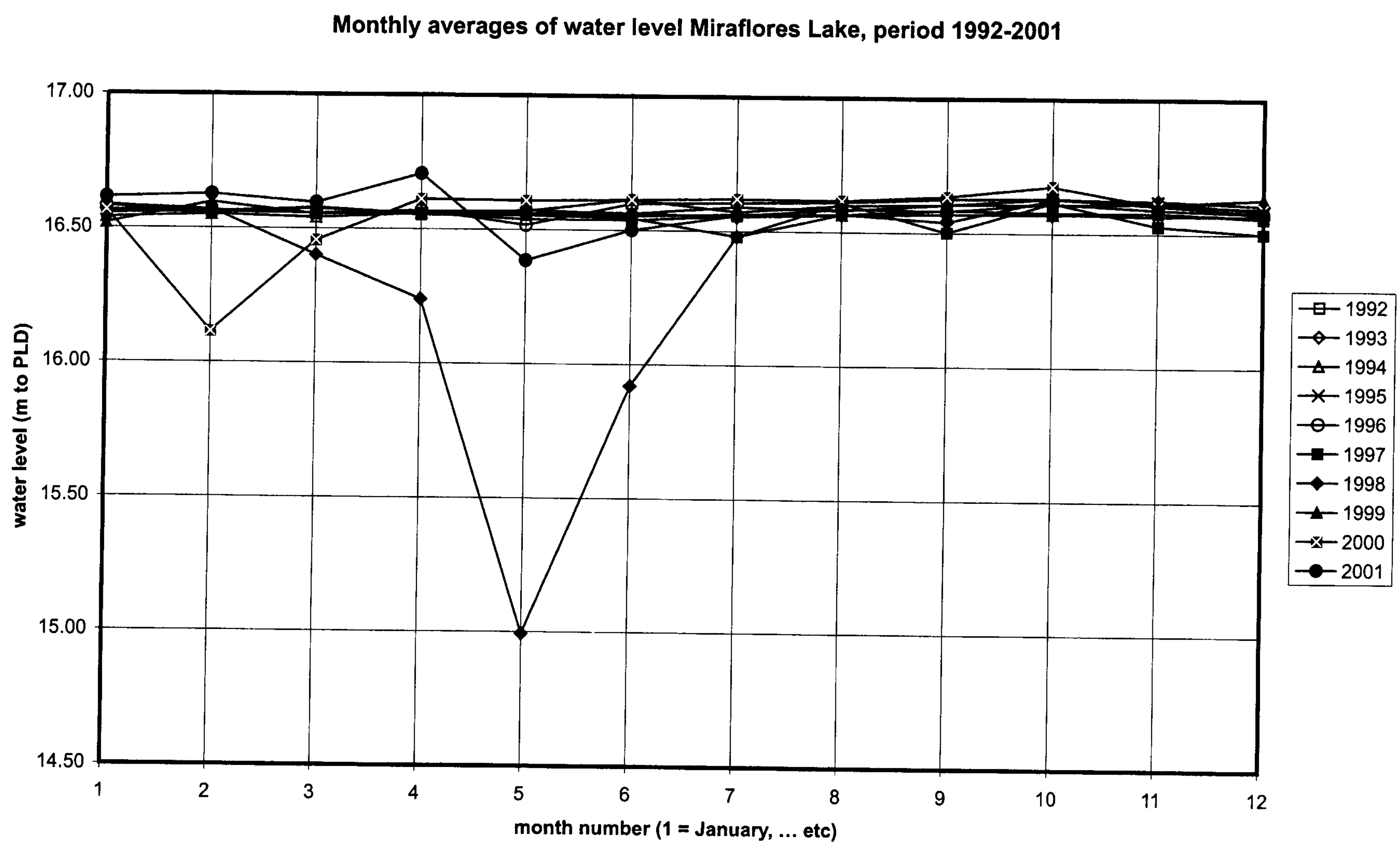


GATUN LAKE: MONTHLY AVERAGES OF WATER LEVEL IN PERIOD 1992 - 2001

WL | DELFT HYDRAULICS

Q 3476

Fig. 8.1

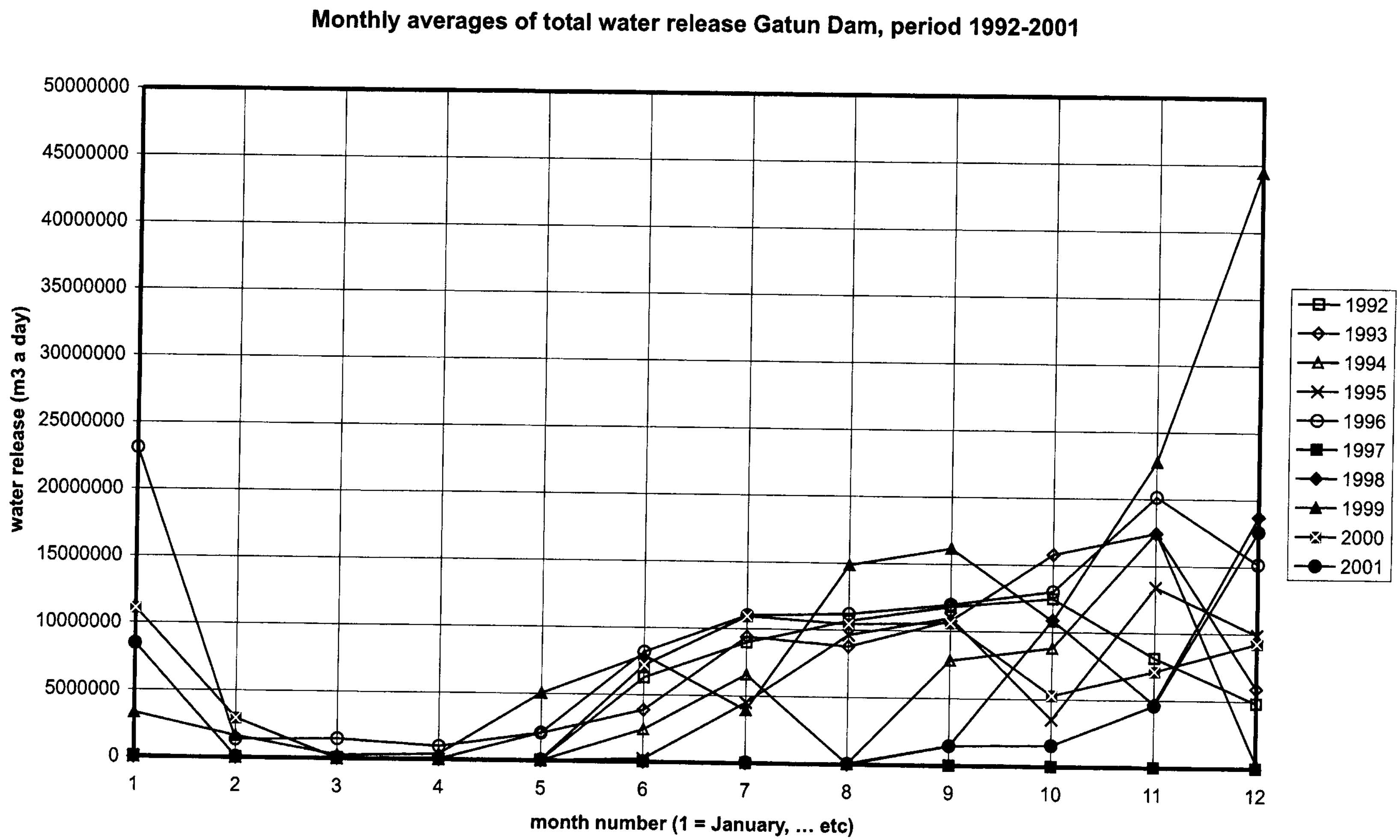


MIRAFLORES LAKE: MONTHLY AVERAGES OF WATER LEVEL IN PERIOD 1992 - 2001

WL | DELFT HYDRAULICS

Q 3476

Fig. 8.2



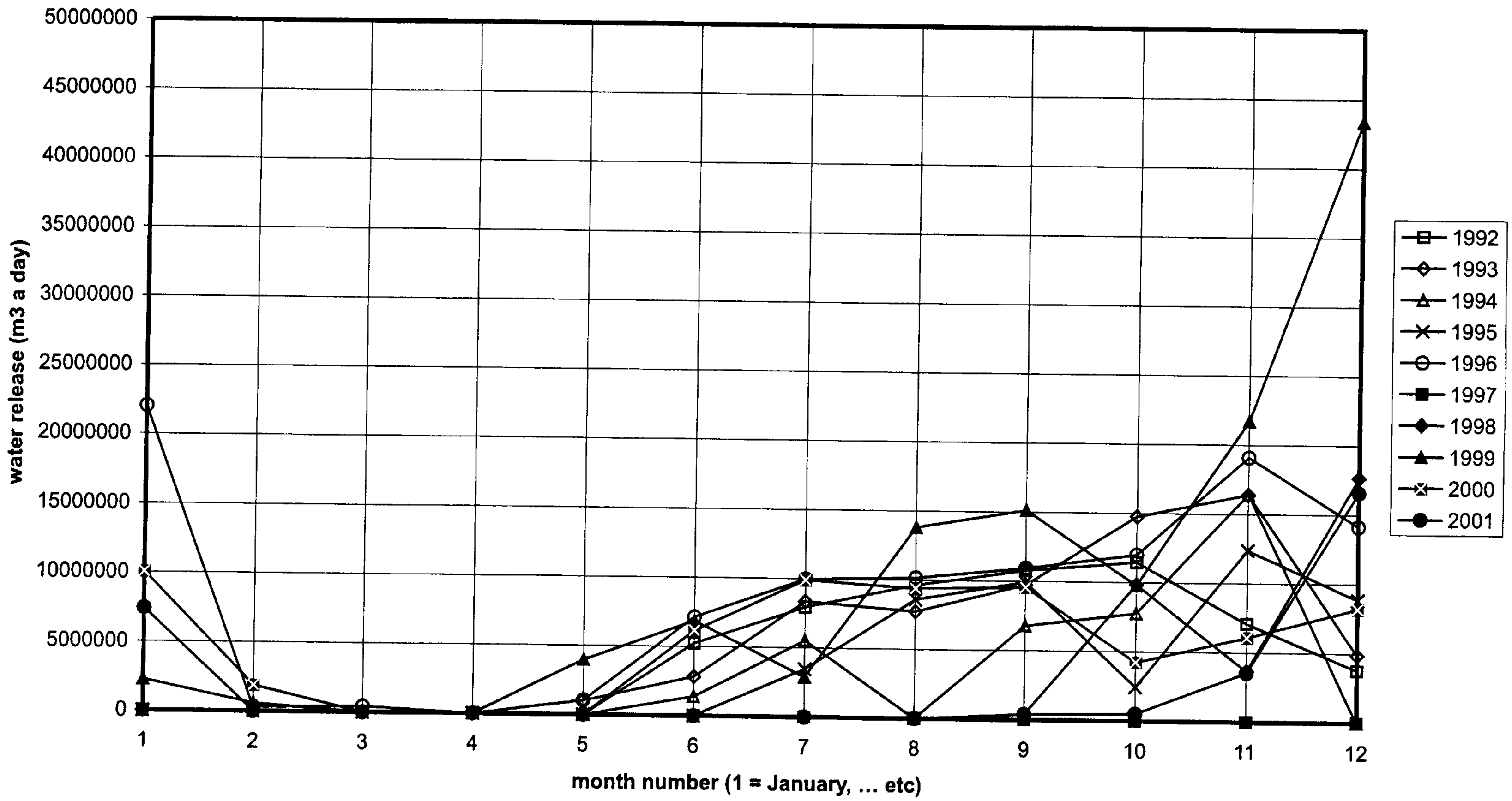
GATUN LAKE: MONTHLY AVERAGES OF TOTAL WATER RELEASE IN PERIOD 1992 - 2001

WL | DELFT HYDRAULICS

Q 3476

Fig. 8.3

Monthly averages of water release at Gatun Dam, hydraulic conditions as in period 1992-2001
5 Post-Panamax ships a day, scenarios 3, 5 and 9



WATER RELEASE AT GATUN DAM IN SIMULATIONS
5 POST-PANAMAX SHIPS A DAY, SCENARIOS 3, 5 AND 9

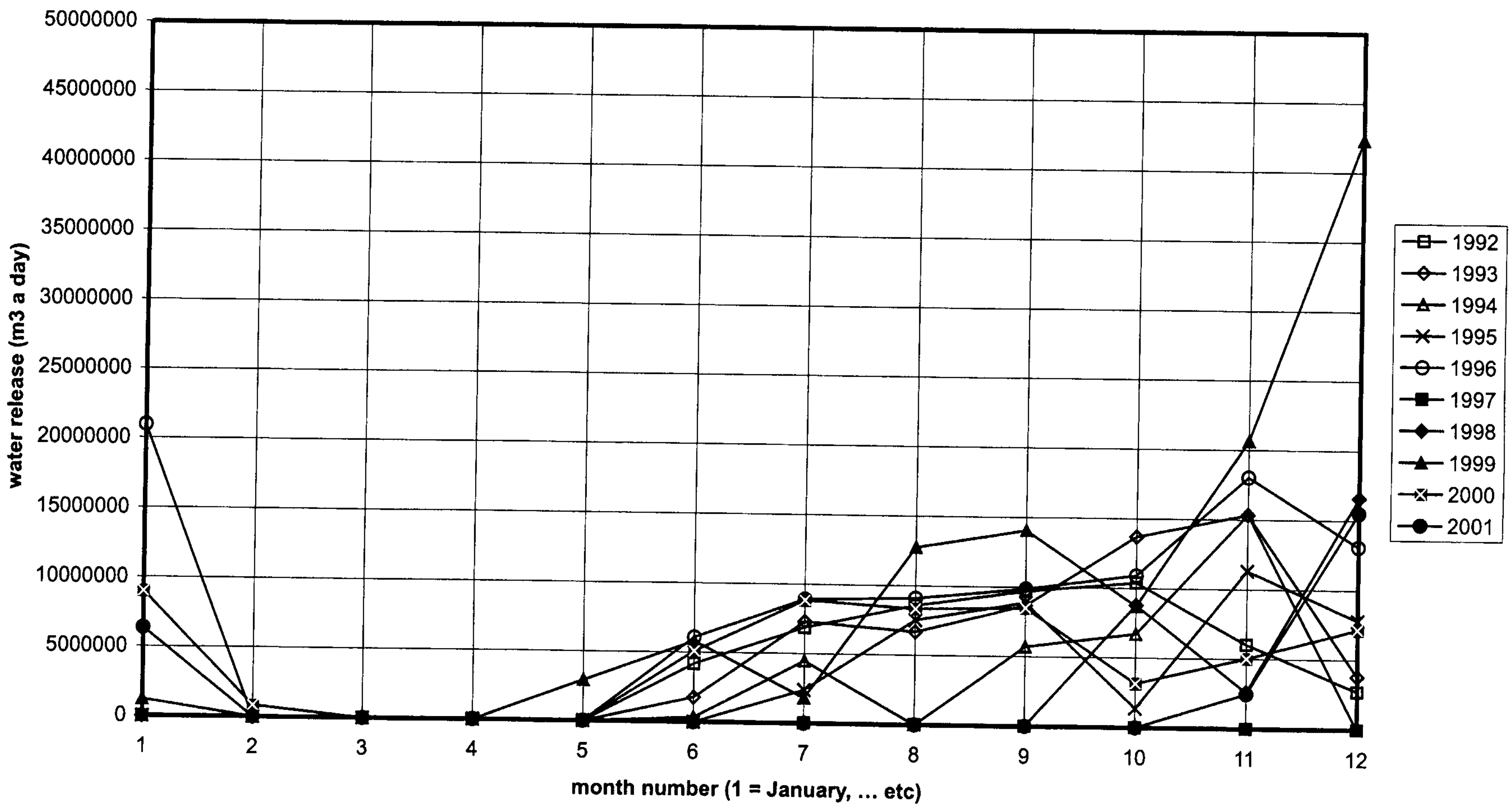
WL | DELFT HYDRAULICS

3-lift locks

Q 3476

Fig. 8.4

Monthly averages of water release at Gatun Dam, hydraulic conditions as in period 1992-2001
10 Post-Panamax ships a day, scenarios 3, 5 and 9



WATER RELEASE AT GATUN DAM IN SIMULATIONS
10 POST-PANAMAX SHIPS A DAY, SCENARIOS 3, 5 AND 9

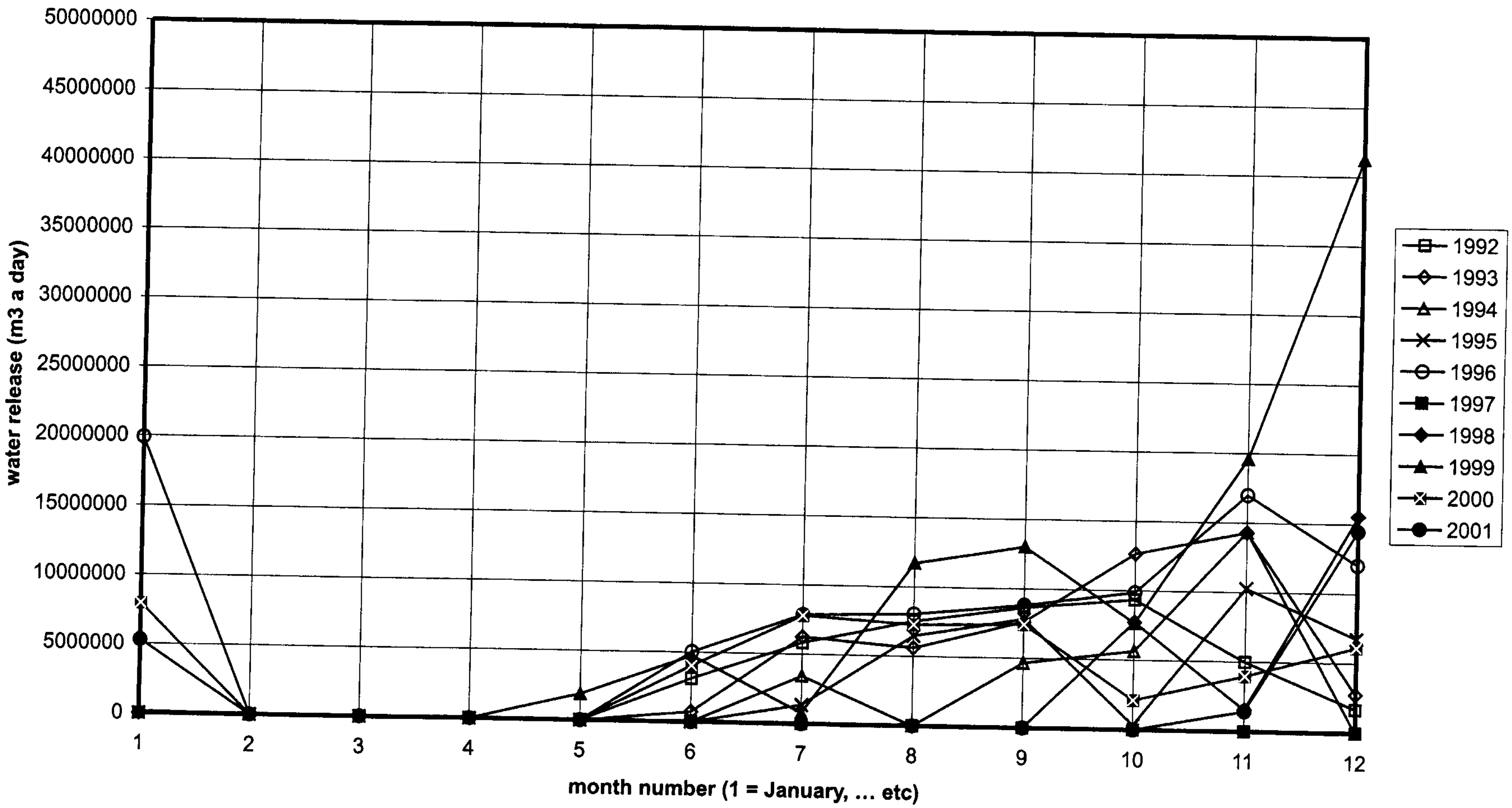
WL | DELFT HYDRAULICS

Q 3476

3-lift locks

Fig. 8.5

Monthly averages of water release at Gatun Dam, hydraulic conditions as in period 1992-2001
15 Post-Panamax ships a day, scenarios 3, 5 and 9



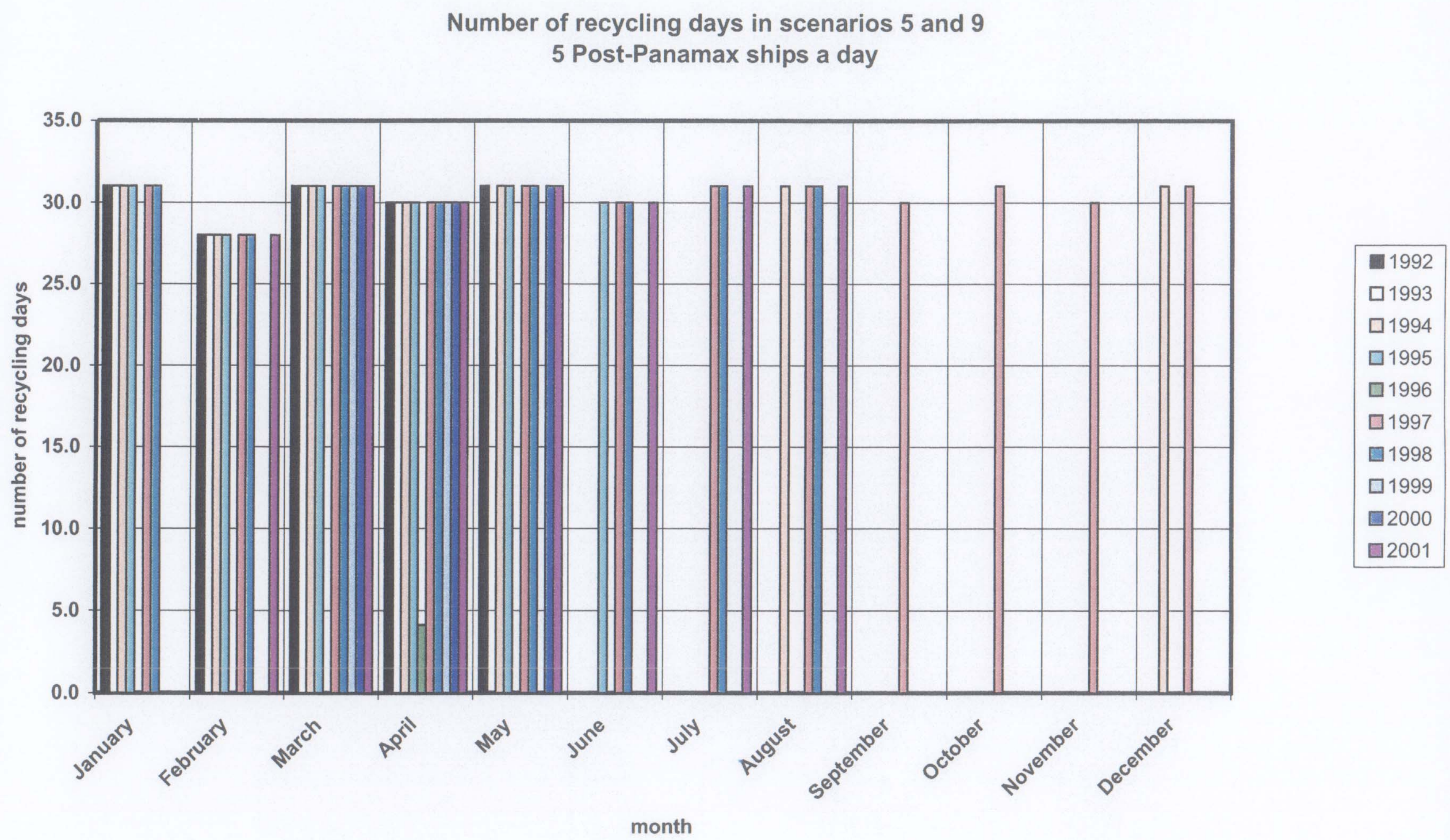
WATER RELEASE AT GATUN DAM IN SIMULATIONS
15 POST-PANAMAX SHIPS A DAY, SCENARIOS 3, 5 AND 9

3-lift locks

WL | DELFT HYDRAULICS

Q 3476

Fig. 8.6



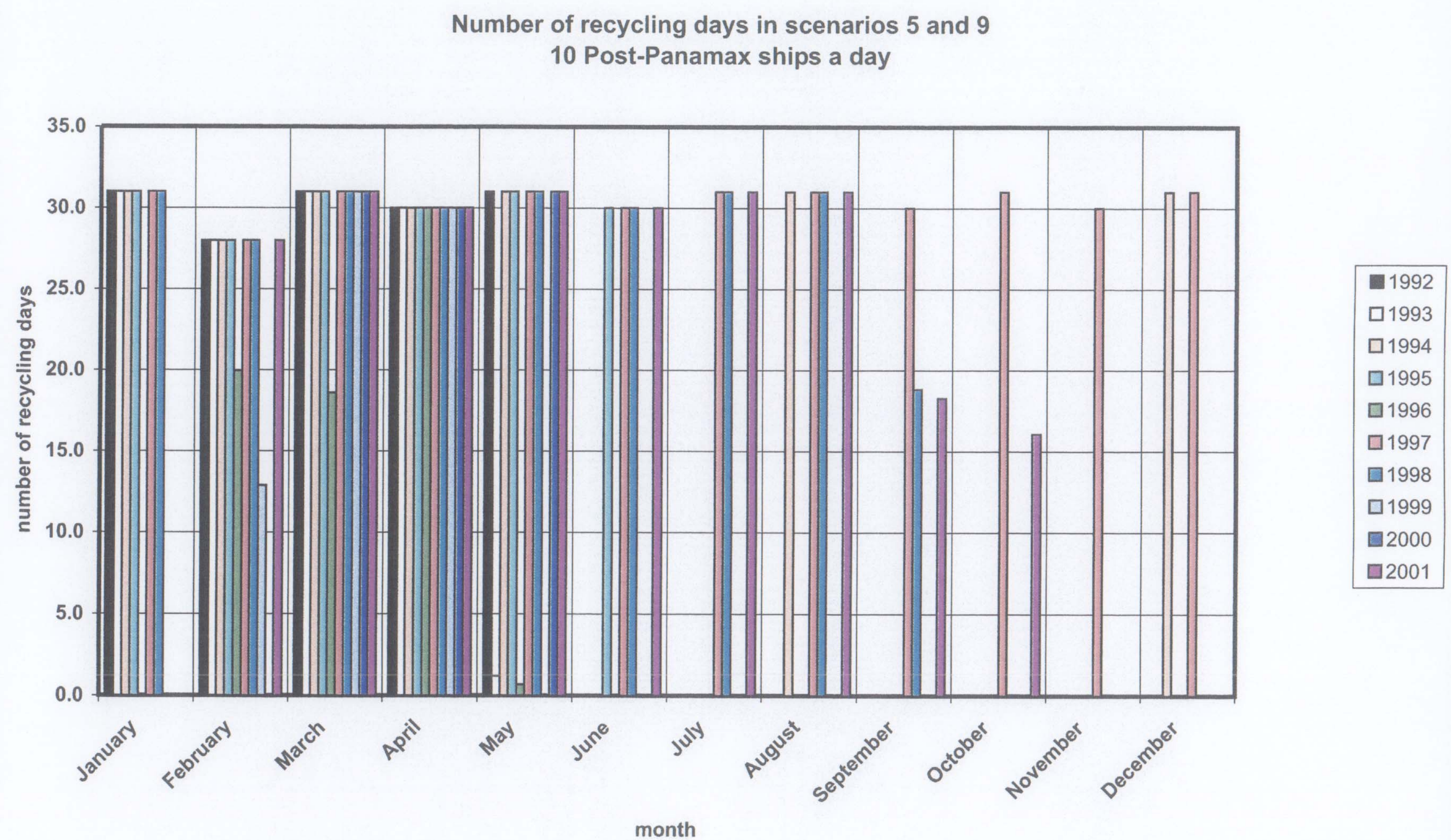
WL | DELFT HYDRAULICS

NUMBER OF RECYCLING DAYS IN SIMULATIONS
5 POST-PANAMAX SHIPS A DAY, SCENARIOS 5 AND 9

3-lift locks

Q 3476

Fig. 8.7



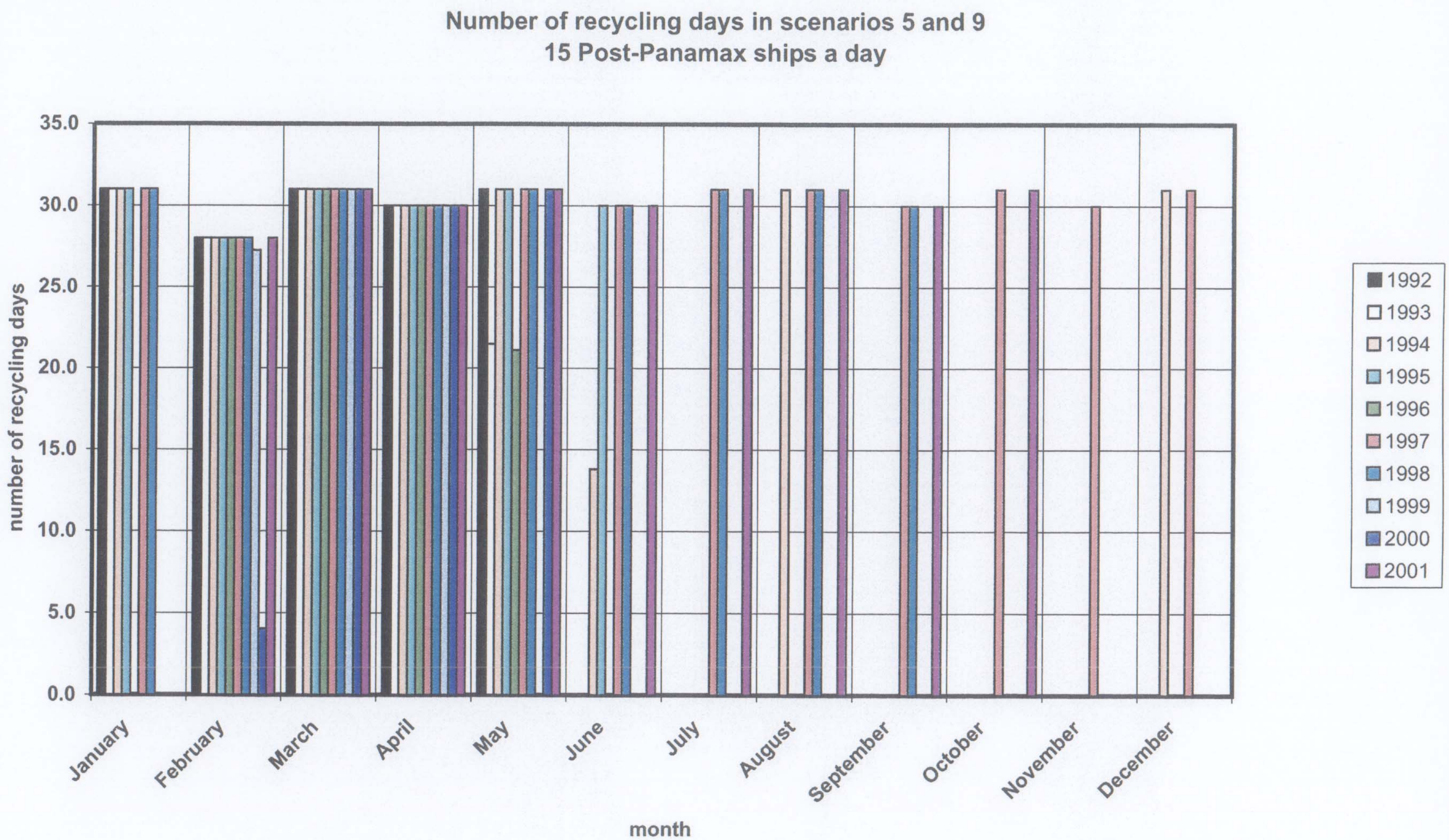
NUMBER OF RECYCLING DAYS IN SIMULATIONS
10 POST-PANAMAX SHIPS A DAY, SCENARIOS 5 AND 9

WL | DELFT HYDRAULICS

3-lift locks

Q 3476

Fig. 8.8



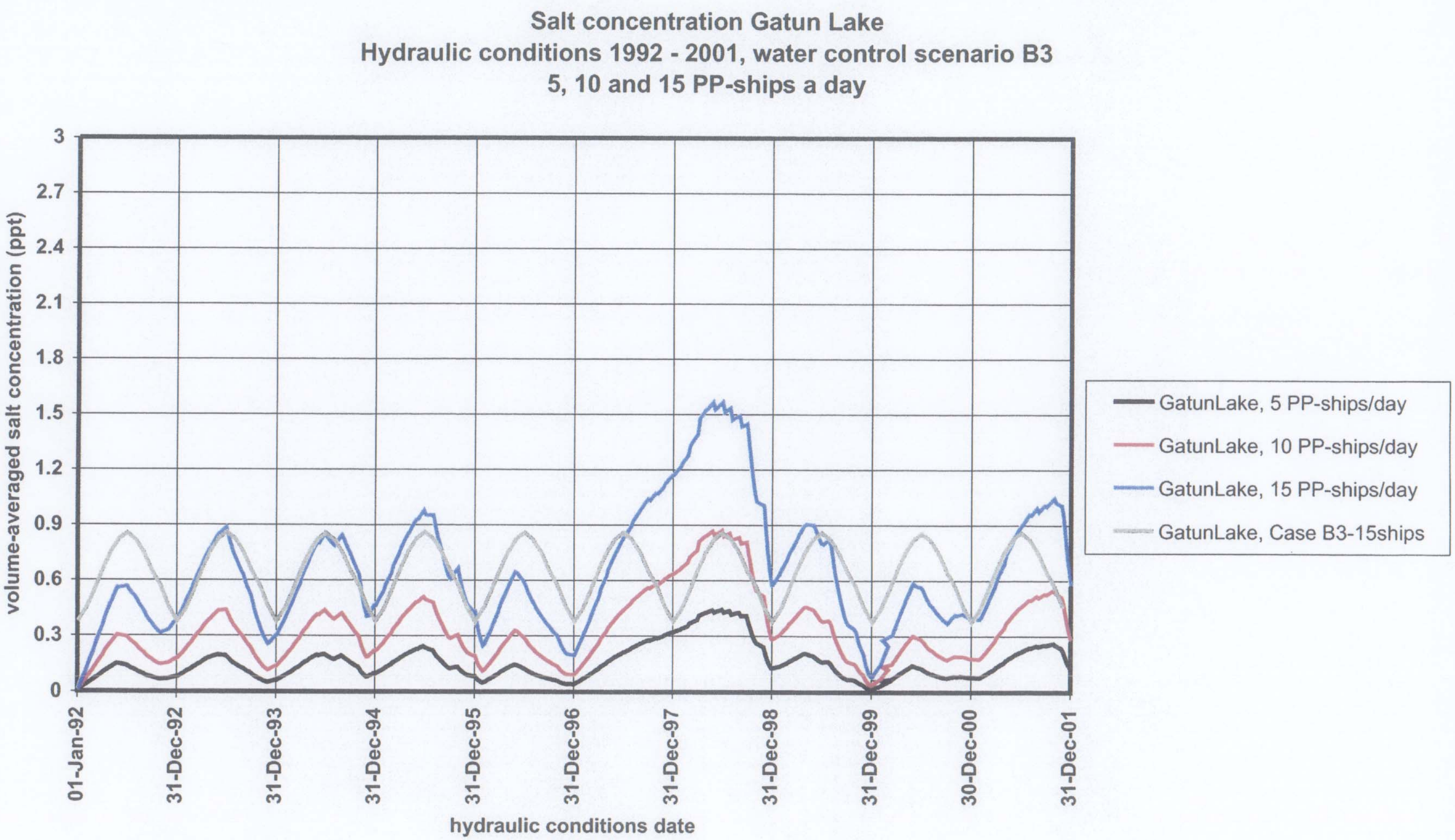
NUMBER OF RECYCLING DAYS IN SIMULATIONS
15 POST-PANAMAX SHIPS A DAY, SCENARIOS 5 AND 9

WL | DELFT HYDRAULICS

3-lift locks

Q 3476

Fig. 8.9



SALT CONCENTRATION GATUN LAKE
5, 10 AND 15 POST-PANAMAX SHIPS A DAY, SCENARIO 3

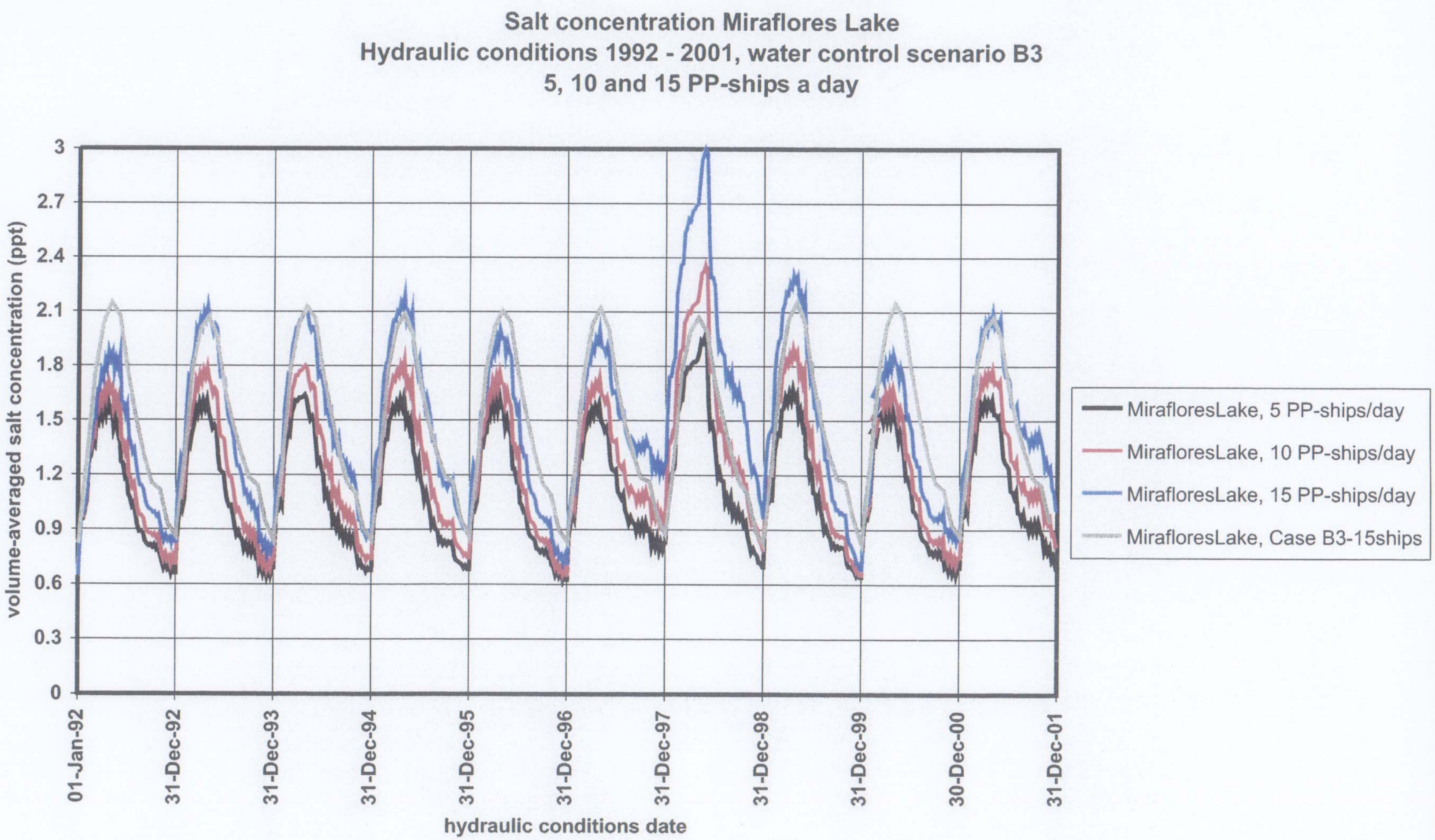
WL | DELFT HYDRAULICS

Swinlocks | Results

3-lift locks

Q 3476

Fig. 8.10



SALT CONCENTRATION MIRAFLORES LAKE
5, 10 AND 15 POST-PANAMAX SHIPS A DAY, SCENARIO 3

WL | DELFT HYDRAULICS

Swinlocks

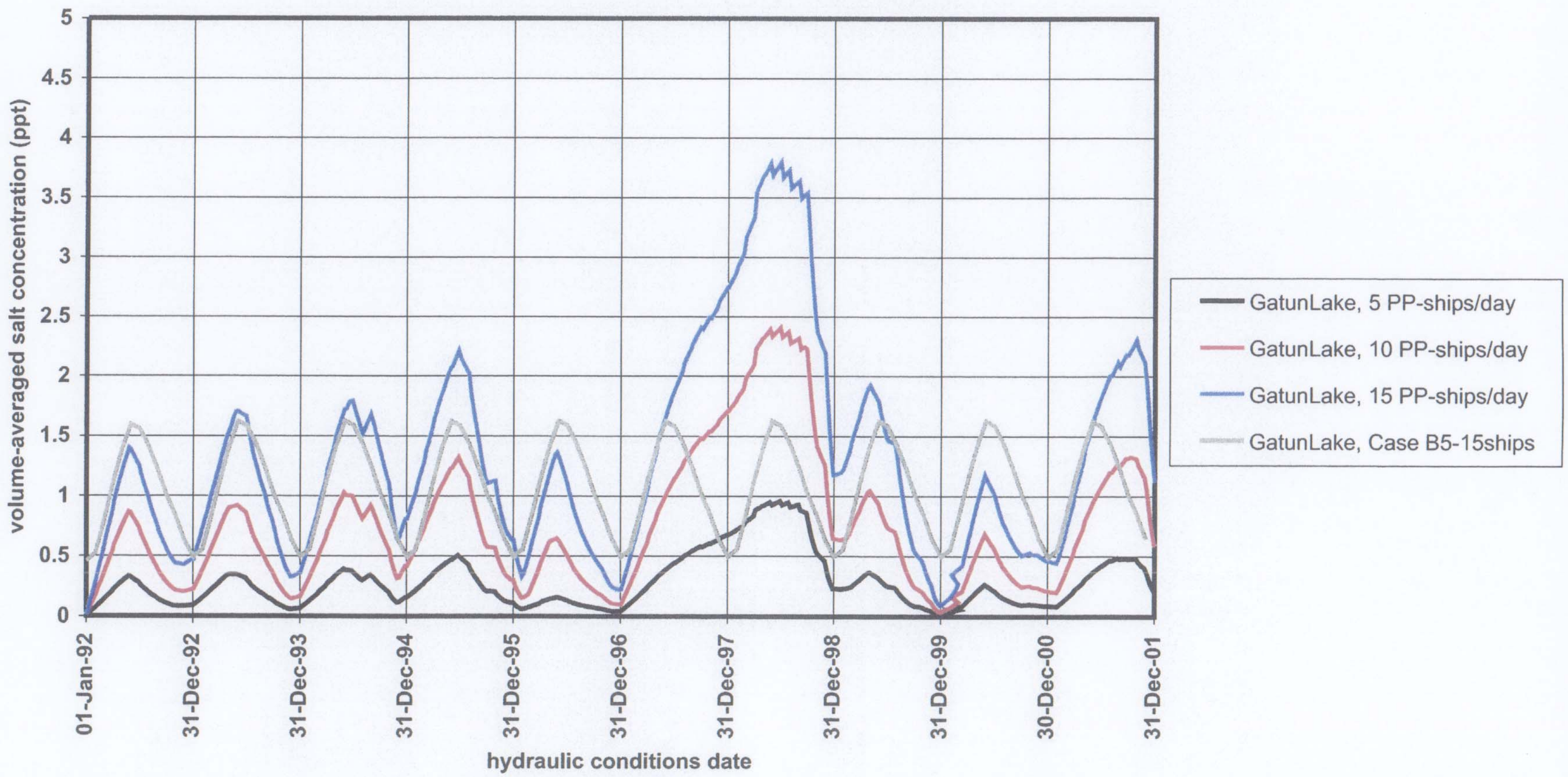
3-lift locks

Results

Q 3476

Fig. 8.11

Salt concentration Gatun Lake
Hydraulic conditions 1992 - 2001, water control scenario B5
5, 10 and 15 PP-ships a day



SALT CONCENTRATION GATUN LAKE
5, 10 AND 15 POST-PANAMAX SHIPS A DAY, SCENARIO 5

WL | DELFT HYDRAULICS

Swinlocks | Results

3-lift locks

Q 3476

Fig. 8.12

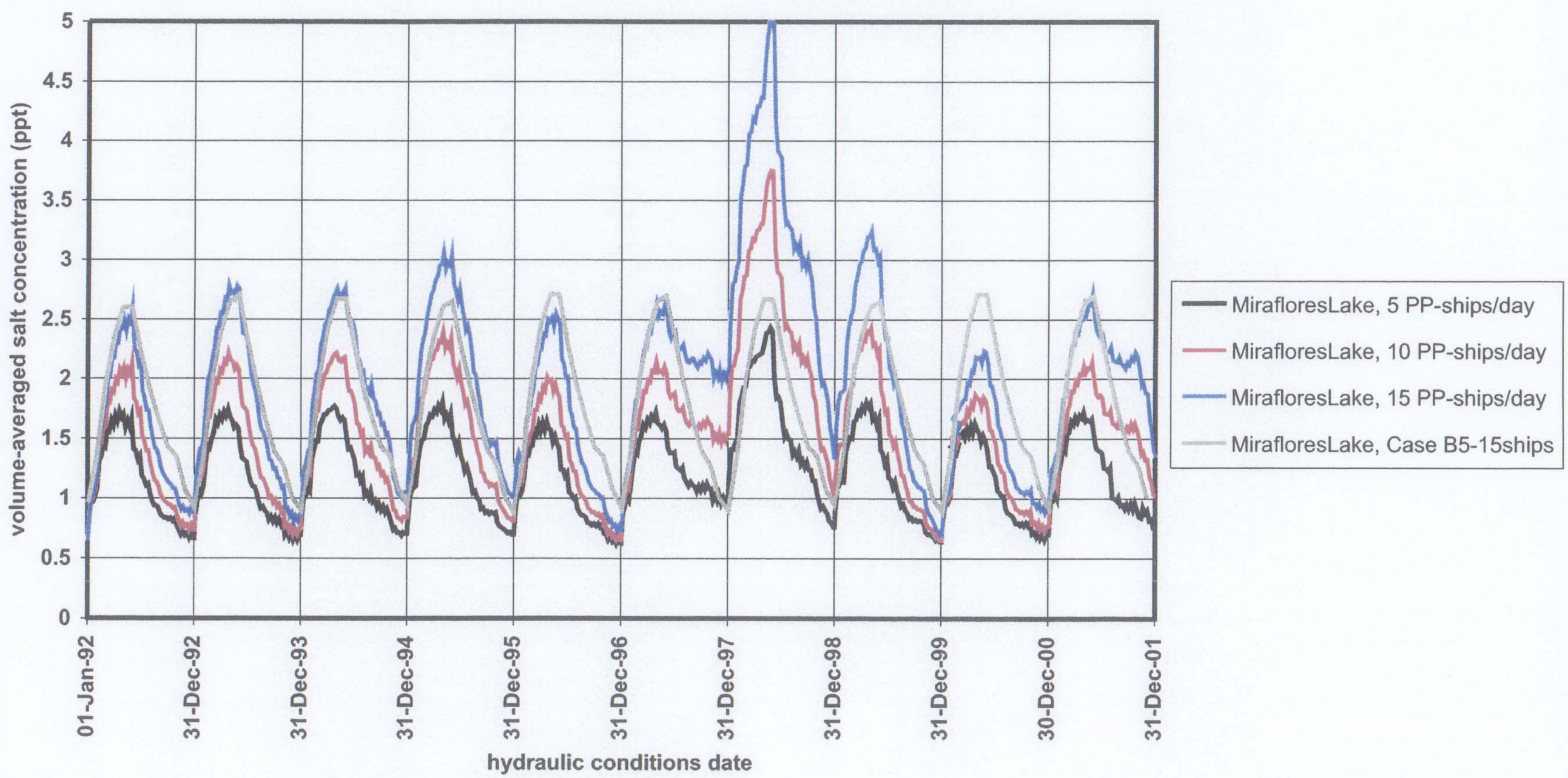
WL | DELFT HYDRAULICS

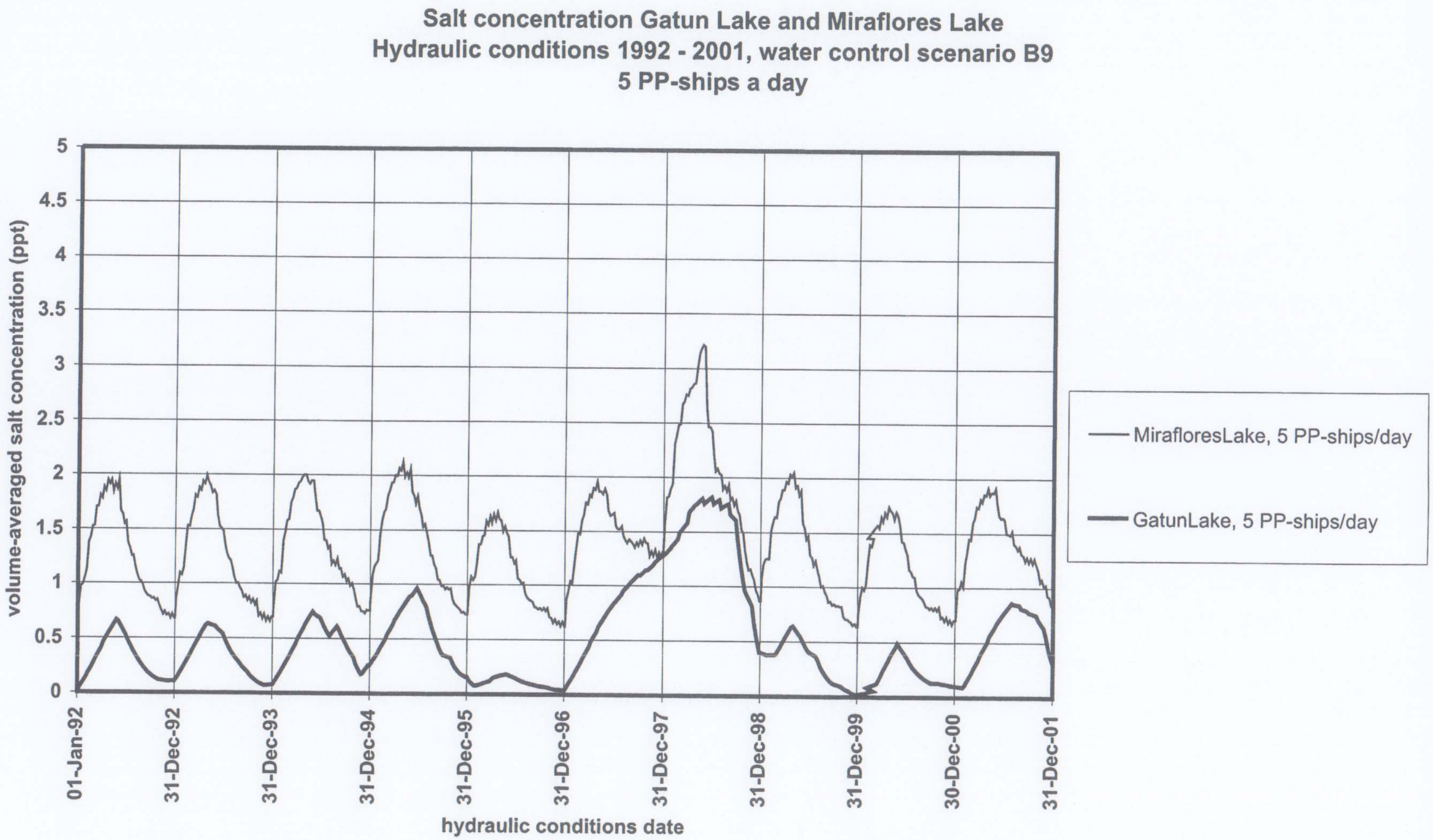
SALT CONCENTRATION MIRAFLORES LAKE
5, 10 AND 15 POST-PANAMAX SHIPS A DAY, SCENARIO 5

Swinlocks | Results
3-lift locks

Q 3476 | Fig. 8.13

Salt concentration Miraflores Lake
Hydraulic conditions 1992 - 2001, water control scenario B5
5, 10 and 15 PP-ships a day





SALT CONCENTRATION GATUN LAKE and MIRAFLORES LAKE
5 POST-PANAMAX SHIPS A DAY, SCENARIO 9

WL | DELFT HYDRAULICS	Q 3476	Fig. 8.14
3-lift locks	Swinlocks	Results

Figures Simulations 3-lift locks

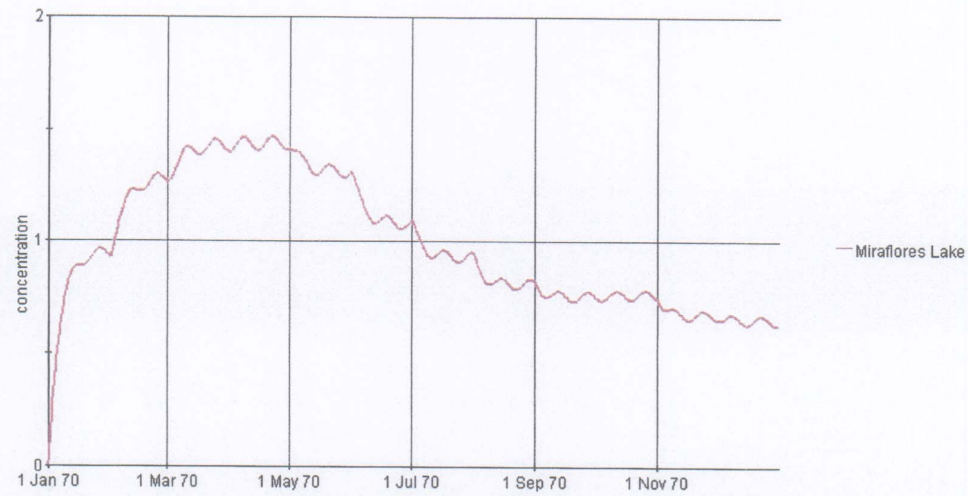


Fig. A-1, 1 **Existing Situation. Case validation. Salt concentration (ppt) of Miraflores Lake after 1 year (output interval: day)**

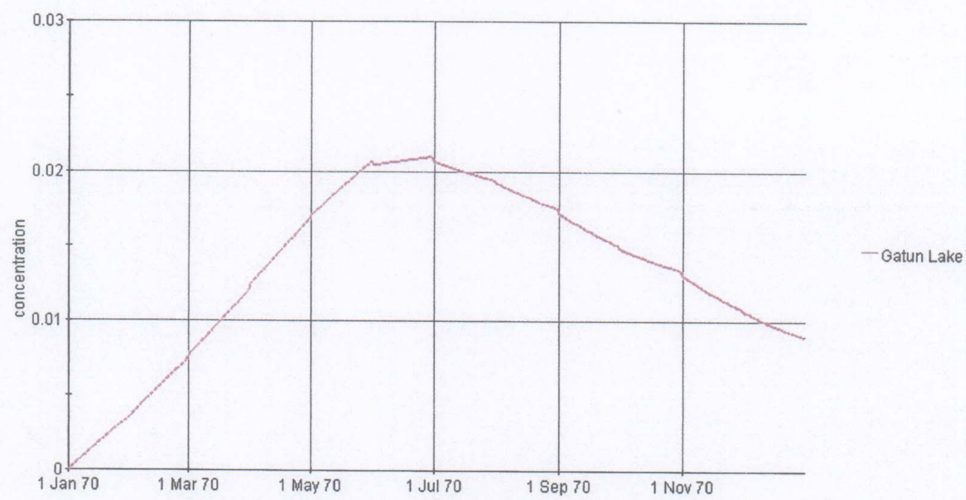


Fig. A-1, 2 **Existing situation. Case validation. Salt concentration (ppt) of Gatun Lake after 1 year (output interval: day)**

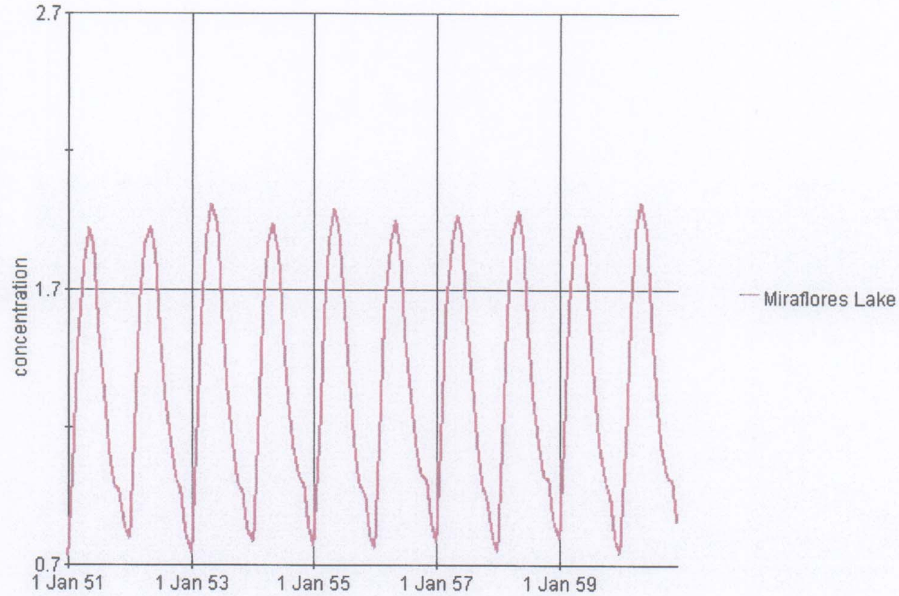


Fig. B1-50, 1 **Case B1-50. Salt concentration (ppt) of Miraflores Lake after 50 years (output interval: month)**

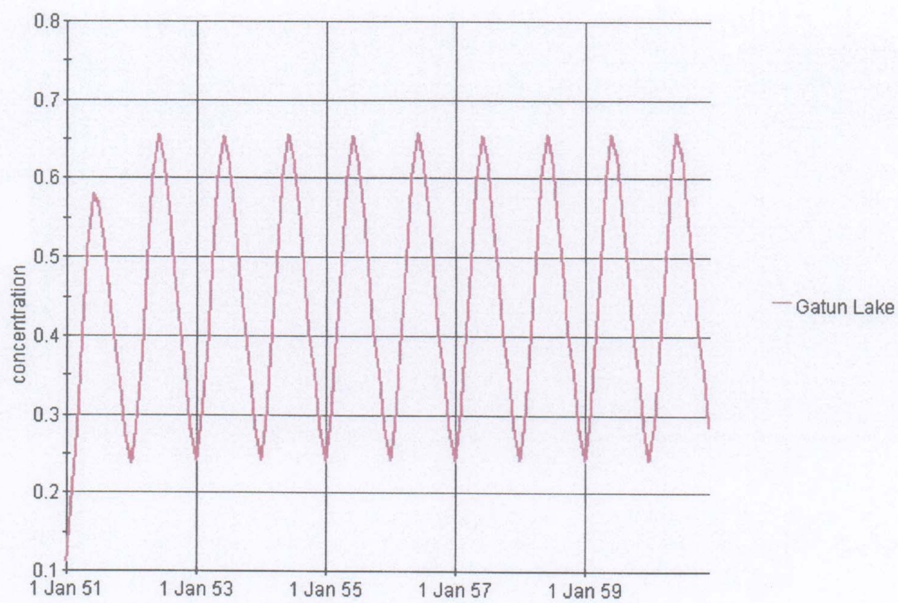


Fig. B1-50, 2 **Case B1-50. Salt concentration (ppt) of Gatun Lake after 50 years (output interval: month)**

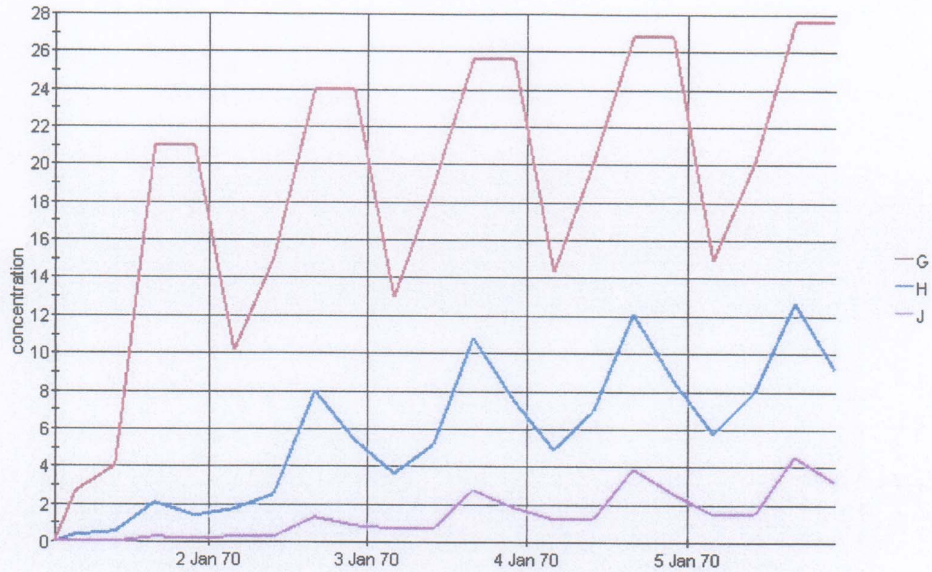


Fig. TC6, 1 **Test case 6. Salt concentration(ppt) of Locks G, H and J (output interval: scenario)**

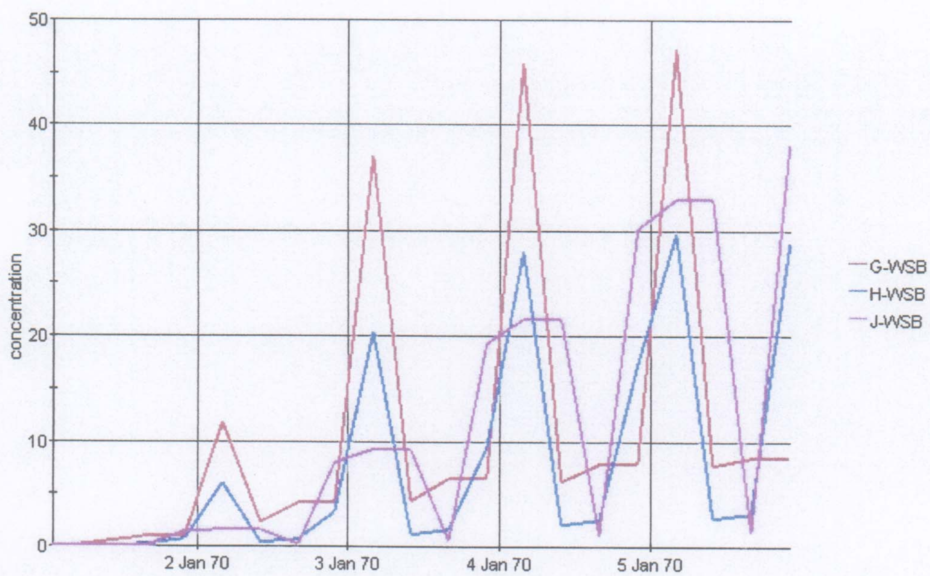


Fig. TC6, 2 **Test case 6. Salt concentration (ppt) of wsb's of Locks G, H and J (output interval: scenario)**

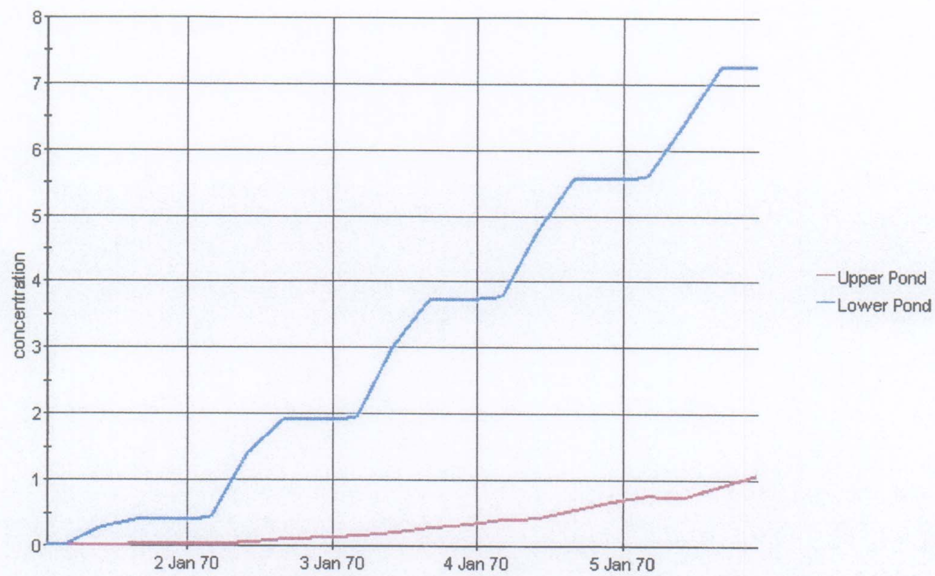


Fig. TC6, 3 **Test case 6. Salt concentration (ppt) of Upper Pond and Lower Pond (output interval: scenario)**

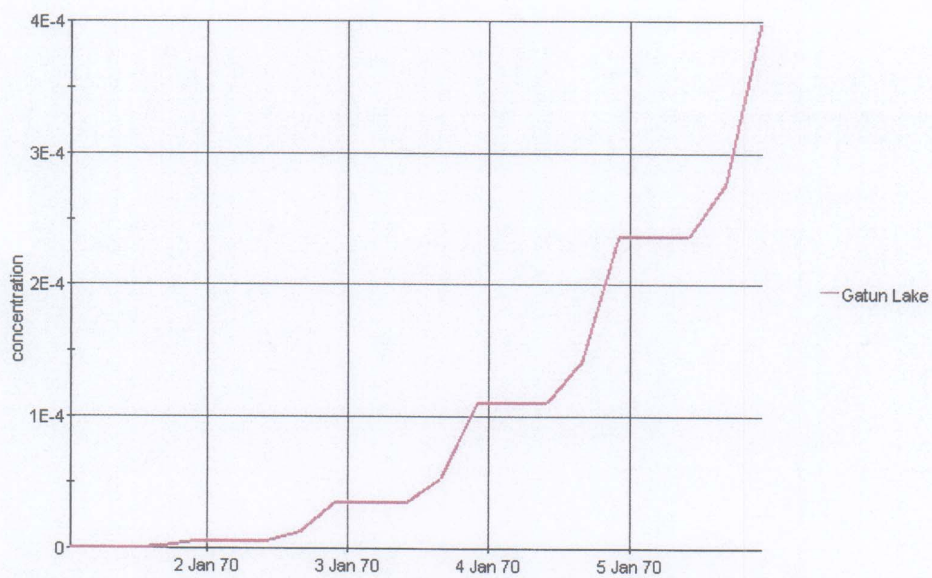


Fig. TC6, 4 **Test case 6. Salt concentration (ppt) of Gatun Lake (output interval: scenario)**

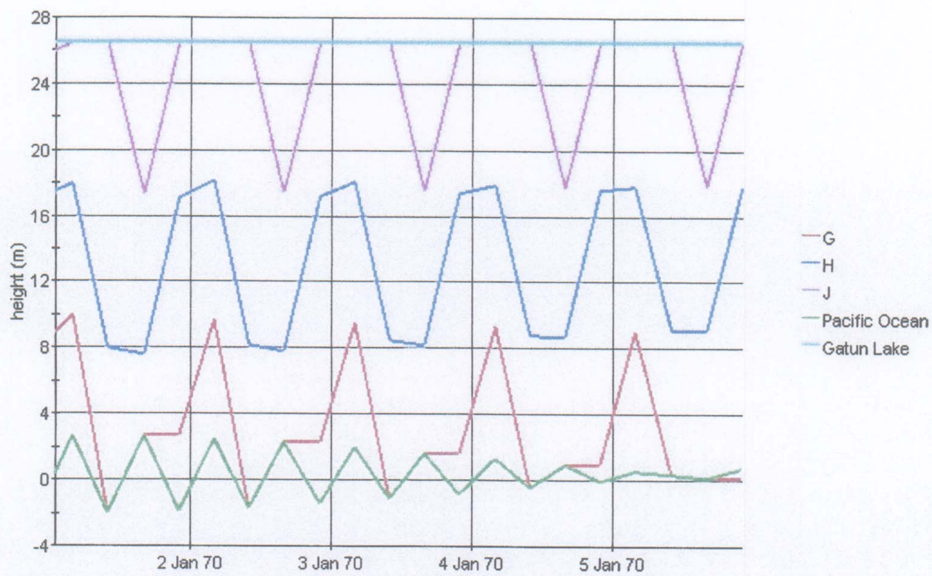


Fig. TC6, 5 **Test case 6. Water level (m to PLD) of Locks G, H and J, Pacific tailbay, and Gatun Lake (output interval: scenario)**

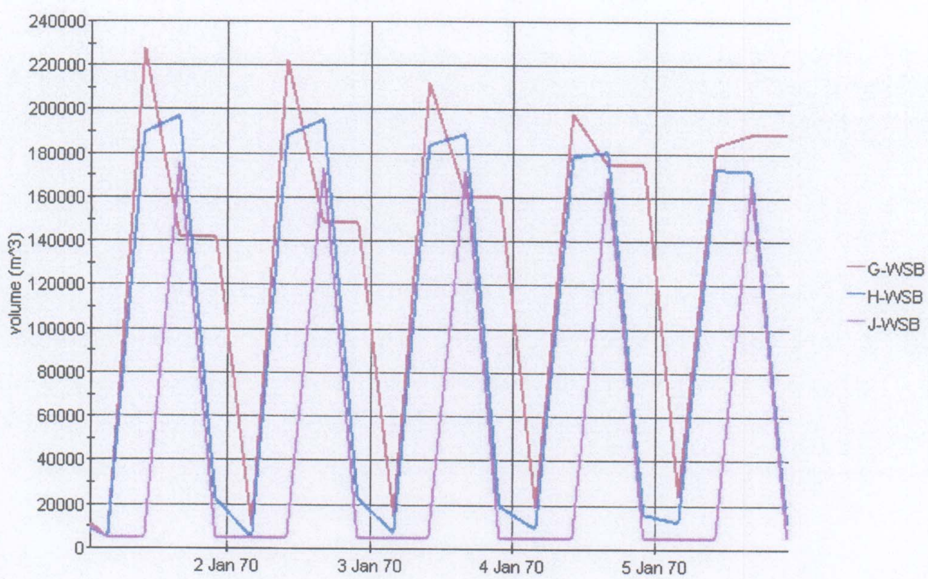


Fig. TC6, 6 **Test case 6. Water volume (m^3) of wsb's of Locks G, H and J (output interval: scenario)**

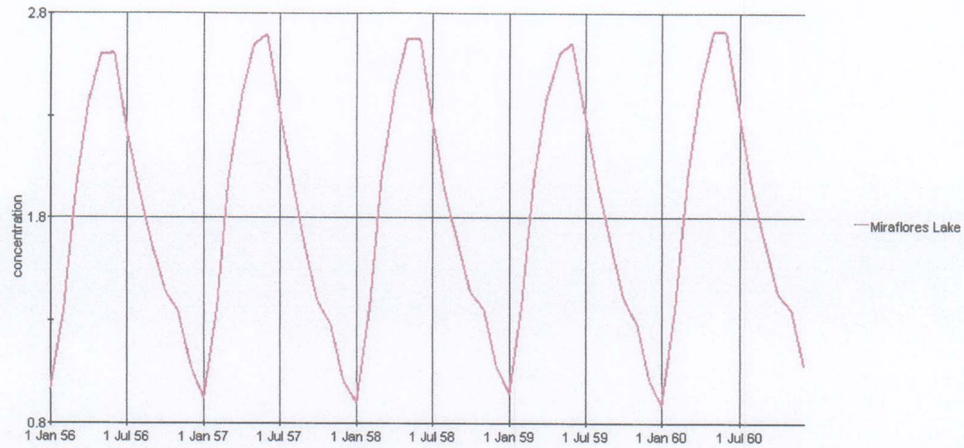


Fig. B5-15s, 1 **Case B5-15ships. Salt concentration (ppt) of Miraflores Lake (output interval: month)**

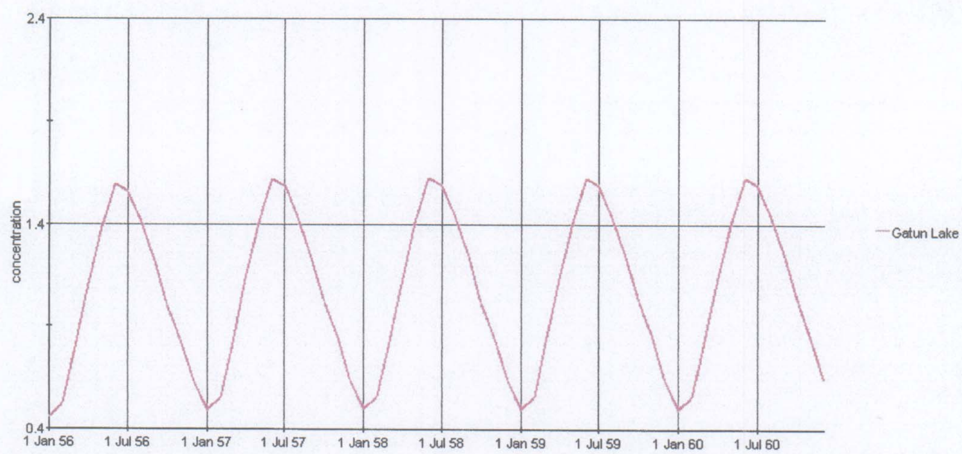


Fig. B5-15s, 2 **Case B5-15ships. Salt concentration (ppt) of Gatun Lake (output interval: month)**

Fig. B6-15s, 1 **Case B6-15ships. Salt concentration (ppt) of Miraflores Lake (output interval: month)**

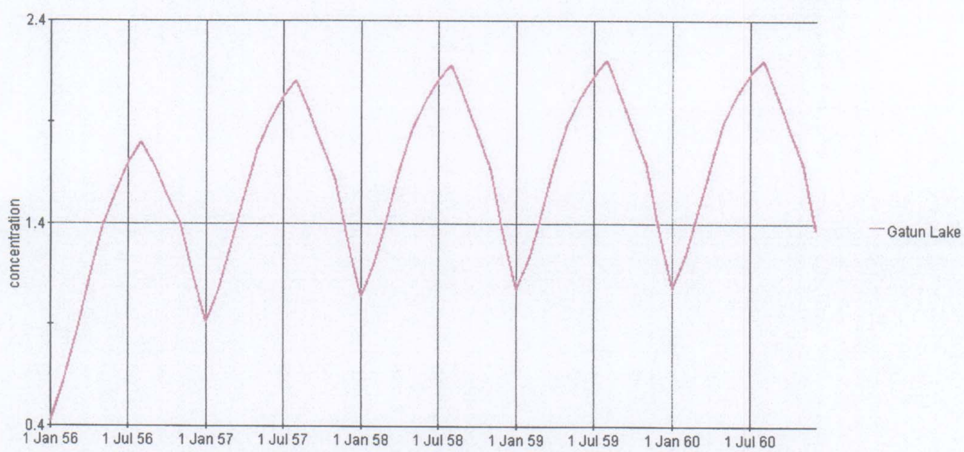


Fig. B6-15s, 2 **Case B6-15ships. Salt concentration (ppt) of Gatun Lake (output interval: month)**

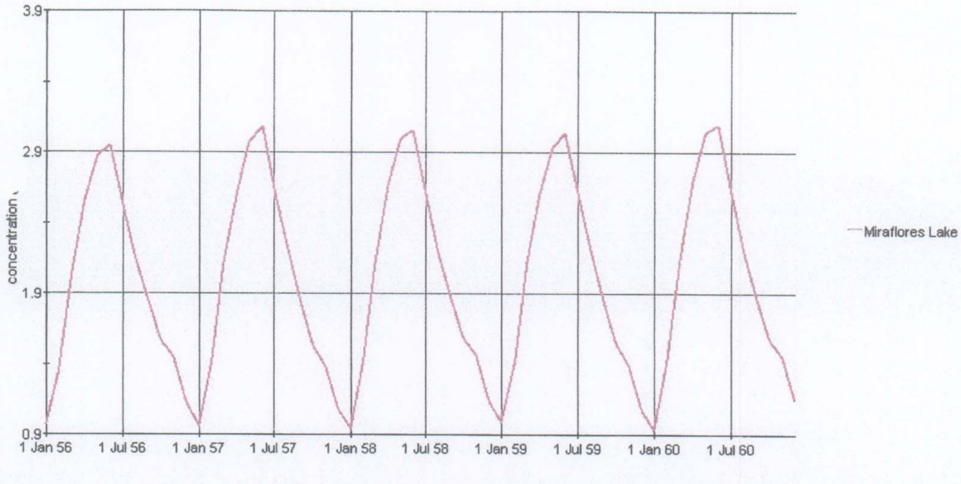


Fig. B7-15s, 1 **Case B7-15ships. Salt concentration (ppt) of Miraflores Lake (output interval: month)**

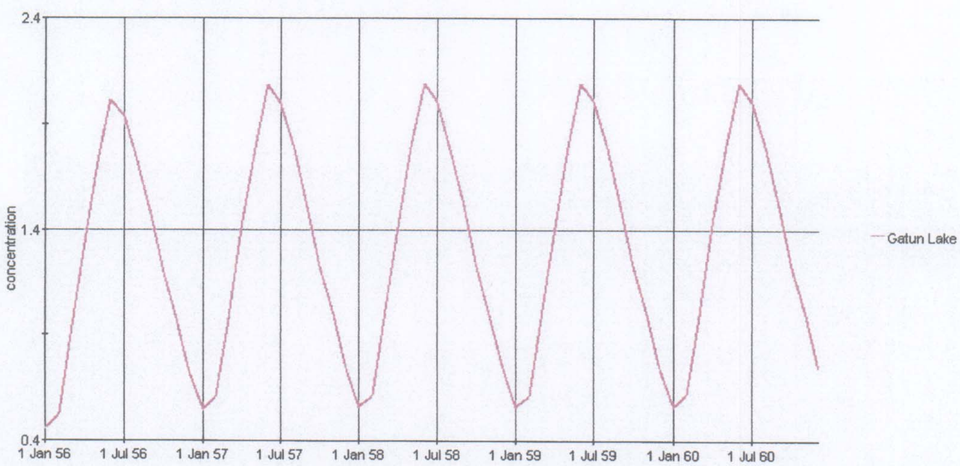


Fig. B7-15s, 2 **Case B7-15ships. Salt concentration (ppt) of Gatun Lake (output interval: month)**

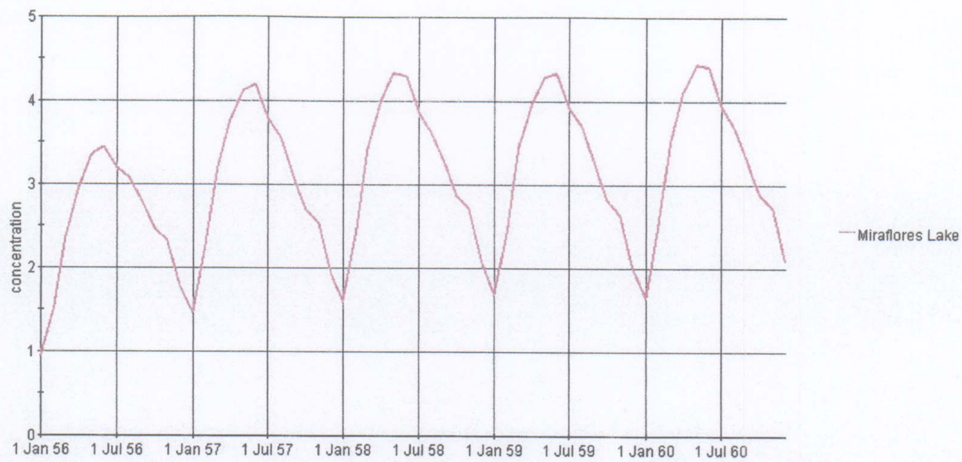


Fig. B8-15s, 1 **Case B8-15ships. Salt concentration (ppt) of Miraflores Lake (output interval: month)**

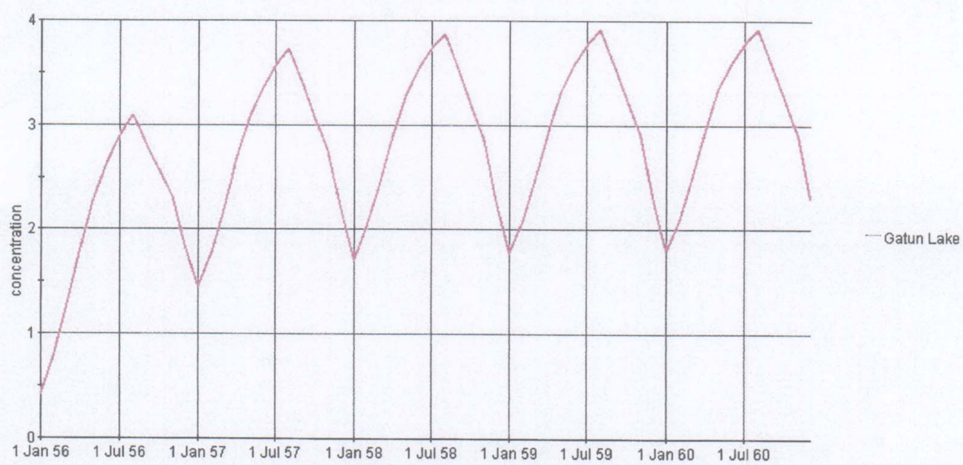


Fig. B8-15s, 2 **Case B8-15ships. Salt concentration (ppt) of Gatun Lake (output interval: month)**

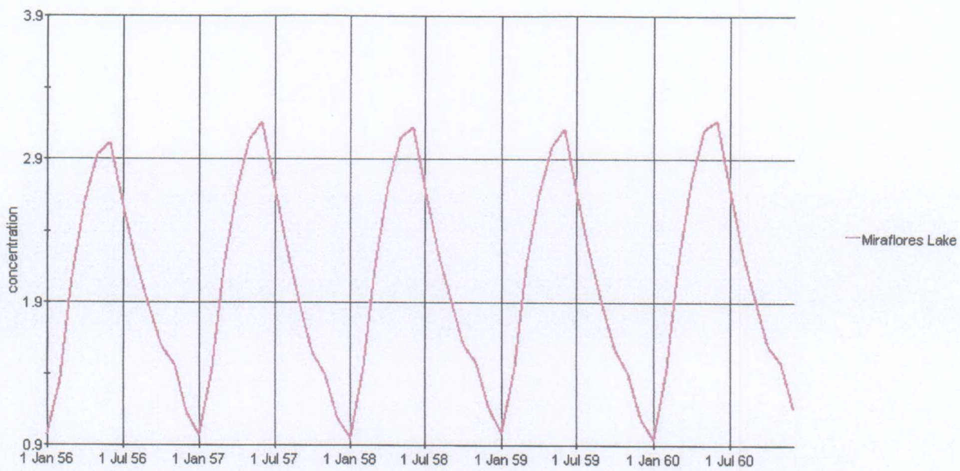


Fig. B9-15s, 1 **Case B9-15ships. Salt concentration (ppt) of Miraflores Lake (output interval: month)**

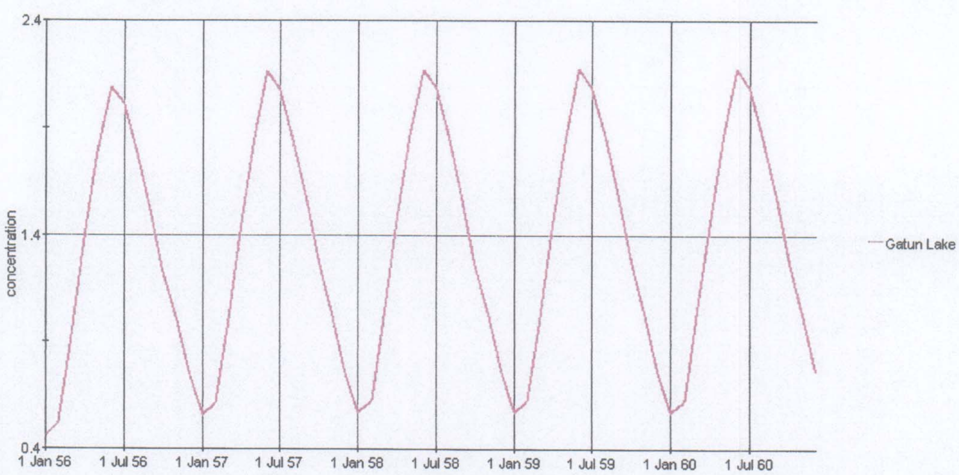


Fig. B9-15s, 2 **Case B9-15ships. Salt concentration (ppt) of Gatun Lake (output interval: month)**

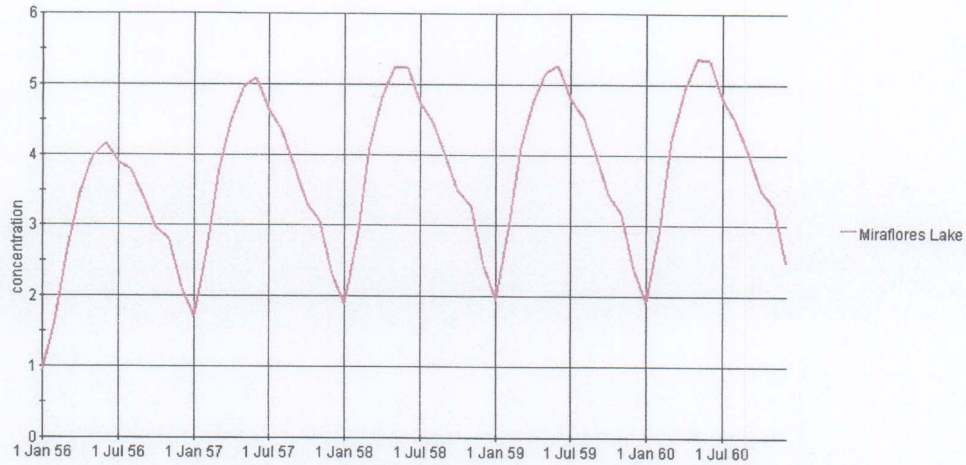


Fig. B10-15s, 1 Case B10-15ships. Salt concentration (ppt) of Miraflores Lake (output interval: month)

Fig. B10-15s, 2 Case B10-15ships. Salt concentration (ppt) of Gatun Lake (output interval: month)

Figures Simulations 2-lift locks

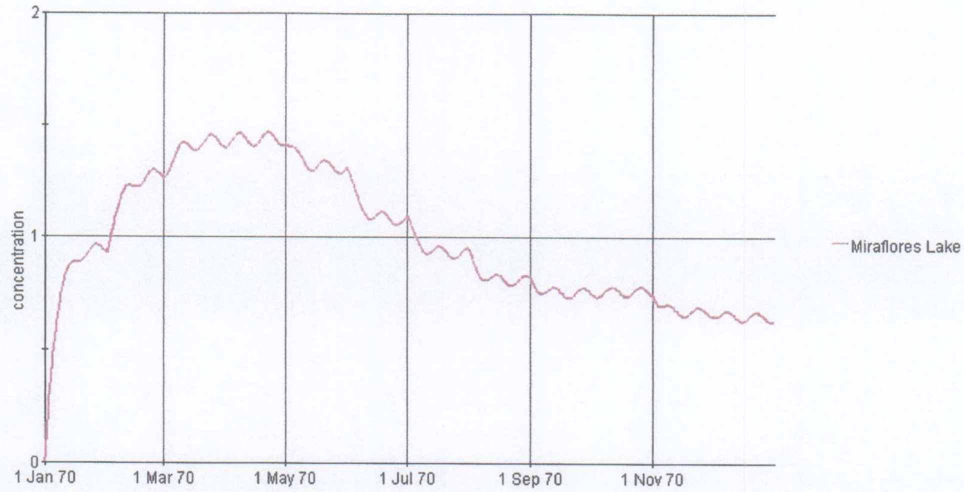


Fig. A-1, 1 Existing Situation. Case validation. Salt concentration (ppt) of Miraflores Lake after 1 year (output interval: day)

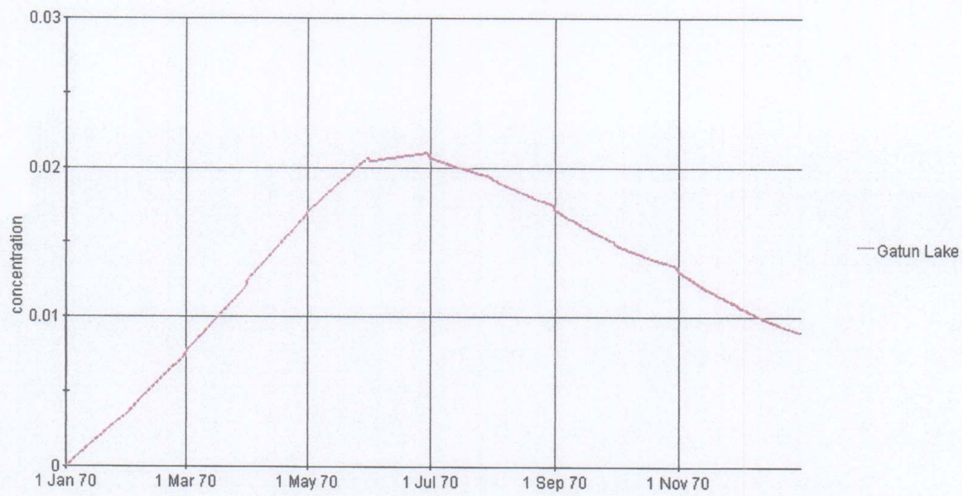


Fig. A-1, 2 Existing situation. Case validation. Salt concentration (ppt) of Gatun Lake after 1 year (output interval: day)

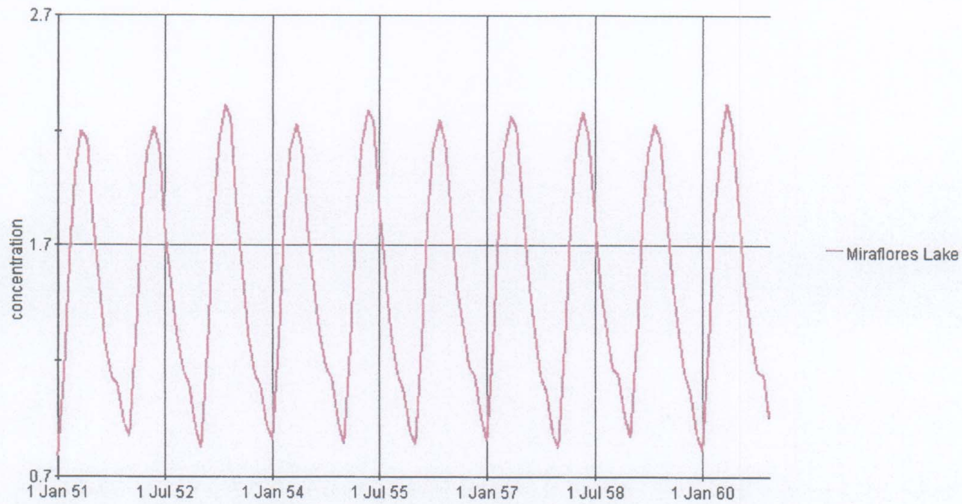


Fig. C1-50, 1 Case C1-50. Salt concentration (ppt) of Miraflores Lake after 50 years (output interval: month)

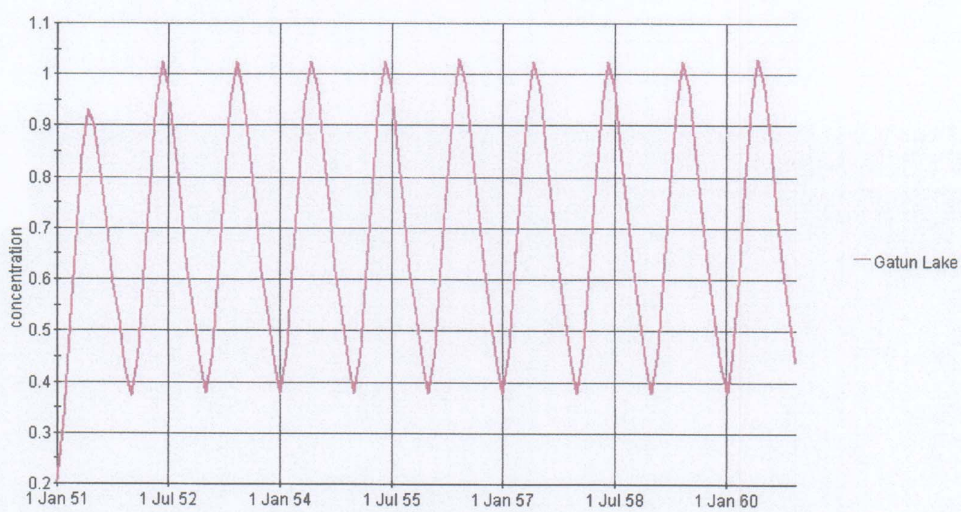


Fig. C1-50, 2 Case C1-50. Salt concentration (ppt) of Gatun Lake after 50 years (output interval: month)

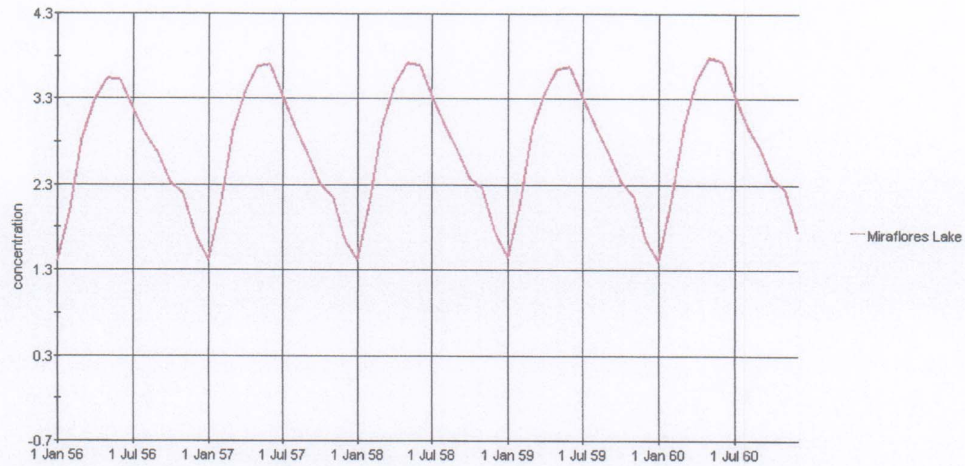


Fig. C5-15s, 1 **Case C5-15ships. Salt concentration (ppt) of Miraflores Lake (output interval: month)**

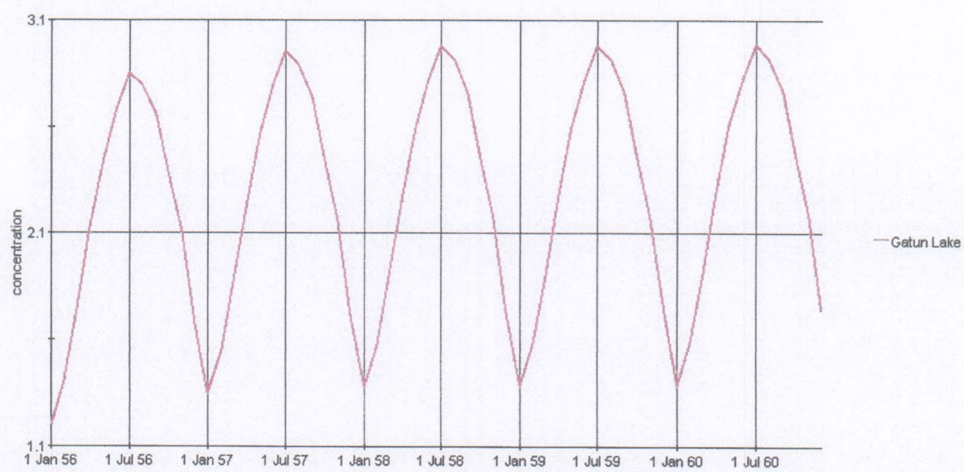


Fig. C5-15s, 2 **Case C5-15ships. Salt concentration (ppt) of Gatun Lake (output interval: month)**

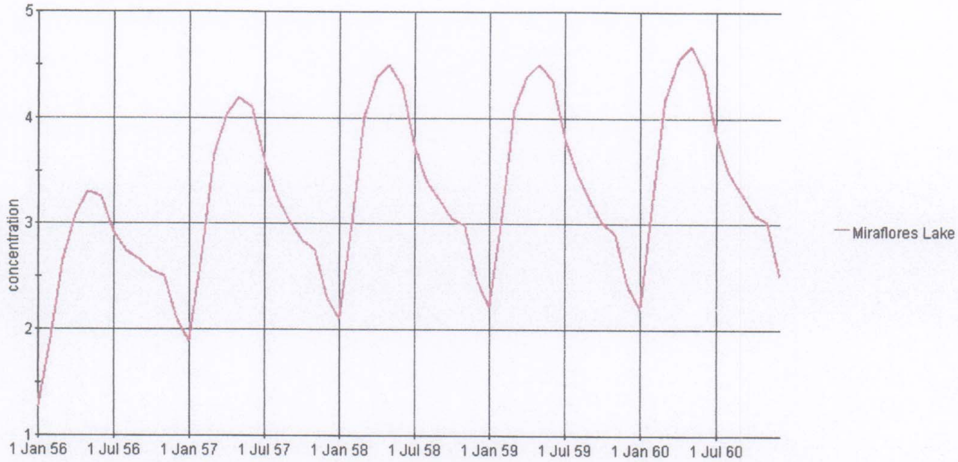


Fig. C6-15s, 1 **Case C6-15ships. Salt concentration (ppt) of Miraflores Lake (output interval: month)**

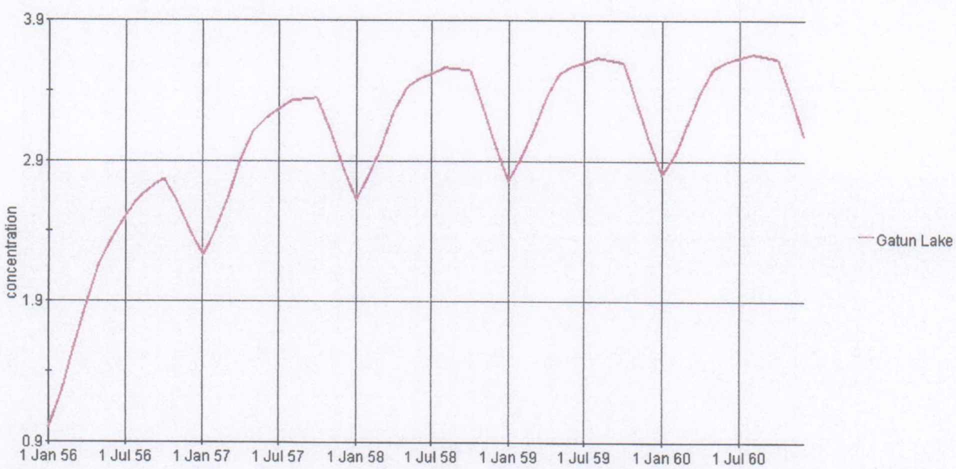


Fig. C6-15s, 2 **Case C6-15ships. Salt concentration (ppt) of Gatun Lake (output interval: month)**

Figures Simulations
I -lift locks

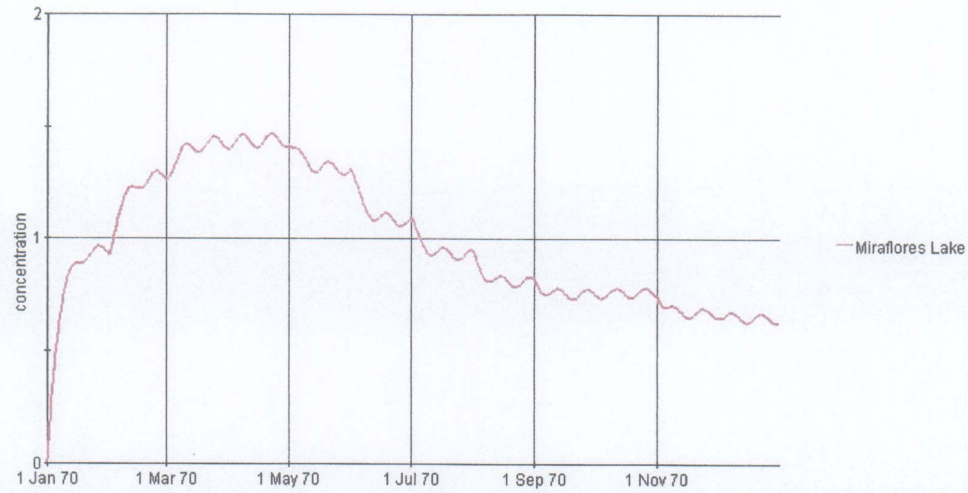


Fig. A-1, 1 **Existing Situation. Case validation. Salt concentration (ppt) of Miraflores Lake after 1 year (output interval: day)**

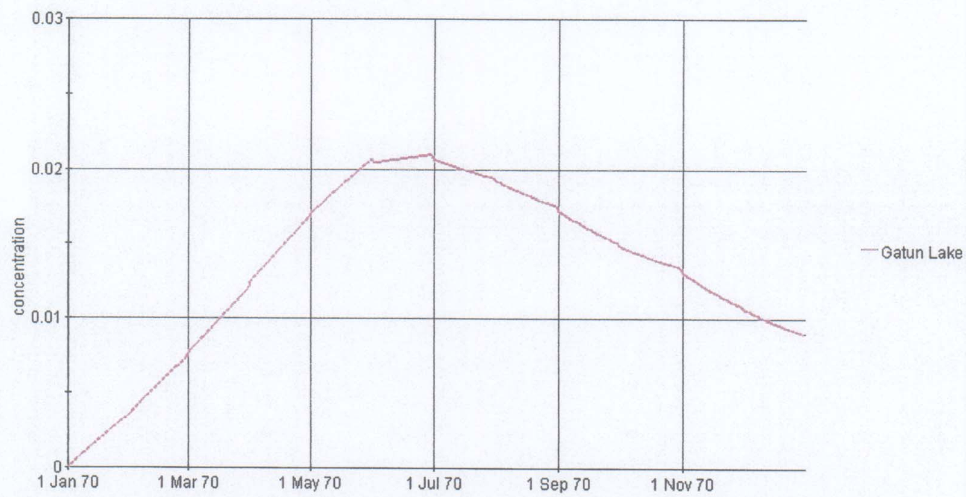


Fig. A-1, 2 **Existing situation. Case validation. Salt concentration (ppt) of Gatun Lake after 1 year (output interval: day)**

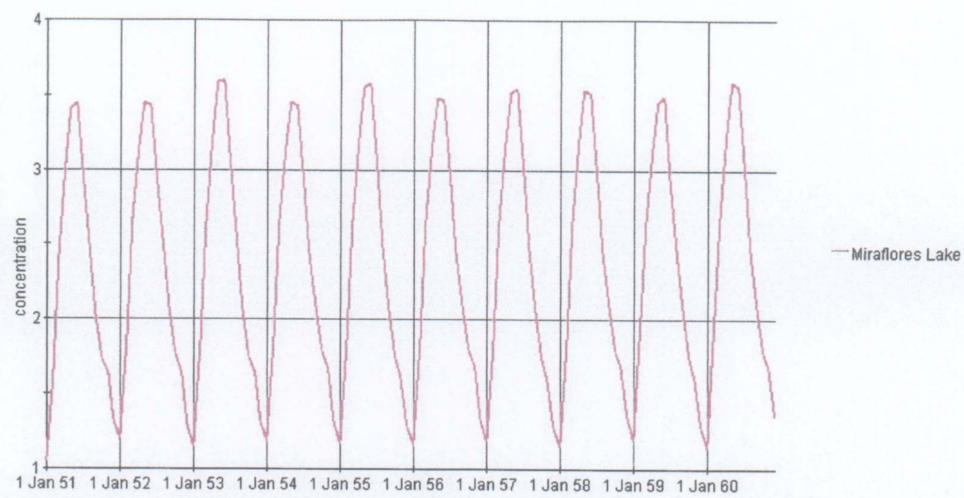


Fig. D1-50, 1 **Case D1-50. Salt concentration (ppt) of Miraflores Lake after 50 years (output interval: month)**

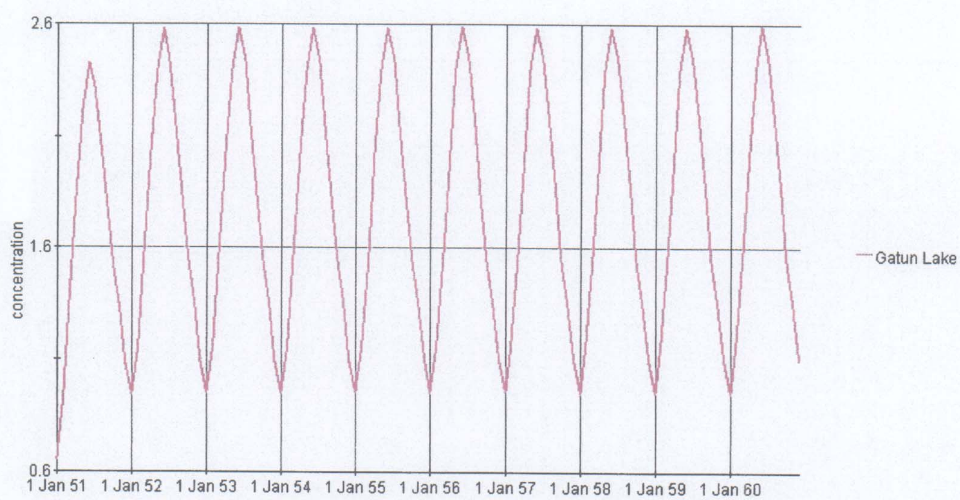


Fig. D1-50, 2 **Case D1-50. Salt concentration (ppt) of Gatun Lake after 50 years (output interval: month)**

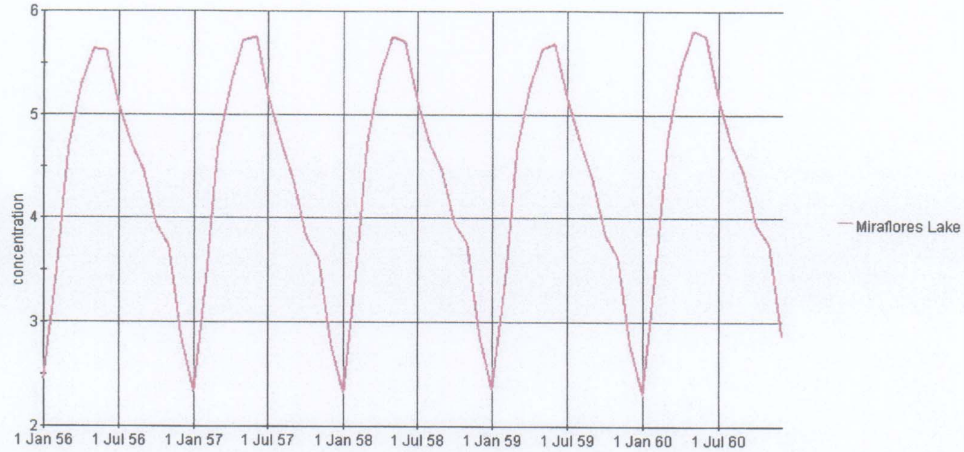


Fig. D5-15s, 1 **Case D5-15ships. Salt concentration (ppt) of Miraflores Lake (output interval: month)**

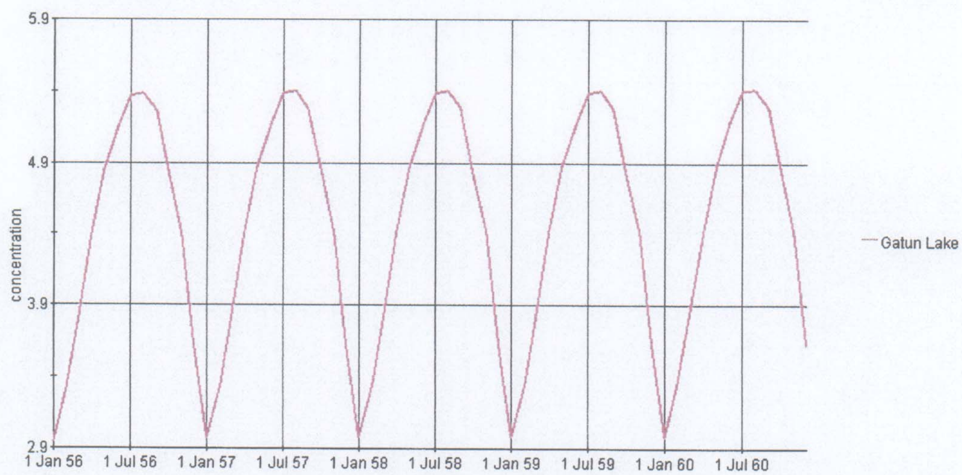


Fig. D5-15s, 2 **Case D5-15ships. Salt concentration (ppt) of Gatun Lake (output interval: month)**

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

Report E, part II

Alternative methods to mitigate salt water intrusion through Post-Panamax Locks

Contents Part II

I Introduction

Autoridad del Canal de Panamá (ACP) has awarded WL | Delft Hydraulics the contract for 'Salt Water Intrusion Analysis of the Panama Canal Locks, Water Recycling System for Post-Panamax Locks' (contract No SAA-110830, dated 3 June 2003, with extension of February 2004).

The objective of this Consultancy is to provide services to the ACP on the subject of salt water intrusion through the shipping locks of the Panama Canal. The services are focused on the future situation with Post-Panamax Locks in a third shipping lane and comprise:

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

The results of the study on water recycling are presented in Part I of this Report E; the present Part II concerns the study on mitigation measures.

The following items are addressed in Part II of Report E:

- process of salt water intrusion through the shipping locks
- measures that can be taken to mitigate the salt-water intrusion
- appropriate measures for the Panama Canal Locks and expected efficiency
- conclusions and recommendations

The studies on water recycling and mitigation measures have been executed in the period September 2003 – February 2004.

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

2 Process of salt water intrusion

The process of salt water intrusion through the locks of the Panama Canal is discussed in this chapter. The analysis provides insight into the most critical moments for salt water intrusion during uplockage and downlockage operations and helps to evaluate the effectiveness of measures which are aimed to mitigate the intrusion of salt water.

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). From these site measurements and from our knowledge obtained from previous studies and experiments we could form a good picture of the physical process of salt water intrusion through the existing locks. The physical process has been described in Report A, June 2003. As an introduction to the next chapters we present here an overview of the main characteristics of the salt-water intrusion process. Notice that the general term 'basin' is used for all canal elements containing a certain quantity of water, for example a lock chamber, a lake, a forebay (part of lake), or a tailbay (part of sea entrance or lake). Next two phases of the lockage process are of importance for the salt water intrusion:

- Phase I: Levelling of the water in adjacent basins (lock-lock, tailbay-lock, lock-forebay). In this phase water is transferred in downstream direction. Filling- and emptying of the lock chambers occurs through the manifold system in the floor. Water is drawn from the forebay through inlets in side wall and centre wall, and is discharged into the tailbay through outlets in side wall and centre wall.
- Phase II: Opening of the lock gates, movement of the ship from one basin to another, and closure of the lock gates. Due to density differences density flows develop between the two basins; the moving ship causes a return current and after the ship has entered the adjacent basin a net quantity of water equal to the ship's submerged volume has been exchanged. This water volume is transferred in downstream direction in the case of uplockage and in upstream direction in the case of downlockage.

The transfer of water in the various phases of the lockage process is the reason that salt water can move from lower basins to higher basins and reverse.
A brief description of relevant phenomena of the lockage process, experienced during our site surveys and derived from an analysis of measurement data, is presented in next paragraphs.

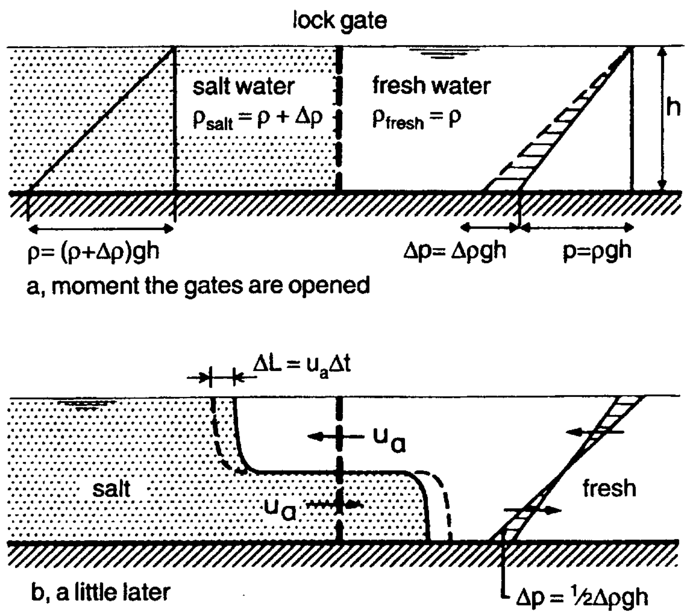
Salt water intrusion process in existing locks of the Panama Canal

The hydraulic processes which govern the intrusion of salt water during uplockage and downlockage of ships are: density flows between basins, return currents caused by the moving ship, propellor action of the ship, and hydraulic phenomena during filling and emptying of the lock chambers.

Density flows develop between adjacent basins with different densities as soon as the lock gates are opened. A salt water tongue intrudes the higher basin along the floor while simultaneously less saline water is flowing out in the upper water region. The front of this less-saline tongue is visible at the water surface; the propagation velocity u_a of the front is dependent on the initial density difference $\Delta\rho = \rho_{salt} - \rho$ and the water depth h:

$$u_a = \alpha.\sqrt{\frac{\Delta\rho}{\rho}gh}$$

where α = coefficient ($\alpha \approx 0.5$). This relationship can be derived equating potential energy and kinetic energy of the two-layer system. Typical values of the propagation velocity are in the range 1,0 m/s (tailbays) and 0,1 m/s (forebays).



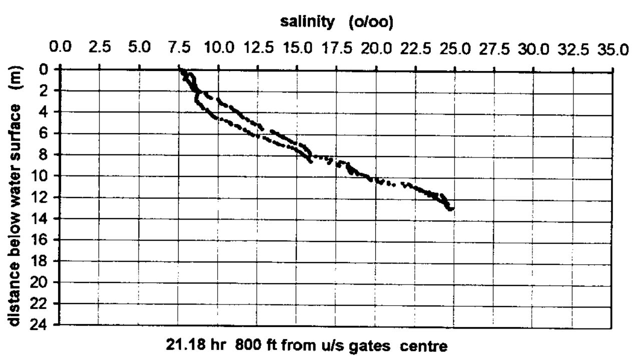
Development of density flows

When there is an upward step at the entrance to the higher basin the salt water that intrudes the higher basin is mainly originating from the water body in the lower basin above the level of the step. The saltier water below the level of the step remains for the greater part in the lower basin, and in this way the step in the floor acts as an effective obstacle for salt water intrusion. However the process of lock filling by means of openings in the floor (which causes a mixing up) and ship movements between the basins (which cause return currents and propellor-generated turbulence) are the reason that the favourable effect of the step is smaller in practice.

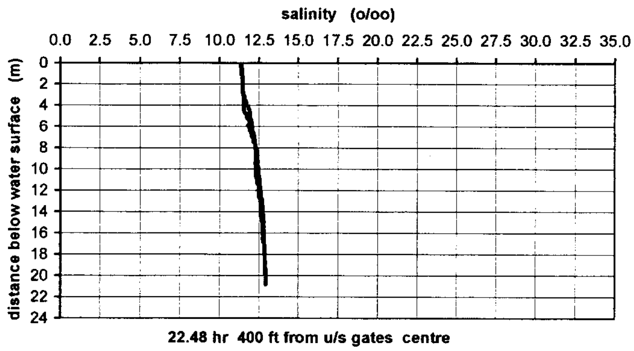
The uplockage process starts in the lower lock, that for the greater part is filled with saline seawater; this holds in particular for the locks at the Pacific side where lock gates are opened far before the ship arrives. When the ship enters, a quantity of water equal to the

submerged volume of the ship is pushed away and flows out to the seaside tailbay. Due to density effects an additional exchange of water between the lock and the seaside tailbay occurs (less saline water in the lock is replaced by more saline water). The running propellor of the ship causes mixing in the water area near the stern of the ship.
This process repeats in each higher lock, but the upward step at the entrance of a higher lock together with the return current along the ship are effective means to limit the salt water intrusion. After the ship has moved and the gates are closed the water in the lock chamber is not immediately at rest. Internal density waves occur which dampen out only very slowly. Before levelling up water with highest density and salinity is near the floor of the lock chamber. When fill water is drawn from the higher adjacent lock, it is drawn from the saltier water region near the floor, and in this way some salt water is sluiced back. The withdrawal of water does not strongly effect the salinity gradient in the remaining upper portion of the water in the higher lock, meaning that no important mixing occurs during levelling down.
Contrary, the upward filling jets of the floor filling system mix up the entire water body around the ship in the lock chamber, causing a more or less uniform salt concentration. This is unfavourable in view of a prevention of salt water intrusion to the adjacent higher basin, since the saltier water does not remain below the level of the step in the floor.

The adverse effect of the filling jets is especially clear during downlockage of a ship. Starting with the upper lock (no ship in the lock chamber), water is filled from the forebay. A relative small part of the earlier intruded salt water is drained back with the fill water. The receiving water in the lock chamber is diluted by the supply of water from the forebay that, generally, has a much lesser salinity. Because the filling jets mix up the entire water body of the lock chamber higher salt concentrations are also present in the region near the water surface. When the ship enters, a water quantity equal to the submerged volume of the ship is pushed out to the forebay. This water has it's origine mainly in the upper region of the water in the lock chamber, and because of the intensive mixing process during filling it contains salt. Density differences cause an additional exchange of water between the lock chamber and the forebay. In this situation the downward step at the entrance to the lock chamber is less effective in blocking the salt water outflow to the forebay.
The described process repeats in each next lower lock. As an example of the mixing effect of the filling jets next pictures show the salt concentration as a function of water depth at one location in the lowest lock (adjacent to the Atlantic tailbay) before and after filling:

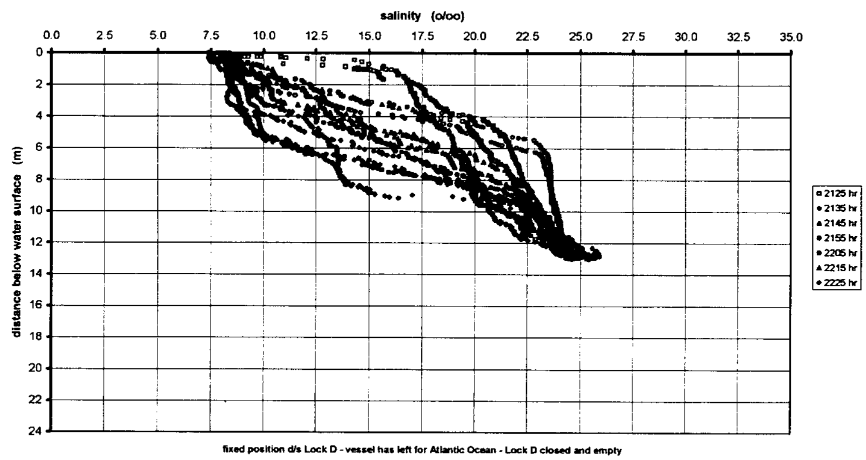


Downlockage: salt concentration lower lock chamber after exit of ship, before filling



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

In the period between the exit of the ship and filling of the lock chamber there was a pause of about 1 hour. Next picture shows the variation of the salt concentration at one location as a function of time. 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.



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

The tide in the sea entrance is in particular of importance for the last phase of the down-lockage process, when the ship enters the lower lock adjacent to the seaside tailbay. At high tide the water level in this lock is high and consequently a smaller quantity of fill water is required to level up. The water in the lower lock is thus less diluted, and water with a higher salt concentration intrudes in the adjacent higher lock. In the phase that the ship moves from the lower lock to the tailbay density currents may be a little weaker because of the smaller density difference, but there is more space under the ship causing a lesser flow resistance and stronger inflow of salt water. This phenomenon is in particular true at the Pacific side, where a large tidal fluctuation occurs. Contrary to high tide, low tide in the sea entrance causes generally a lesser salt water intrusion. In the long run, however, the effects of a large tidal fluctuation will be small.

General conclusions

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

- the lock filling system with openings in the floor causes a mixing up of the water in the lock chamber, resulting in a more or less uniform salt concentration after the lock has levelled up; this is unfavourable in view of a prevention of salt water intrusion
- 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 after the gates have been closed
- the propellor of the ship causes a local mixing in the area near the stern
- emptying of the lock chamber through the openings in the floor does not strongly effect the vertical salinity gradient in the remaining upper portion of the water (no important mixing during levelling down); the water is mainly drawn from the region with more saline water near to the floor
- 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 floor 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

Generally spoken, 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 mimimum 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 floor (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 dissimination 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 off 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, 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, above the fresh-water limit.
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 discharged 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 floor filling system or a wall filling system with openings immediately above the floor. The latter system causes an almost similar mixing effect as a floor fillling system; both variants are comparable with the floor 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 floor - 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 floor filling system of a 3-lift lock system.
The future locks may be provided with water recycling basins; their effect is limited to phase I, when water levels of neighbouring locks are equalized. The water saving basins are connected to the floor / wall filling system and are always operated in the same sequence. The initial water level difference between water saving basin and 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 in 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 levelling process. This is clearly unfavourable, in particular at downlockage, since this mixing is the cause that more salt water migrates to higher locks and forebay.

Generally spoken, downlockage of ships is most critical in view of salt water intrusion. More salt water is transferred in upstream direction when a ship sails down than when a ship sails up. This has two major reasons: (i) in the semi-convoy mode of operation the empty lower lock chamber (downlockage) contains more salt water before the water is levelled up than at uplockage when a ship is in the lower lock chamber, and (ii) when after levelling up the next ship enters the lock chamber (downlockage) more salt water is transferred in upstream direction because of the water displacement of the ship. Measures to limit or mitigate the intrusion of salt water should therefore preferably optimal be designed for downlockage operations.

3 Mitigation measures

Several methods can be applied to mitigate salt water intrusion. An overview of possible and also realized methods, mainly in the Netherlands, Belgium and France, is presented in Appendix A. These methods 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 mixing of salt and fresh water, which is unfavourable in view of a mitigation of salt water intrusion.
In low-situated delta areas the sea level rises at high tide above the canal water level; this complicates the measures aimed to prevent salt water intrusion. Most of the methods described in Appendix A are adapted to the situation with a temporarily higher sea level. Because of the high water level of the Panama Canal relative to the sea level the design of salt water intrusion mitigation measures may be less complicated than for locks in delta areas.

Copies of key publications on the subject of salt water intrusion mitigation measures are presented in Appendices B through D.

In this chapter we will discuss the effectiveness and applicability of possible mitigation measures for the future Post-Panamax Locks.

3.1 Overview of methods

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 are distinguished:

1 Reduce the quantity of salt water that intrudes a lock chamber and subsequently intrudes the canal:
   - 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)
   - Delay and reduce the exchange of salt water and fresh water between tailbay and lock chamber or lock chamber and forebay by means of pneumatic barriers (or air bubble screens)

- Limit the exchange of salt water and fresh water between lock chamber and forebay by means of special provisions, like an adjustable sill on the floor

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

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

Each of these groups of measures will be discussed in next sections in coherence with the extra quantity of fresh water that is needed to effectuate the measures.
Special lock systems such as mechanical lifts are not discussed since they have not been developed so far for large seagoing vessels and are also not considered by ACP as a viable alternative for the conventional locks.

3.2 Reduce the intrusion of salt water

3.2.1 Operational measures

The operator of shipping locks has in general some measures available which are useful in the combat against the intrusion of salt water into the locks. These measures are obvious and most of them will usually form a part of the standard operation procedures. In short they are: collect as much as possible ships in the lock chamber (this reduces the number of lockages), open the lock gates only shortly before the ship sails into or out of the lock chamber and close the gates immediately (this is in particular important for ship movements between the seaside tailbays and the lower locks), limit lockages to the low tide period, open the gates not farther than stricktly necessary for a safe passage of the ship, apply intermediate gates to reduce the size of the active part of the lock chambers (in the case of small ships), and apply an alternate mode of operation (applicable to 1-lift locks only). All these measures are aimed at a reduction of the salt water intrusion caused by density flows. The salt water exchange that is bound up with the submerged volume of the ship, is not reduced. Obviously most of the measures do not promote a fast handling of the ship traffic.

The *first measure*, utilize the locks as much as possible, is already practised by ACP for the existing locks. When Post-Panamax Locks have been realized, application of this measure may mean that only ships, which do not fit in the existing locks, are handled in the new locks. When a number of ships is collected in the lock chamber for a simultaneous locking up or locking down the total opening time of the lock gates is considerably greater than for a single ship. This is unfavourable (see hereafter), but the favourable effect of a reduction of the number of lockages will most probably prevail.

The *second measure*, limit the open times of the lock gates, requires some further explanation. As described in Section 2.1 density flows develop when the lock gates are opened. Now let us consider the density flows between the salt tailbay and the lower lock. For the tailbay we assume a salt concentration of 30 ppt and a temperature of 30 °C, giving a density of 1018 kg/m^3. For the lower lock chamber we assume a uniform salt concentration of 15 ppt and a temperature of 30 °C, giving a density of 1007 kg/m^3. With formula

$$u_a = 0.5\sqrt{\frac{\Delta\rho}{\rho} gh}$$

and ρ = 1007 kg/m^3, Δρ = 11 kg/m^3, h = 20 m, we find u_a = 0.7 m/s. The salt tongue propagates with velocity u_a along the bottom of the lock chamber, reflects against the closed end and is, in theory, back after a period T_a :

$$T_a = \frac{2L}{u_a} \approx 24 \text{ minutes}$$

where L is lock chamber length (about 500 m). The extreme condition with only fresh water in the lock chamber (Δρ = 22 kg/m^3) would give: T_a = 16 minutes. So, when the lock gates are opened about 20 minutes before the ship enters (uplockage), the water of the lock chamber is almost fully replaced with the salt water of the tailbay at the time that the ship starts moving. Also when the ship has sailed out of the lock chamber (downlockage), and salt water has taken the place of the ship, density flows may be the cause that within a period of 20 minutes the remaining fresh water portion of the lock is replaced by salt water of the tailbay.

The period that the ship moves is also important. During this period density currents are temporarily slowed down (uplockage) or enforced (downlockage). This holds mainly for big ships which develop a strong return current. In the case of small ships there is almost no effect on density currents. It means that big ships cause a forced exchange of salt and fresh water in addition to the exchange caused by density differences, while with small ships the exchange caused by density currents is dominant. In general, for the analysis of the exchange caused by density differences, the full period that the gates are open, including the period that the ship moves, should be taken into account.

This leads for the Post-Panamax Locks to the conclusion that if the total opening time of the lock is between 25 and 30 minutes, an almost full exchange of the water of the lowest lock chamber with salt water is inevitable, both at uplockage and downlockage. If the period that the ship moves can be limited to about 10 minutes and the total opening time of the lock gates to about 15 minutes, a meaningful reduction of the salt water intrusion may be achieved.

The *third measure*, limit lockages to the low tide period, is only relevant for the Pacific side of the canal, where a large tidal fluctuation occurs. Because of the smaller water depth at low tide and the greater amount of fresh water used in the lockages, the intrusion of salt water would be reduced. Such a measure would, however, considerably effect the efficiency of ship handling and lead to a reduction of the capacity of the canal. The measure may only be feasible shortly after opening of the new shippping lane, when the number of Post-Panamax ships is still small.

The *fourth measure*, minimize the gate opening, can be applied when the beam of the ship is considerably smaller than the width of the lock chamber. This measure is aimed to reduce the exchange of salt and fresh water caused by density differences; the exchange of water caused by the water displacement of the ship remains. In the case of miter gates the ship must sail along the centre line of the lock, with a single rolling gate the ship must sail along the lock wall. Especially the latter may not be feasible. When a safe ship handling takes much more time when the gates are partly opened than when the gates are fully opened, this measure is not having an important favourable effect, since the salt water intrusion is both a function of time and gate opening. Lock operators do not allow this method in the case of free sailing ships, because the risk of a collision is considered too high. When the ship is guided with the help of locomotives, the risk may be acceptable.

The *fifth measure*, reduce the active part of the lock chamber volume (apply intermediate gates), may be of interest for the Post-Panamax Locks when short but wide ships with great draught are expected in the future. This is however doubtful and smaller ships will most probably have such a width and draught that they can be handled in the existing locks. In rare cases that short, but wide and deep ships have to be handled in the future Post-Panamax Locks they can possibly also be combined with other ships (see first measure).

The *sixth measure*, apply an alternate mode of operation, is only possible for 1-lift locks. This measure may reduce the salt water intrusion in the phase that lock gates are open. A ship sails from the lock chamber to the tailbay (downlockage) and the next ship sails in from the tailbay (uplockage). The quantity of salt water in the lock chamber is, generally, smaller than with a semi-convoy mode of operation. Consequently, after levelling up the salt concentration is also somewhat smaller. Than the ship sails out to the forebay and the next ship sails in from the lake. After the first ship has moved out, the water in the lock chamber has become less homogenious (more fresh water is present in the upper layer) than when no ship had moved out. When the next ship enters the water that is pushed out will therefore be less saline. Also the salt accumulation effect in the lock and forebay, which occurs in the case of a semi-convoy mode of operation is reduced.
This measure is probably not feasible since the handling of the ship traffic in Gaillard Cut does not allow so.

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

The obtained reduction with these two measures alone, is expected to be only a small portion of the required reduction, in particular since the ship-bound salt water intrusion is not effected. The measures may cause some delay of the shipping.

3.2.2 Pneumatic barriers: delay and reduce the exchange of salt water and fresh water

The exchange of salt water and fresh water caused by density flows can be delayed and partly prevented with the application of air bubble screens (pneumatic barriers). For a description of this screens reference is made to Appendix A, Section A3.1.

Air bubble screens are installed at the entrance to the lock chamber. The required air discharge is greater as the density difference $\Delta\rho$ and the water depth h increase. Theoretically the exchange of salt water and fresh water through the air bubble screen can fully be prevented. In practice, however, it is difficult to limit the exchange to 30% of the exchange that would occur when no screen was active. Beyond a certain, optimal point the efficiency reduces, even when the air discharge is increased. This is due to the intensive mixing in the screen when a large amount of air is blown in.
When the ship passes, the screen is temporarily broken and the return current of the ship and the propellor action are the reason that a lot of salt and fresh water is exchanged through the screen. This exchange is inevitable and is of the same extent as when no screen is present. Clearly, the air bubble screen has almost no effect on the ship-bound salt water intrusion. When, as an average, ships dimensions are such that the submerged volume of the ship is large compared to the volume of the lock chamber, the ship-bound salt water intrusion is dominant and the effect of the pneumatic boundary is only small.

The ratio of the ship volume and the volume of the lock (Post-Panamax Locks) is about 275000 m^3 / 600000 m^3 = 0.45 (low water level in the lock chamber, water depth about 20 m; volume of lock chamber without ship is reference water volume V_{ref}).
We now consider the movement of the ship between the tailbay and the lower lock. When we suppose that the gates are open during a period of about 30 minutes, an almost full exchange of the water in the lock chamber with the salt water from the tailbay may be expected, both at uplockage and downlockage (we assume 90% salt water in the lower lock; at uplockage this corresponds to 0.9 x (1 - 0.45) = 50% of V_{ref}, at downlockage this corresponds to 90% of V_{ref}, giving an average salt water quantity in the lower lock chamber of 70% of V_{ref}).
In the case of an optimal pneumatic barrier at the seaside with efficiency of 0.7, the salt water content of the lower lock chamber can roughly be estimated as:

At uplockage:
Salt water content = (1 - 0.7) x (1 - 0.45) = 17% of V_{ref}.
At downlockage:
Salt water content = 45% of V_{ref} caused by the exchange of the ship volume plus (1 - 0.7) times the remaining 55% caused by density flows, giving a total salt content of 61% of V_{ref}.

The average salt water content of the lower lock chamber is thus about 39% of V_{ref}, which, when compared to the situation without a pneumatic barrier with an average salt water content of 70% of V_{ref}, means a reduction of 44%. Since the quantity of salt water in the lower lock chamber is the decisive factor for salt water intrusion, one may assume that the intrusion of salt water into the lake is as well reduced with about 44%. When a second pneumatic barrier is applied at the upstream side of the locks, the reduction factor may even rise to about 50% (the salt water exchange between upper lock and forebay is dominated by the ship-bound water transport and consequently the effect of the second pneumatic barrier is smaller). The total efficiency can be improved when lock gates are only open during a period of say 15 minutes.

We expect, however, that the above estimated 50% reduction of the salt water intrusion as a result of pneumatic barriers at both sides of the locks, is an optimistic estimate. Probably, an upper limit estimate of 30% is more realistic. This value corresponds to measurements in the Noordzeekanaal (Netherlands), which were executed before and after the installation of pneumatic barriers at the sea locks IJmuiden.
Pneumatic barriers have not yet been applied in water with a depth of 18 – 24 m as near the Post-Panamax Locks (the maximum water depth at locations where a pneumatic barrrier has been installed in the Netherlands is about 15 m). Before the pneumatic barriers are applied in deeper water they need a further examination.

For an optimal efficiency the theoretical air discharge q_a follows from (see also Figure A3 in Appendix A):

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

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 which 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 (the air pressure is equal to the pressure near the bottom of the lock chamber). With a total width of 61 m the pneumatic barrier requires thus an air discharge of about 250 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 250 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 0.4 m^3 per m^3 of mixture. As a result the density of the mixture drops locally from a value of about 1000 kg/m^3 to a value of 600 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 uncontrollable.

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

yet been applied in water with a depth of 20 m or more, a further study into the efficiency is advisable.
The pneumatic barrier has the advantage that it neither causes an additional fresh water loss, nor a delay of shipping.

3.2.3 Limit the salt water intrusion by means of an adjustable sill

An adjustable sill may be applied at the entrance to the forebay. This sill is aimed to heighten the step in the floor from upper lock chamber to the forebay and to strenghthen the blocking effect of the step. The crest of the sill is set at such a level that there is still sufficient keel clearance for ships with maximum draught. Obviously, the sill can not be applied when the water level of Gatun Lake is at a minimum, but at higher water levels the adjustable sill may reduce the inflow of salt water.

The sill may be constructed as a vertical lifting gate, rising from a slot in the floor, or as a flap gate that rotates about hinges onto the floor. Since a visual check of the position of the gate is not possible the system must such be designed that it is fully secure, can fully be controled, and causes no damage when it is hit by a ship. A measure to limit the possible damage in the case of a collision may for example be the mounting of blocks of foam along the top of the lifting gate. Possibly, also an inflatable rubber dam instead of a lifting gate is an option, but this dam has only position when inflated.

The floor of the forebay is designed at such a level that ships with maximum draught can safely pass the locks at the lowest navigable water level of the lake. The difference between the minimum navigable water level and the maximum navigable water level of the lake forms the operational range for the adjustable sill. The minimum water depth above the sill amounts to 18.3 m for the Post-Panamax Locks, which corresponds to a sill level of PLD +5.6 m at the minimum navigable water level of PLD +23.9 m. The maximum water level of Gatun Lake is PLD +26.7 m, which means that the range for the adjustable sill is between 0.0 m and 2.8 m. In normal years the water level fluctuates between PLD +25.5 m and PLD + 26.7 m, giving a range for the adjustable sill between 1.6 m and 2.8 m. Since mainly the water of the upper lock chamber above the level of the sill is exchanged, the maximum reduction of the salt water intrusion in a normal year caused by density flows can roughly be estimated as 8% - 13%. The ship-bound salt water intrusion is not reduced, so that the total reduction of salt water is about 5%.
The effect may be strengthened (a few percent) when adjustable sills are also applied at the entrance to upper lock and middle lock (but not at the entrance from tailbay to lower lock where an adjustable sill is almost useless, since gates are open during a long period of time). However, since the low water level in the lock chambers varies with the tide (in particular at the Pacific side) there is a somewhat greater risk of a collision.

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

3.3 Remove the salt water that has passed the locks

In this section we discuss the methods that can be applied to remove the salt water once it has passed the Post-Panamax Locks.

3.3.1 Flush the area near the locks

When sufficient fresh water is available flushing may be an option to remove a part of the intruded salt water. The method is aimed to remove in particular the salt water that is concentrated in a layer near the bottom. The part of the salt water that is diffused is automatically discharged with the flushing water, but this is most probably only a small fraction. Flushing can best be applied in channels with a more or less uniform cross section and flat bottom as in Gaillard Cut; in wide areas with a 'hilly' bottom as near Gatun Locks this method is hardly effective when the removal of a concentrated salt water layer is intended.

It is known from experiments that a relatively high flow velocity is required to break up the salt underlayer and subsequently convey the salt water to the draining station. For that reason an intermittent flushing at high discharge is more effective than a continous flushing at little discharge.
When flushing is applied as a method to remove the salt water from Gaillard Cut at the Pacific side of the canal the required water quantity may be 5 – 10 times greater than the quantity of salty water that enters the canal as a result of lock operations. The flushing water can be discharged through the culverts of the lock filling system, but may than cause hindrance for shipping in forebay and tailbay. To prevent hindrance a separate flushing channel that bypasses the locks may be advisable. At the Atlantic side flushing of the area near Gatun Locks is hardly effective without special provisions.

The effectiveness of flushing is expected to be relatively small at the Panama Canal, since the required fresh water quantity can most probably not made available each day of the year. In particular the dry season is a difficult period. This may mean that salt water can freely intrude Gatun Lake during a considerable part of the year. When salt water has reached the deeper areas of Gatun Lake, it can not longer directly be removed by the flushing method. Such deeper areas are amongst others located near Gatun Dam (the intruded salt water may follow the old Chagres River bed).

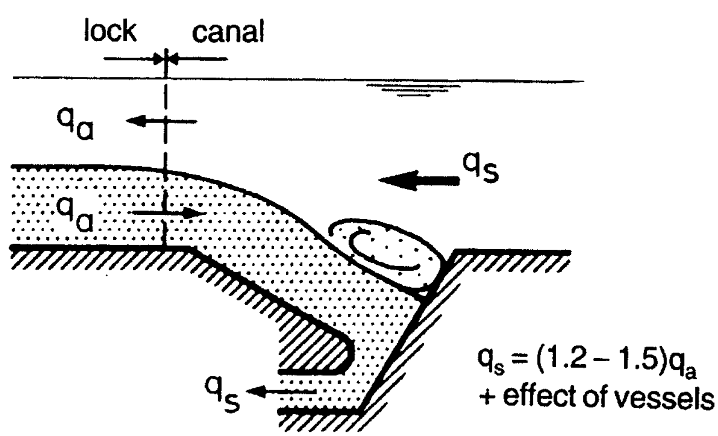
At present an abundant quantity of water is spilled at Gatun Dam and a similar quantity is used for hydropower generation, mainly in the wet season. In this way a part of the salt water is flushed, but since the crest of the overflow spillways and the inlets of the power station are far above the bottom, it is mainly the diluted fraction of the salt water that is spilled away. When no new water sources can be explored in the future, a lesser water quantity will be spilled at Gatun Dam and more water will be lost through the locks. This will change the dominant flow patterns (for example, more water will flow through Gaillard Cut to the Pacific side). The effect of this change on salt water dissemination has to be studied more into detail when the flushing method is considered for a mitigation of the salt water intrusion.

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

3.3.2 Drain the salt tongue through a slit in the floor

A more efficient mitigation method is the direct drainage of the intruding salt water tongue through a slit in the floor at the upstream side of the locks (see also Appendix A, Section A3.4). The salt water tongue develops immediately after the lock gates have been opened. The salt water should preferably be drained away before the salt tongue widens in the forebay.

This direct withdrawal method requires special provisions: a slit in the floor (over the full width of the lock), a connection to the tailbay (by means of a tunnel or culverts) and water control valves.



Direct withdrawal of salt water tongue (Kerstma et al, 1994)

The layout of the slit must such be designed and the valves so far be opened that a minimum of fresh water is drained together with the salt water. Scale model tests show that a fresh water quantity equal to 20% - 50% of the salt water quantity may be drained with the salt water in well controled operational conditions. This finding holds for the situation that no ship is present.
When a ship moves into or out of the lock chamber the return current and the propellor cause higher local flow velocities, turbulences and mixing, which are the reason that the process of salt water drainage is less efficient. For the Post-Panamax Locks this may mean

that a fresh water quantity equal to the quantity of drained salt water is spilled, even when the drainage operation is carefully executed, while simultaneously salt water escapes to the lake.

The total quantity of water to be spilled is dependent on the sailing direction of the ship (uplockage or downlockage) and the time that lock gates are open. Most salt water flows into the forebay at downlockage (forced outflow), and the capacity of the drain has to be designed on this situation. Consequently, the control valves have to be opened wider at downlockage than at uplockage. As an average, when lock gates are only shortly opened (see also Section 3.2.1), the total quantity of water (salt water and fresh water) that is spilled through the slit within a period of about 15 - 20 minutes is roughly estimated as 50% of the water volume of the lock chamber above the level of the step in the floor. This corresponds to 10 m water, about 40% of the total water level difference between Gatun Lake and the tailbay. The estimated water quantity is more or less equal to the normal water loss of 3-lift Post-Panamax Locks (without water saving basins). The spilled water quantity may even be greater when the lock gates and the drain are open during a long period of time.
Initially the salt content of the drain water is relatively high but will than reduce, also under the influence of the passing ship. This makes it difficult to fully control the process, in particular since differences exist between uplockage and downlockage. Hindrance for shipping may occur when the water is directly spilled into the tailbay.

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

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

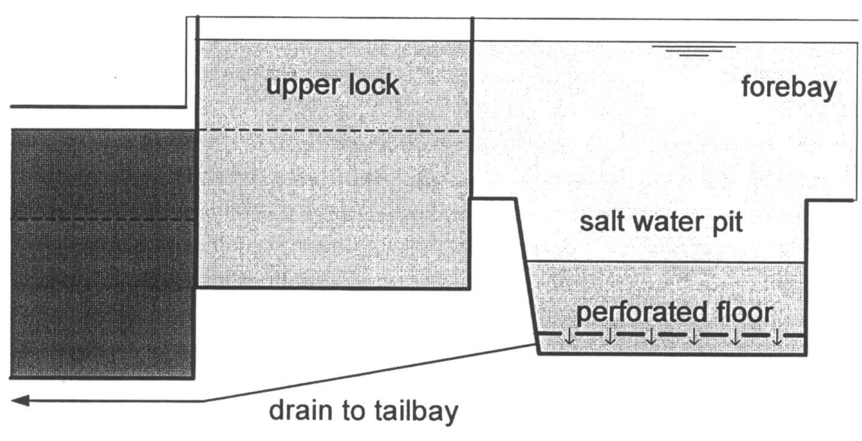
The above discussed drain system has the disadvantage of a relatively great fresh water loss. This is caused by the fact that the salt water must be drained at a relatively high speed during the short period that the lock gates are open and the ship moves into or out of the lock chamber. The process of drainage can also not fully be controled. It would therefore be better to collect the salt water and to discharge the salt water at a lower speed during a longer period of time.

To that purpose a salt water pit can be constructed at the upstream side of the upper locks (see also Appendix A, Section A3.3). The function of the pit is to catch the salt water that intrudes into the forebay when the lock gates are open. After being caught the salt water is slowly discharged from the pit to the tailbay.
This system requires - apart from the construction of a salt water pit - the construction of return conduits to the tailbay and control valves. The pit should at least have a volume that is sufficient to store the salt water that intrudes when a ship moves from forebay to upper

lock chamber (downlockage). This means that with horizontal dimensions of the pit equal to the dimensions of the lock chamber, the depth of the pit should approximately be equal to 50% - 75% of the water depth above the step of the upper lock chamber (about 10 - 15 m). In order to prevent a mixing up of salt water and fresh water when ships sail over the pit, the interface between salt water and fresh water must be kept sufficient far under the bottom level of the forebay. The pit can alternatively also be situated beside the shipping lane, when space is available. A part of the salt water is not caught in the pit but escapes since the salt water is mixed up when the ship sails into or out of the lock chamber.

The lesser fresh water is discharged together with the salt water, the better the results are in terms of efficiency and fresh-water loss. The drain from the salt water pit must therefore only be opened when sufficient salt water has been collected in the pit. To that purpose a monitoring of the salt water content of the pit may be required. On the other hand, when the salt water is kept in the pit during a long period of time, sailing ships (especially manoeuvring ships) may cause a mixing up of salt water and fresh water, which reduces the efficiency. The salt water should therefore be discharged in a period of 1 – 2 hours.
The salt water that has been collected in the pit moves along the floor of the pit towards the outlet. Especially when the salt water layer is thin, friction forces are the reason that the flow velocity of the salt water is smaller than the flow velocity of the fresh water in the pit, and a considerable loss of fresh water may occur.
The loss of fresh water can for the greater part be prevented when the salt water is drained away through a perforated floor, in a similar way as water is drained through the floor of the existing locks. This option requires the construction of a floor in the pit with openings and with transverse culverts underneath. These openings in the floor, which are well distributed, enable an equally outflow of salt water. When the salt water – fresh water interface is kept above the perforated floor, the loss of fresh water is limited.

Since the discharge of the drain is relatively small, less hindrance for shipping may occur in the tailbay.



Withdrawal of salt water from salt water pit with perforated floor

In conclusion
When a salt water pit is constructed at the upstream side of the locks the greater part of the salt water that intrudes the forebay can be caught and subsequently be discharged at low

speed into the tailbay. The pit should be sufficient deep to minimize mixing of salt water and fresh water when ships sail over. The loss of fresh water through the drain can be reduced when a perforated floor is applied in the pit (vertical withdrawal of salt water similar as in the existing locks). In that case the total loss of water (salt water and fresh water) will be much smaller than with a slit in in the floor (direct withdrawal system, see Section 3.3.2). The risk of hindrance for shipping caused by the discharge of water into the tailbay is also smaller; a delay for shipping is therefore not likely.

3.4 Prevent the upward migration of salt water from the lower lock chamber

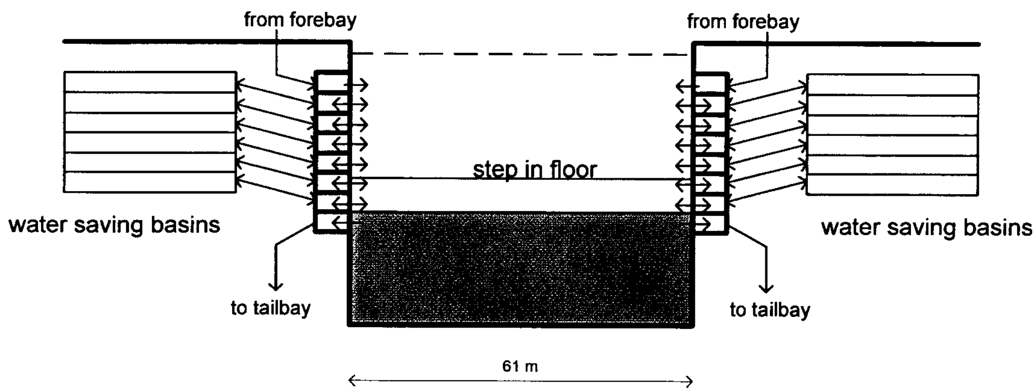
When the escape of salt water from the lower lock chamber to higher levels is prevented, a considerable reduction of the salt water intrusion can be achieved. Hereafter two systems are described which are aimed to reduce the upward migration of salt water from the lower lock chamber.

3.4.1 Prevent the migration of salt water from the lower lock chamber

It is inevitable that a large quantity of salt water intrudes the lower lock chamber in the phase that the lock gates are open and the ship enters from or exits to the tailbay. If it was possible to keep this salt water in the lower lock chamber during the lockage process (no mixing with the fresh water, no escape to higher levels), the salt water intrusion to higher locks and the forebay would be prevented.

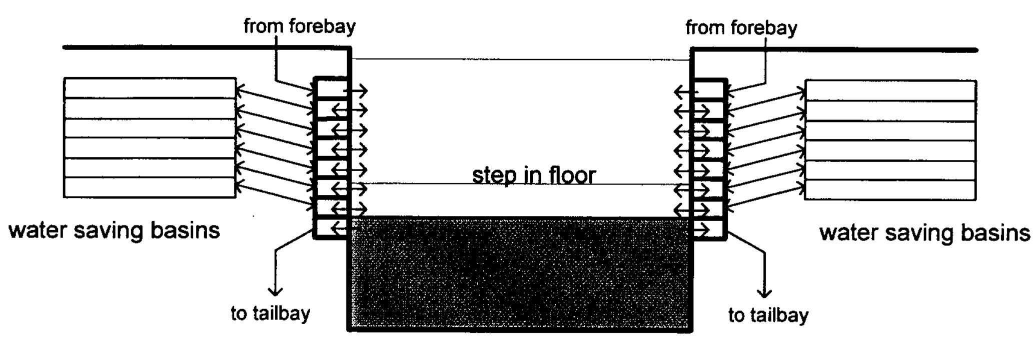
A full separation of salt water and fresh water can in practice not be realized, but it is possible to prevent to a large extent mixing during levelling up or levelling down. As has been discussed in Chapter 2 the fillling system of the locks with openings in the floor or openings in the side walls just above the floor is the reason that salt water and fresh water are almost fully mixed during levelling up. This strong mixing does not occur when fresh water is supplied to the lock chamber as a separate layer on top of the salt water. This can be realised when filling and emptying is done through openings in the lock walls above the level of the salt water. If this process is carefully executed, mixing can be minimized.
In the next phase, when the lock gates of the adjacent higher lock are opened, the salt water in the layer above the floor of the lower lock will partly escape when the step in the floor is at a lower level than the interface between fresh and salt water. This is especially true with the 3-lift locks: when we assume that the salt water layer is as thick as the water height before levelling up, the thickness of the salt water layer varies between 17.2 m and 24.2 m when the tidal extremes PLD +3.60 m and PLD -3.44 m at the Pacific side are considered, which is considerably greater than the step height of about 10 m. Also the step height of the 2-lift locks, about 13.7 m, is not yet sufficient to prevent an escape of salt water. Only the 1-lift locks, with a step height of about 26.2 m, fulfils this condition. In the case of the 1-lift locks the ship is lifted spacious above the salt water – fresh water interface, which limits the intrusion of salt water caused by the ship-bound return currents and propellor action. The 1-lift Post-Panamax Locks with water saving basins (the design without wsb's is not considered) are therefore best suited for this salt-water intrusion mitigation option.

Next figures show a possible design for 1-lift locks. Fill water is supplied through openings (long horizontal slits) in both side walls; the openings are provided at various levels, corresponding to the levels of the water saving basins (wsb's).



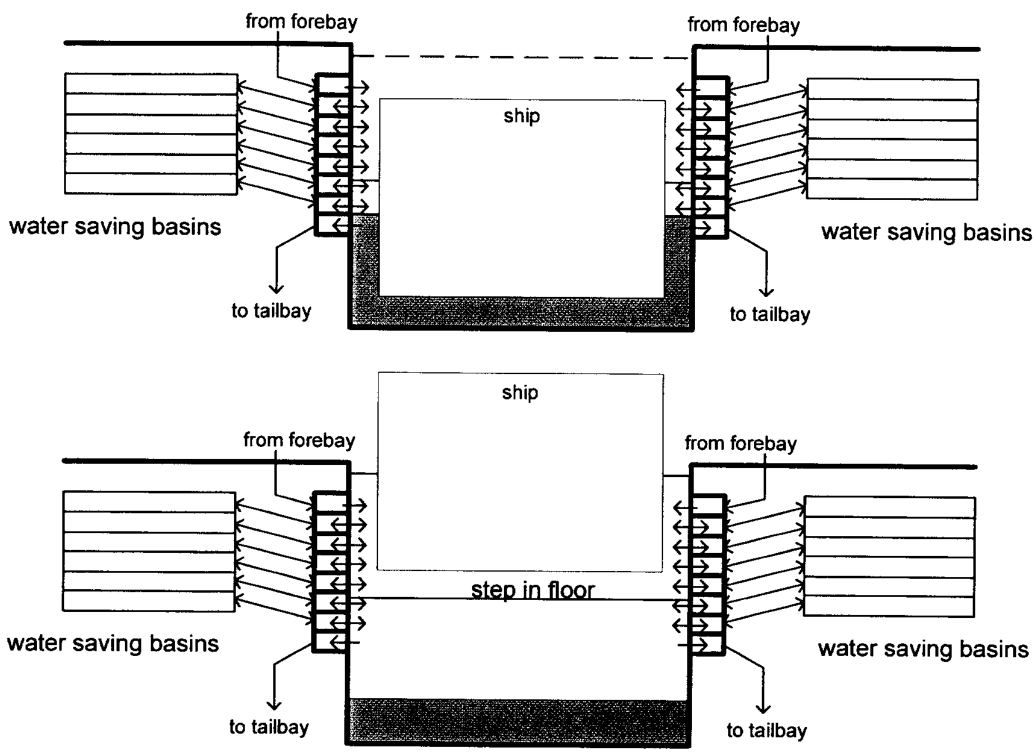
1-lift Post-Panamax Locks with wsb's and wall filling / emptying system; before filling

Each of the wsb's is connected to a separate inflow channel that runs along the full length of the lock chamber. The openings to the lock chamber enable an equally distributed inflow of fresh water. The discharge is controled by a valve in the culvert between wsb and inflow channel. Especially the lowest wsb's have to be emptied slowly and carefully, so that the fill water can flow at low speed from the side walls to the centre of the lock chamber, without mixing too much with the salt water. The upper portion of the lock chamber is filled with water from the forebay.



1-lift Post-Panamax Locks with wsb's and wall filling / emptying system; after filling

When a ship is in the lock chamber (uplockage) the fresh water fills up the space at both sides of the ship and when the ship is sufficiently lifted the fresh water flows also underneath the ship.



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

To prevent transverse forces on the ship the filling discharge at both sides of the ship must be equal and the ship must be positioned in the centre line of the lock chamber.

Emptying is in the reverse sequence (the upper wsb's are first filled, than the second ones etc.). Again, when a ship is in the lock chamber (downlockage) the water at both sides of the ship must withdrawn at the same speed. The last portion of the water can not be stored in the wsb's and is spilled into the tailbay. Since this portion is most mixed up it is also better not to store it. Some salt water accumulation occurs in the wsb's, but at each lockage fresh water from the forebay is supplied to the lock chamber, which limits the accumulation.

In this system the inflow of water from only one side is not permitted, both in view of transverse forces on the ship and the efficiency of the system. The efficiency is strongly dependent on the way the fresh water is supplied to the lock chamber. The lowest inflow openings must be located near the salt water surface. When they are deep under the salt water surface too much mixing occurs and the same holds when they are far above the salt water surface (plunging of water). At the Pacific side, where large tidal fluctuations occur, vertically moveable gates may therefore be required to position the lowest flow openings near the salt water surface.

The openings at higher level discharge into the fresh water layer; generally one may assume that the higher the level of the fill openings the less mixing will occur with the salt water. This may mean that the filling discharge can be higher as the lock chamber gets more filled. It is important that also emptying is done with care since otherwise too much salt water may be taken away and stored in the wsb's. The last water portion of the lock chamber that is not stored in the wsb's, can be discharged at normal speed into the tailbay.

Since the interface between salt water and fresh water is below the level of the step in the floor, the salt water can not escape to the forebay. When a ship sails from the forebay into the lock chamber, the return current may take some salt water to the forebay. The efficiency of the system can be improved when a downlocking ship enters the lock chamber slowly and carefully without using too much it's engine. In the case of uplockage the return current is directed towards the lock chamber, which prevents the escape of salt water. But, also in that case the ship should slowly exit the lock chamber in order not to disturb the salt water layer by the action of the return current and the screw race of the ship (which would result in some mixing of salt water and fresh water and storage of salt water in the wsb's).

The system does not cause an additional water loss from the lake, which is a great advantage. Because filling and emptying of the lock chamber require more time, shipping will be delayed. However, when the system is applied to 1-lift locks the total lockage time may be smaller than with a normal 3-lift lock system or even a normal 2-lift lock system.

The system has similarities with the 'salt-trough' system, which has been developed in the Netherlands (see Appendix A, Section A4.3 for a description). This system was not realized, but from preliminary computations and experiments it was concluded that the efficiency can be very high (reduction of salt water intrusion > 90%). The application was meant for a relatively small navigation lock. When this system is considered for implementation in the much bigger Post-Panamax Locks a detailed study has to be undertaken into all relevant aspects of the system, such as dimensions and position of fill openings, fill and emptying discharge, effect of ships and ship movements on the efficiency, transverse forces on the ship, accumulation of salt water in the wsb's, operation of the system and lockage time.

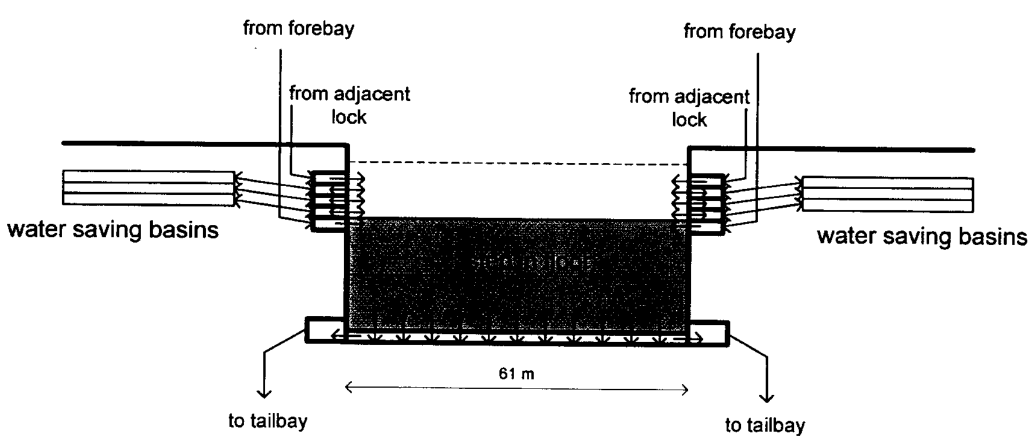
In conclusion
A considerable reduction of the salt water intrusion can be obtained with a system that is designed to keep the salt water in the lower lock chamber during lock operations. The upward step in the floor at the upstream side of the lower lock chamber forms a crucial element of this system.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

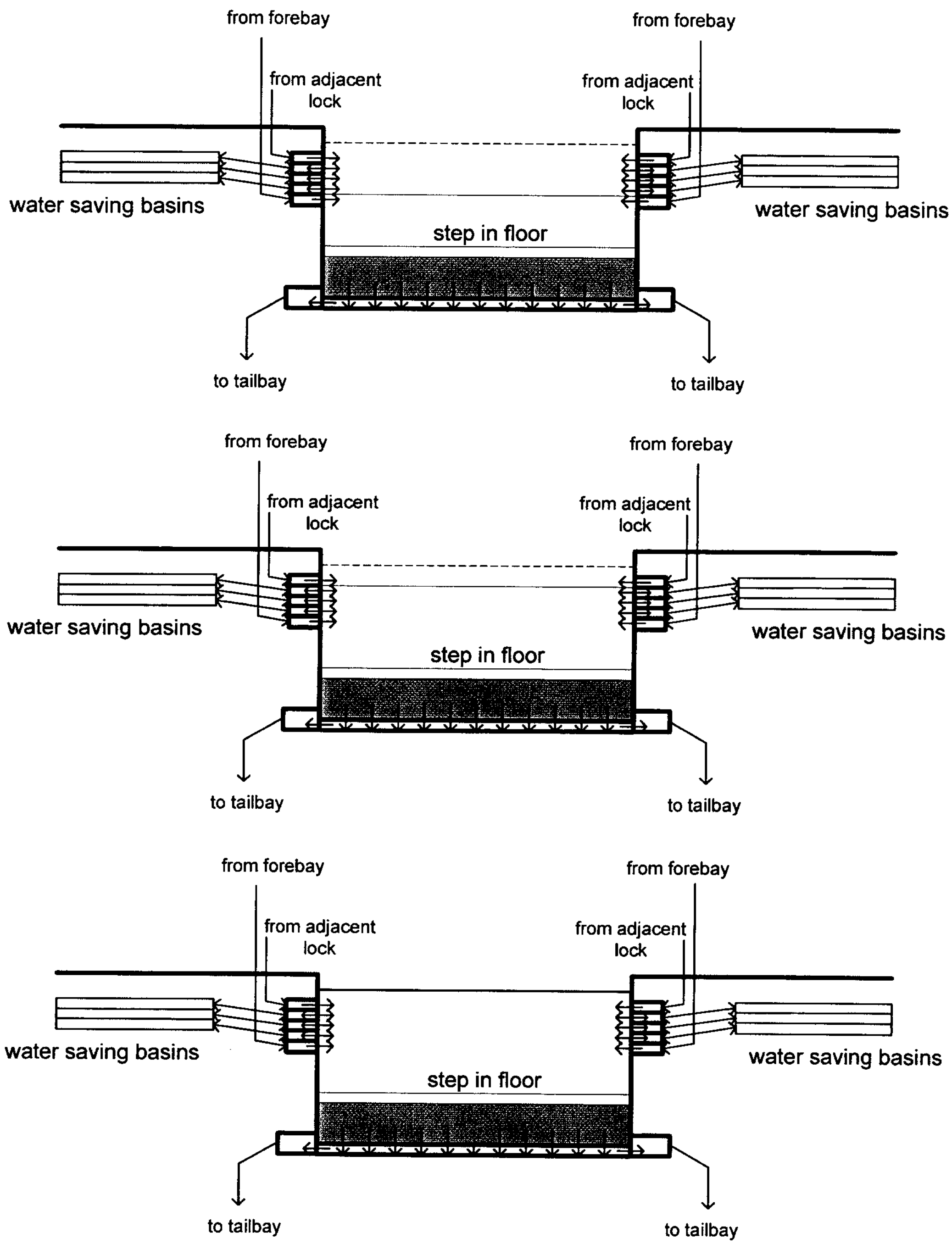
3.4.2 Remove the salt water from the lower lock chamber

The above described system can in practice only be applied to a 1-lift lock configuration. If it was possible to lower the salt water – fresh water interface below the level of the step in the floor, the system could also be applied to 3-lift or 2-lift lock configurations. A system that enables the lowering of the interface, that means the removal of salt water and replacement with fresh water, has been developed for navigation locks in the south-western delta of the Netherlands. A decription of these locks is given in Appendix A, Section A4.1. The locks have a combined wall filling and floor emptying system that enables a simultaneous withdrawal of salt water through the floor and filling of fresh water through both lock walls.

When applied to the Post-Panamax Locks the design could be as shown in next figures for a 3-lift lock configuration with three water saving basins per lift. The arrows in these figures indicate the possible flow direction in culverts. The system is only needed in the lower lock adjacent to the tailbay.
The wall filling system is similar as described in the previous section. Each wsb is connected to a separate inflow channel with openings in the lock walls; in addition one inflow channel (the lowest one near the salt water surface) is connected to the forebay. The floor is provided with an emptying system that is similar to the system in the existing locks.

Levelling up starts with a supply of fresh water from the forebay and a simultaneous withdrawal of salt water through the perforated floor. This salt water is discharged into the tailbay. The replacement of salt water with fresh water is a delicate process: the fresh water quantity must balance with the salt water quantity, while the fresh water must carefully be supplied so that the fresh water can form a separate layer on top of the salt water, without too much mixing up with the salt water. When the salt water – fresh water interface has lowered below the level of the step, the exchange is stopped. Subsequently the water from the wsb's is supplied and finally, in the phase that the water levels of lower lock chamber and adjacent lock chamber are equalized, water from the adjacent lock chamber is added.



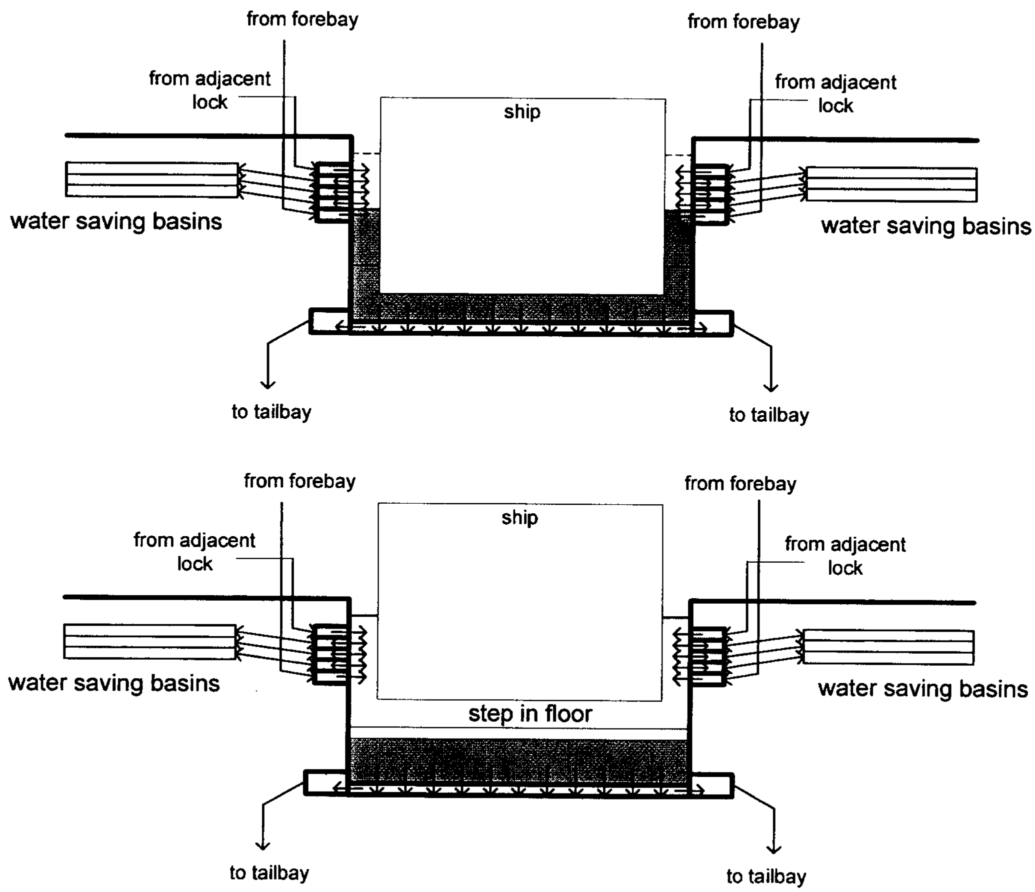


3-lift Post-Panamax Locks with wsb's and wall filling / floor emptying system; different phases of levelling up

The replacement of salt water by fresh water from the forebay means a considerable extra loss of water (this loss can for the 3-lift locks roughly be estimated as a 12 m thick water layer in the lock chamber).

Emptying of the lock chamber occurs in the reverse sequence. Firstly, the wsb's are filled starting from the upper wsb and than downwards, next the remaining portion is discharged through the perforated floor into the tailbay. No extra losses occur when the lock chamber is emptied.

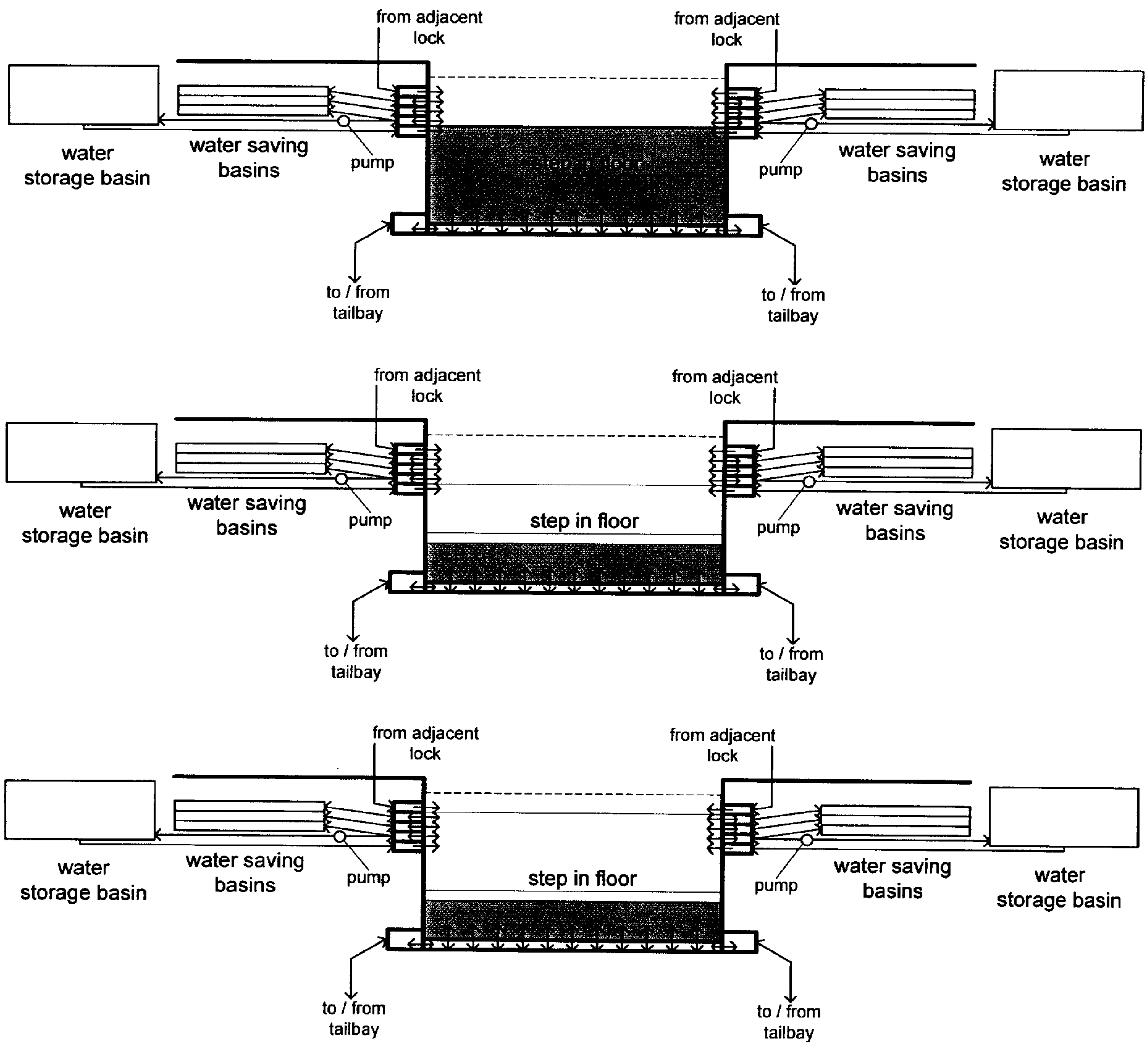
In the case that a ship is present in the lock chamber (uplockage) there is less water in the lock chamber, and consequently a lesser quantity of salt water needs to be replaced by fresh water from the forebay during levelling up (see next figures). For Post-Panamax vessels (beam up to 54 m, draught up to 15.2 m, length up to 386 m) the replaced water quantity may be estimated as a 2 m thick water layer in the lock chamber. As an average value (for uplockage and downlockage operations) the extra loss of water per lockage can roughly be estimated as a 6 m thick water layer. This value corresponds to about 25% of the total water level difference between Gatun Lake and the tailbay, and is somewhat smaller than the normal loss of a 3-lift lock without water saving basins.

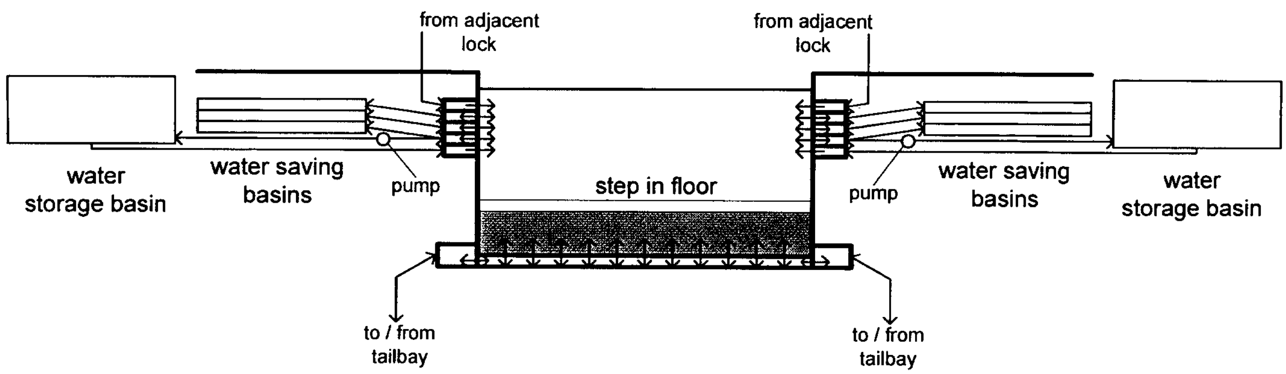


3-lift Post-Panamax Locks with wsb's and wall filling / floor emptying system; ship in lock chamber; situation before and after filling

The extra loss of water caused by the exchange of salt water in the lower lock chamber with fresh water from the forebay can be prevented when a separate water storage basin is applied for temporarily storage of the exchanged water. A possible design for the 3-lift lock configuration is shown in next figures.

Levelling up starts with a supply of fresh water from the storage basins instead of the forebay. This supply of water occurs through the lowest fill openings in the lock walls. Simultaneously water is withdrawn through the perforated floor and spilled into the tailbay. After the fresh water – salt water interface has sufficiently sunk below the level of the step, the exchange of salt water and fresh water is stopped. Next, fresh water is supplied from the wsb's. The remaining portion is supplied from the adjacent lock.





3-lift Post-Panamax Locks with wsb's and extra water storage basins; wall / floor filling and emptying system; different phases at levelling up

Emptying is in a reverse sequence. Firstly the wsb's are filled (from upper wsb downwards), than the valves in the culverts to the water storage basins are opened and the water in the lock chamber is equalized with the water in the water storage basins. Subsequently the water storage basins are further filled using the pumps in the return culverts, while the valves in the culverts to the tailbay are opened, so that simultaneously salt water can flow into the lock chamber through the openings in the floor. This exchange of fresh water with salt water stops when the water storage basins are filled.

The exchange process of salt water in the lock chamber with fresh water from the storage basins and, reversely, the exchange process of fresh water in the lock chamber with salt water from the tailbay are the most difficult operations. Fresh and salt water quantities have to balance and the exchange process must carefully be executed in order not to mix up salt water and fresh water. The operation is in particular complex at the Pacific side, where large tidal fluctuations occur. Inevitably, some salt water will accumulate in the water storage basins, which makes this system less effective. But this is the price that has to be paid for a lesser loss of water from the lake.

Whether or not water storage basins are applied lock operations require more time than in a normal lock system. Shipping may thus be delayed.

In conclusion

Salt water intrusion can effectively be reduced with a system that is designed to exchange the salt water in the lock chamber with fresh water from the forebay. The system is only necessary in the lower lock chamber and is suited for 3-lift and 2-lift lock configurations. The fresh water is supplied through openings in the lock walls (the lowest openings are located near the initial salt water surface), while the salt water is simultaneously discharged to the tailbay through openings in the floor. This is a delicate process since the supplied fresh water and the withdrawn salt water have to balance, while the supplied fresh water may not mix with the salt water. If carefully executed, mixing of salt water and fresh water can for the greater part be prevented. The exchange of salt water is stopped when the salt water – fresh water interface is ample below the level of the step in the floor at the entrance to the next lock. The step in the floor prevents an escape of salt water to higher locks and forebay in the phase that lock gates are open, provided that ships move slowly and don't use too much the engine. The system causes an additional water loss. This water loss can be

prevented when water storage basins are applied, but the application of these basins reduces the effectiveness of the system, since accumulation of salt water in the storage basins will occur. In addition, pumps are required in this system. Lock filling and - emptying as well as ship manoeuvring have to be done very carefully, which are the reason that a delay of shipping is inevitable. The system is rather complex and requires a careful operation, in particular at the Pacific side, where a large tidal fluctuation occurs.
Similar as for the system described under Section 3.4.1 a thorough study into all relevant aspects of the system is required when applied to the Post-Panamax Locks.

4 Comparison of mitigation measures

The salt intrusion mitigation measures which have been discussed in Chapter 3, will be 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

The cost of the measures do not form a part of this comparison but are of course highly important in decision making. 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). Three groups are distinguished (similar as in the previous Chapter 3): group A: measures meant to reduce the intrusion of salt water, group B: measures meant to remove the salt water that has passed the locks, and group C: measures meant to prevent the migration of salt water from the lower lock to higher locks and forebay.

	Mitigation measure	*1*	*2*	*3*	*4*	*5*	*Reference*
A	1 Operational measures	0/+	0	-	0	-/0	Section 3.2.1.
	2 Pneumatic barriers	+	0	0	-/0	0	Section 3.2.2
	3 Adjustable sill	0/+	0	0	0	-	Section 3.2.3
B	1 Flush the canal (Gaillard Cut)	0/+	--	0	-	0	Section 3.3.1
	2 Drain salt tongue	+	--	-/0	-/0	-	Section 3.3.2
	3 Flush from pit	+/++	-/--	0	-/0	0	Section 3.3.3
C	1 Keep salt water in the lock chamber	++	0	--[b]	-/0	-	Section 3.4.1 (1-lift locks)
	2 Remove salt water from lower lock[a]	++	--	--	-/0	--	Section 3.4.2 (3-lift, 2-lift locks)

[a]) without water storage basin; [b]) delay may be acceptable when compared to 3-lift locks

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 floor 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 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 floor at the upstream side of the locks) may be effective in reducing the salt water intrusion (expected upper limit 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 efficiency (expected upper limit of salt water 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 in the pit a perforated floor is constructed that enables an equally distributed outflow of salt water (similar as in the existing locks), without taking fresh water.

Measure C1 (keep the salt water in the lock chamber) is expected to be highly effective in reducing 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 floor 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. The system is rather complex and needs a 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.

5 Conclusions and recommendations

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

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

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

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

Promising, highly effective mitigation measures are:

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

effectiveness); the lock operation is even more complex than with measure C1 and requires a longer operating time, which is the reason that ship handling is delayed.

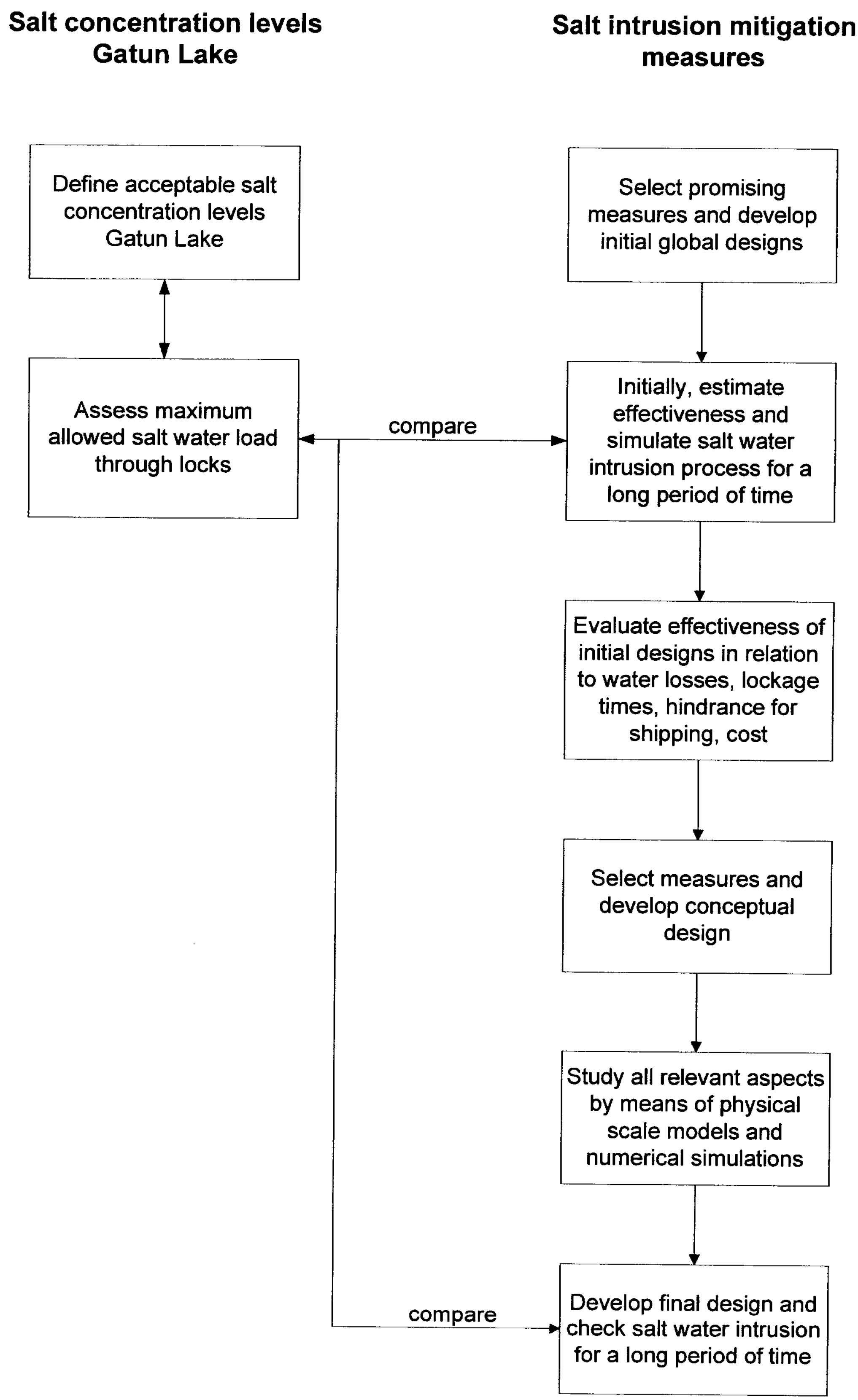
- *Measure B3* (catch the intruded salt water in a deep pit and flush); this measure is suited to all lock configurations, but causes a considerable extra loss of water (the loss of water is smaller when a perforated floor is constructed in the pit, which limits the escape of fresh water)

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

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

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

The above activities are reflected in the next schedule:


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

Appendix A: Literature review

A1 Introduction

This Appendix A presents the outcome of a literature review on alternative systems to mitigate salt water intrusion through shipping locks. Most of the literature is based on studies and experiments, which have been conducted in the Netherlands. A list of relevant literature is appended.
Mitigation measures and systems to reduce the salt water intrusion through locks are described and reviewed. All systems are designed for single-lift locks, but may also be applied to multiple-lift locks. In most of the described systems the sea water level can both be higher and lower than the canal water level.

There are different types of measures that can be taken to reduce the salt water intrusion in shipping locks. The following sub-division will be used in the presentation of the measures:

1. Operational measures
2. Mitigation measures meant to reduce the salt water intrusion in the phase that lock gates are open and ships sail in or out
3. Mitigation measures meant to reduce the salt water intrusion in the phase that lock gates are closed, the ship is in the lock chamber or waiting outside, and the water level of the lock chamber is equalized with the water level of the adjacent higher or lower basin.

The focus is on possible mitigation measures that require special provisions or adaptations of the locks (measures mentioned under points 2 and 3), but some operational measures are also described.
A detailed description of measures developed and applied in The Netherlands, Belgium and France is presented in various papers. Copies of key papers are appended to this report (Appendices B, C and D).

A2 Operational measures

The operator of shipping locks has various options to reduce to a certain extent the intrusion of salt water. No special provisions are needed for these measures, but their application depends strongly on what is permitted in view of a smooth and efficient handling of the ships. Generally, however, the available options will somewhat limit the lock operations and thus adversely effect ship handling. Examples of operational measures are described in next sections.

A2.1 Short opening time of lock gates

The period that lock gates are open is as much as possible reduced; gates are opened shortly before entering or leaving of the ships and are next immediately closed. This measure reduces the quantity of water that is exchanged as a result of density differences, and is in particular effective in the case of long and shallow locks and small density (salinity) differences. In that case the propagation velocity of the intruding salt tongue is small and it takes a lot of time to exchange the fresh water in the lock chamber with salt water. When the duration of a full exchange of the lock chamber is about as long as the time required for a safe sailing into or out of the lock chamber, this measure is not effective.

A2.2 Minimum number of lockages with maximum use of lock capacity

In the case of multiple locks constructed parallel to each other one or more locks may be used to handle as many as possible vessels at a time in one lock chamber. Besides the fact that this reduces the number of lockages, the actual water volume of the lock is reduced, which is favourable in view of a reduction of the salt water intrusion caused by density differences. There is also more time required to handle a number of ships simultaneously, meaning that the lock gates are open during a longer period of time. This may reduce the effect of the measure.

In the case of a lock complex with differently sized locks parallel to each other the smallest lock may preferably be used. In ship handling it are the dimensions of the ship which are decisive for the selection of the lock.

In the case of a single lock it is worth aiming at a reduction of the number of lockages by waiting until the required number of ships has arrived. Normally, this extra waiting time is only acceptable for yachts.

A2.3 Use of lock partitions

When intermediate gates are available, a lot of fresh water can be saved and salt water intrusion can considerably be limited, when lock partitions are made. In that case the water volumes involved in levelling operations and exchange of water are much smaller. The intrusion of salt water occurs in the phase that the lock gates are open and salt water is exchanged with fresh water of the small partition. When the sea water level is higher than the canal water level, levelling up causes also salt water intrusion, but it is limited to the fill volume of the partition.

The measure is most effective when ships, which are small enough to be locked using the partition, are collected and handled in a joined series.

A2.4 Opening of a single gate

In the case that small vessels pass the lock, the lock gate(s) may only partly be opened. This measure reduces the exchange of salt and fresh water, provided that the time required for ship manoeuvring is not considerably increased.

A2.5 Limiting lock operations to low tide

In the case that the sea water level during a part of the tidal cycle rises above the canal water level a reduction of the salt water intrusion can be obtained by limiting lock operations solely to the period of low tide. This measure clearly obstructs a fast handling of ships and may only be acceptable at low traffic intensities.

A2.6 Flushing

Flushing of the canal is only possible when a sufficient quantity of fresh water is available. In most cases the intruded salt water is found in a relatively thin layer near the bottom of the canal. Effective flushing requires than that the flow velocity of the fresh water above the salt sublayer is high enough to break up the salt layer and mix the salt water with the fresh water, so that it can carried back. For this reason it is better to flush at high flow velocity during shorter periods of time than to flush continuously at small flow velocity. When the salt water in the canal is mixed up as a result of sailing ships and, possibly, the action of wind, it is easier to flush the canal, but a large quantity of flushing water is still required.
The flushing water may be discharged using the filling/emptying system of the locks or a separate sluice. Flushing and discharging operations may cause hindrance for shipping, in particular near forebays and tailbays, and lock operations may not be possible.
Discharging of the water in the forebay may cause a temporarily decrease of the salt concentration of the forebay. This effect may be utilized to reduce the salt water intrusion during the next lockage operations.

A3 Mitigation measures, lock gates open

Mitigation measures aimed to reduce the salt water intrusion in the phase that lock gates are open and ships move in or out of the lock chamber require special provisions. The operation of such a lock becomes more complicated than with a conventional lock. Some of the measures discussed in next sections, cause a greater loss of fresh water during lock operations and require thus the availability of sufficient fresh water sources.

A3.1 Pneumatic barriers

Pneumatic barriers or air bubble screens may be applied both at the downstream and upstream side of the lock. They are meant to delay and reduce the exchange of fresh water and salt water at the entrance to the lock chamber, and should be placed near to the lock gates. They can not fully prevent the exchange of water and are therefore most effective in combination with short opening times of the gates. The air bubbles rise from perforated pipes that are constructed in the floor of the lock chamber perpendicular to the axis of the lock. The rising bubbles generate a vertical flow in the water above the pipe, which is the reason that the exchange of water through the pneumatic barrier is hampered. The efficiency is strongly dependend on the quantity of air that is blown into the water. The greater the density difference $\Delta\rho$ between lock chamber and tailbay / forebay and the larger the water depth, the more air is required.

Flow pattern

In the case that a difference in fluid density (salinity) exists between water bodies with uniform density at both sides of a lock gate (horizontal bottom), an exchange flow will occur after opening of the gate (see Figure A1, upper picture). A two layer flow situation will develop with the fresh water flowing over the salt water. The interface between the two layers is halfway the water depth.

Now we consider the situation with an air screen at the location of the lock gate, but we assume that there is no difference in fluid density (homogeneous situation). The air bubbles generate an upward flow above the perforated pipe and drag the water at both sides in upward direction in the way as indicated in Figure A1, middle picture. Water is transported towards the pneumatic barrier in the lower water area close to the bottom and flows away near to the water surface.

In the third situation a density difference is present between the water bodies at both sides of the lock gate, and prior to opening a pneumatic barrier is put in operation, see Figure A1, lower picture. Contrary to the homogeneous situation, an eddy with horizontal axis forms at the fresh water side of the barrier under the influence of density- and pressure differences over the screen and the leakage flow through the screen. This leakage flow develops to an exchange flow, which is stronger as the density difference and the water depth are greater. The air bubble screen causes also a mixing of the water, which may be unfavourable in view of additional mitigation measures. In theory the exchange of water can fully be suppressed by applying a sufficiently large quantity of air.

The above considerations hold when no ship is present. When a ship passes the air bubble screen, the action of the screen is temporarily disturbed, mainly due to the return current of the ship.

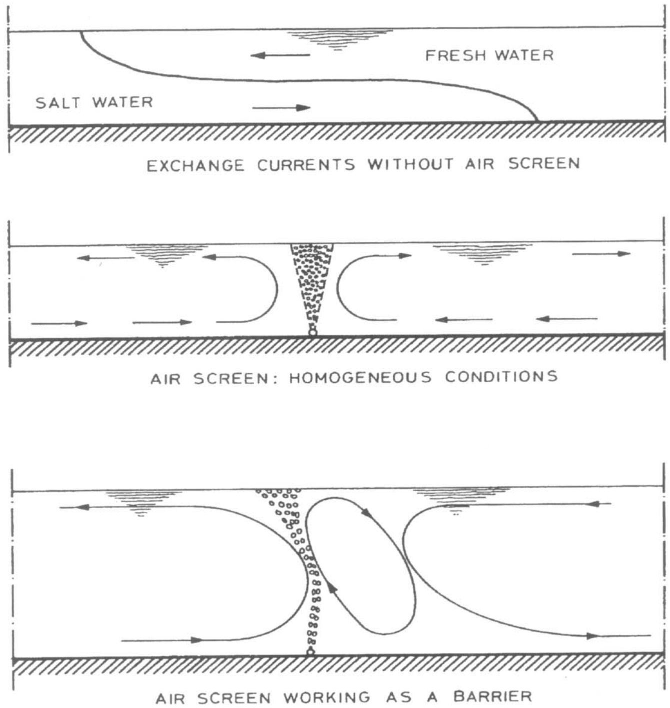


Figure A1 Air bubble screen: homogeneous condition and condition with density difference (Kolkman and Slagter, 1976).

Figure A2 Pneumatic barrier in operation after opening of lock gates, Volkerak locks, Netherlands (Rijkswaterstaat, 2000).

Reduction of salt water intrusion

A dimensionless parameter Q has been defined by Abraham and Van der Burgh (1973) that relates the air discharge q_a of the air bubble screen to the propagation velocity of the density current:

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

in which:
- q_a = air discharge per m' width at *atmosferic* pressure (m^3/s.m)
- g = acceleration by gravity (m/s^2)
- h = water depth (m)
- $\Delta\rho$ = density difference between salt water and fresh water (kg/m^3)
- ρ = density of fresh water (kg/m^3)

The reduction of the salt water intrusion brought about by a single air bubble screen at the entrance to a lock with flat, horizontal floor, is expressed in terms of the intrusion factor N:

$$N = \frac{q_{in}}{q_{in,0}}$$

in which:
- q_{in} = salt water intruding through air bubble screen (m^3/s.m)
- $q_{in,0}$ = salt water intruding the lock chamber, when no air bubble screen is in operation (m^3/s.m)

With an intrusion factor N = 100% no reduction is achieved.
The theoretical relationship between N and Q has been derived by Abraham and Van der Burgh (1973) and checked with experiments in the sea locks at IJmuiden (Van der Burgh and De Vos, 1962). The results were also checked with other theories. The comparison is shown in Figure A3 for a water depth of 15 m (deepest lock at IJmuiden). The measurements indicate a salt water intrusion which, dependent on the quantity of air used in the experiments, varies between 40% and 70% of the salt water quantity that intrudes without an air bubble screen.
Figure A3 shows that the theoretical solutions allow for a full prevention of the salt intrusion (N = 0), but this zero-intrusion is not proven in practice.

The above relationships for the quantities Q and N indicate that the greater the water depth h and the greater the density difference $\Delta\rho$ the more air is required to obtain a similar result.

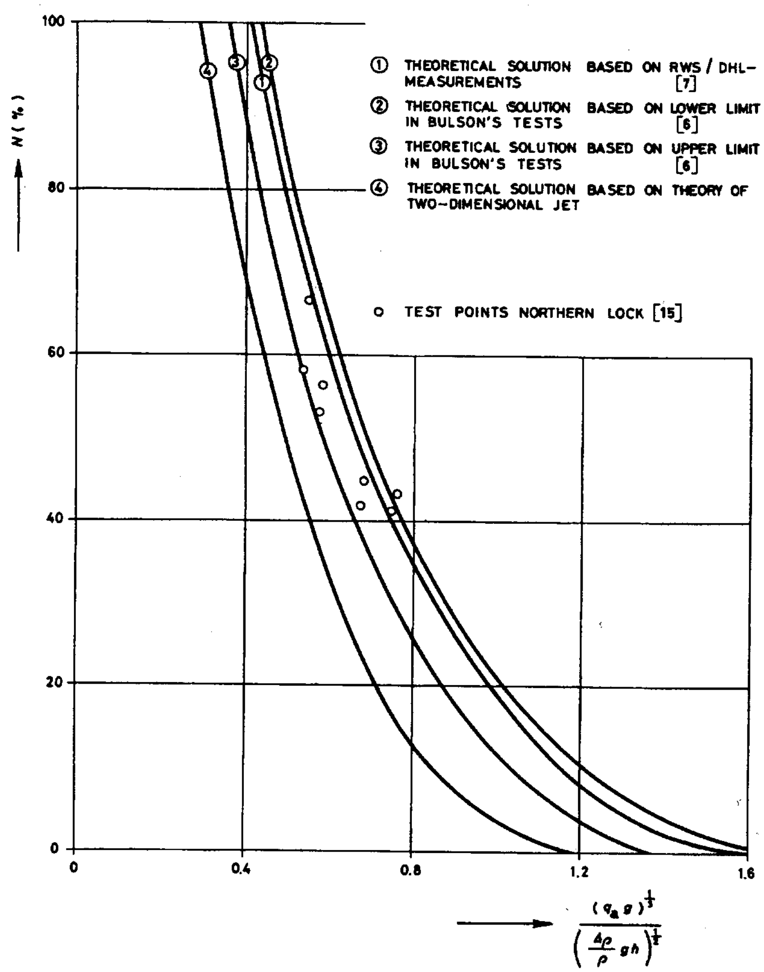


Figure A3   Comparison of theory and experiments in Lock IJmuiden, h = 15 m (Abraham et al., 1973)

The salt water that intrudes through the air bubble screen, propagates along the floor of the lock chamber (salt water tongue) and reflects against the closed gate at the other side of the chamber. Simultaneously, a fresh water tongue exits at the open side of the lock chamber and escapes through the air bubble screen. It is interesting to know to what extent the fresh water in the lock chamber is exchanged with the salt water as a function of time. To that purpose Abraham and Van der Burgh (1973) defined the dimensionless time factor T:

$$T = \frac{t}{4L} \cdot \left(\frac{\Delta\rho}{\rho} gh \right)^{0.5}$$

in which: t = time (s)
L = length of lock chamber (m)

In this relationship the propagation velocity u_a of the salt tongue is defined as:

$$u_a = 0.5\sqrt{\frac{\Delta\rho}{\rho}gh}$$

Theoretically, the salt tongue that propagates along the lock chamber floor, reflects against the closed gates and returns to the open end of the lock chamber, is back at the entrance of the lock chamber at time t = T_a:

$$T_a = \frac{2L}{u_a}$$

which corresponds to T =1.
The dimensionless, time-dependent exchange rate U(t) was defined as: U(t) = ratio of the intruded salt water volume and the total water volume of the lock chamber at a certain moment of time t.

From the experiments in the Northern Lock at IJmuiden with water depth h = 15 m and chamber length L = 413 m the following exchange rate U was observed at T = 1:

Q (dimensionless air discharge)	*Exchange rate U (-) at T =1*
0	0.92
0.5	0.59
0.6	0.43
0.7	0.35

Table A1 Exchange rate U versus dimensionless air discharge Q at T =1, Northern Lock, IJmuiden

The above table clearly shows that the exchange of water reduces with the quantity of air that is used in the air bubble screen.

The exchange rate U(t) was also determined from experiments for other sea locks. The results for different water depths are shown in Figure A4 as a function of the ratio q_l/q_{l0}. Contrary to the earlier defined quantity q_a, the quantity q_l is the air discharge of the pneumatic barrier with a pressure equal to the hydraulic pressure at the insertion level (at the bottom of the lock). The quantity q_{l0} is the theoretical air discharge that is required to prevent any exchange of salt and fresh water through the air bubble screen. As can be read from Figure A4, the exchange rate U(t) does not drop below a value of about 30%, also when $q_l/q_{l0} > 1$. The latter proves that a zero exchange rate is not possible in practice. This is caused by the mixing effect of the screen. Generally, one may assume that the effectiveness of the air bubble screen hardly increases above a value $q_l/q_{l0} = 0.8$.

All results shown are valid for the situation without a ship. When a ship passes the screen it temporarily breaks the pneumatic barrier (see Figure A5). The return current and the propellor of the ship are the reason that more salt water passes the air bubble screen, in particular when the ship sails to the sea. When the submerged volume of the ship is large compared to the lock volume the effectiveness of the air bubble screen strongly reduces.

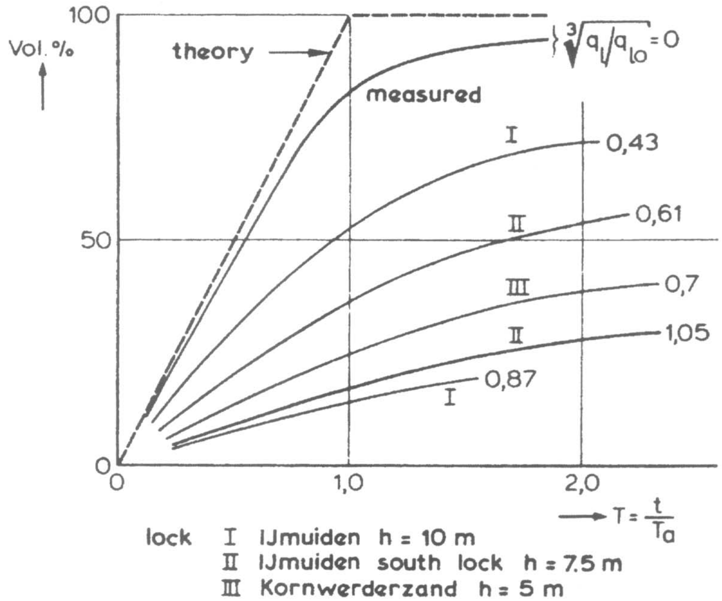


Figure A4 The exchange rate U(t), in % Vol, found with experiments (Kerstma et al, 1994).

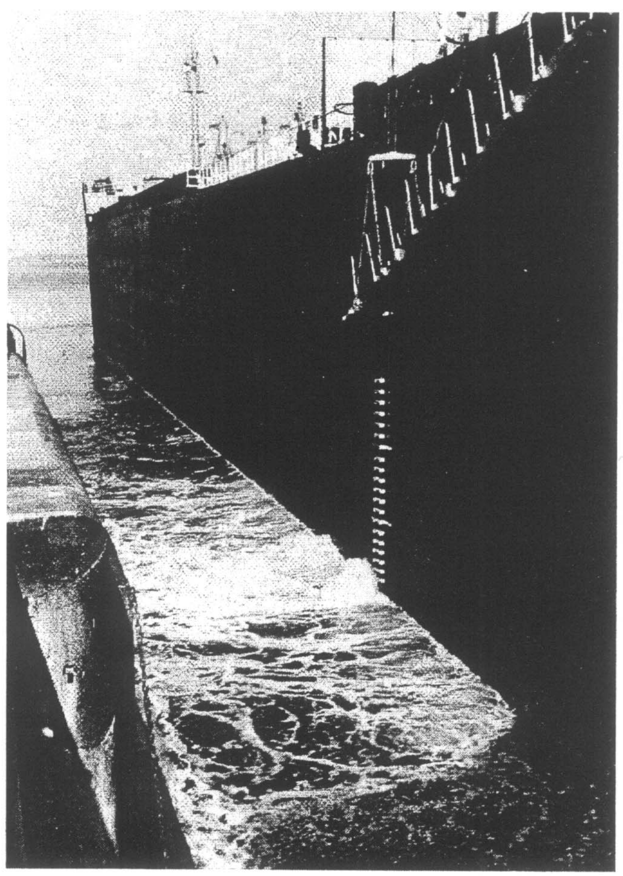


Figure A5 Northern lock IJmuiden, seaward gate. Ship crossing pneumatic barrier (Abraham et al., 1973).

Measurements have been carried out along the Noordzeekanaal in The Netherlands to study the impact of the pneumatic barriers of the sea locks IJmuiden. The first measurements were carried out before the pneumatic barriers were installed. The second series of measurements were carried out two years after the installation of the barriers. Water samples were taken while the canal was flushed (the canal is also used to drain the rain water from the surrounding area). From the water samples which were taken near the water surface, it could be concluded that the cloridity (a measure for the salt concentration) was reduced with about 30% at a distance of 3 km to the locks (flushing range 30 m^3/s – 80 m^3/s). At a greater distance of 24 km to the locks the reduction was also 30%, but a stronger reduction appeared at a higher flushing discharge. The results demonstrate that pneumatic barriers are effective and also that diluted salt water can be flushed from a canal. Unfortunately, no samples were taken near the bottom of the canal, so that information is missing on the reduction of the salt water that intrudes as a density current along the bottom.

Applicability

Air bubble screens reduce the exchange of salt water and fresh water in the phase that the lock gates are open. They are switched off after the gates have been closed. Ships that pass the air curtains cause a temporarily break. The return current imposes inevitably an exchange of water through the curtain: the exchanged water quantity equals the submerged volume of the ship. The screens are not tested for water depths greater than 15 m.

The system is especially useful in the case of long lock chambers and small density differences, provided also that the ratio of ship volume and lock chamber volume is relatively small. The best effect is achieved when air bubble screens are used at both sides of the lock chamber, and when short gate opening times are applied. The system can be installed after construction of the locks.

The method requires the installation of air compressors with sufficient capacity. Smaller ships (yachts) may experience difficulties with crossing the air bubble screen. For this reason, it was sometimes required to reduce the air discharge in locks in the Netherlands. Larger vessels have less difficulty with crossing the air bubble screen.

Alternatives to air bubble screens are water curtains (water jets from the bottom, which have a similar effect as rising air bubbles) or curtains of artificial reed (bundles of floating ropes, 'planted' in the bottom, which provide hydraulic resistance). The application of these two systems has major disadvantages, however. They have not been applied in practice.

A3.2 Adjustable sill at the bottom of the lock

In case of an adjustable bottom sill in front of the landside gate the exchange of salt water with fresh water from the forebay takes place above the sill (see Figure A6). The salt water in the lock chamber under the level of the sill remains for the greater part in the lock chamber, irrespective of the time during which the gates are open. The reduction of the salt water intrusion is thus proportional to the reduction of the water depth above the sill. Return currents of moving vessels and propeller races do, however, have an adverse impact on the efficiency of the bottom sill.

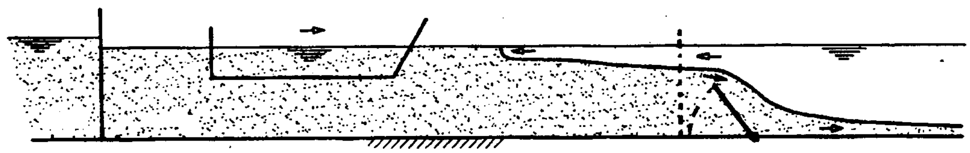


Figure A6 Adjustable bottom sill (Rijkswaterstaat, 2000).

Applicability

For an effective use of an adjustable bottom sill the sill should be placed near to the lock gates, preferably outside of the lock chamber. The crest level of the sill should, if possible, be adjustable so that only a small clearance exists between the crest of the sill and the keel of the vessel, for instance 1 meter. This implies that the system should be very much reliable and accurately be adjustable to the draught of the ship and the actual water depth.

The adjustable sill can be designed as a vertical lifting gate that slides into a vertical slot in the bottom, or constructed as a flap gate that rotates about a horizontal hinge on the bottom (see Figure A6). In small locks the single lock gate itself may be designed as a flap gate.

The largest effect can be expected in deep shipping locks which are designed to handle big ships with a great draught, but with a low frequency. In the normal situation with regular ships the sill is in upright position; the sill is lowered when a big ship passes.

The system has not been applied so far because the risk of a collision of the ship with the adjustable sill is considered too high.

A3.3 Withdrawal of salt water from a receptor basin

This system is used with conventional locks. The salt water that intrudes the forebay is caught in a deep basin adjacent to the lock. The salt water is subsequently pumped back from the basin or flushed back (when the canal water level is sufficiently high), see Figure A7.

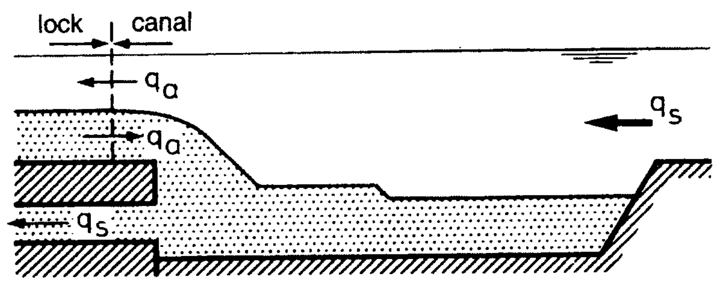


Figure A7 Continuous flushing from deep receptor basin (Kerstma et al, 1994).

The inflow of salt water into the receptor basin causes some blending with the fresh water, which is inevitable, but reduces the efficiency of the system.

The most effective way to guide the salt water from the lock chamber into the receptor basin is to have a short distance between the lock chamber and the receptor basin. In addition, the width of the salt tongue should not increase too much. This situation can be obtained by constructing the receptor basin directly adjacent at the landward side of the lock chamber or by constructing a sloping channel with limited width at the landside of the lock chamber that leads towards the receptor basin.

The water that is collected in the receptor basin should at low velocity be pumped / flushed back from the deepest point of the basin. This reduces the loss of fresh water. Most effective is a horizontal narrow discharge opening that is positioned well below the salt-fresh water interface.
It may be useful to construct the receptor basin beside the navigation route in order to prevent mixing by sailing ships.

The dimensions that are required for the receptor basin depend on a number of factors. On the one side this is determined by the volume of salt water that is caught each lockage in the receptor basin, the extent of blending between the salt and fresh water, the number of lockages per day and the possibility that more locks are linked with the same receptor basin. On the other side this is determined by the available pump capacity or flushing capacity, and whether it is possible to return the salt water during the period that ships move in and out the lock chamber. The receptor basin should be large enough to prevent the overflow of salt water.

Applicability

In the Netherlands the receptor basin is applied at the Terneuzen shipping lock complex and the shipping lock complex Den Helder.

The receptor basin at Terneuzen (Figure A8) has a volume that is twice the lock chamber volume. The depth is about 3 m (below canal bed level). In the design it was taken into account that a part of the intruded salt water is directly pumped back (see next paragraph).

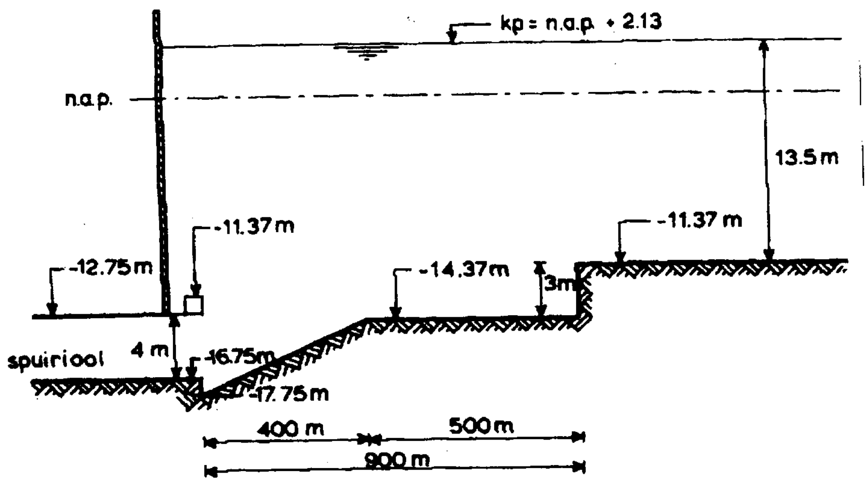


Figure A8 Longitudinal cross-section salt receptor basin Terneuzen lock (Rijkswaterstaat, 2000).

At Den Helder (see Figure A9) a salt receptor basin has been constructed close to the largest salt water source, the Koopvaarderlock. The salt water that intrudes the forebay flows through a tilting side channel towards the receptor basin. This receptor basin is constructed beside the navigation route. The maximum depth of the receptor basin is 3 m. The outlet to the pump is located behind a vertical screen, that is provided with a slit near the bottom. At Den Helder a significant sedimentation took place in the receptor basin, which had a negative impact on the performance of the system. Fortunately, the connecting canal can also be kept free of salt by a regular flushing.

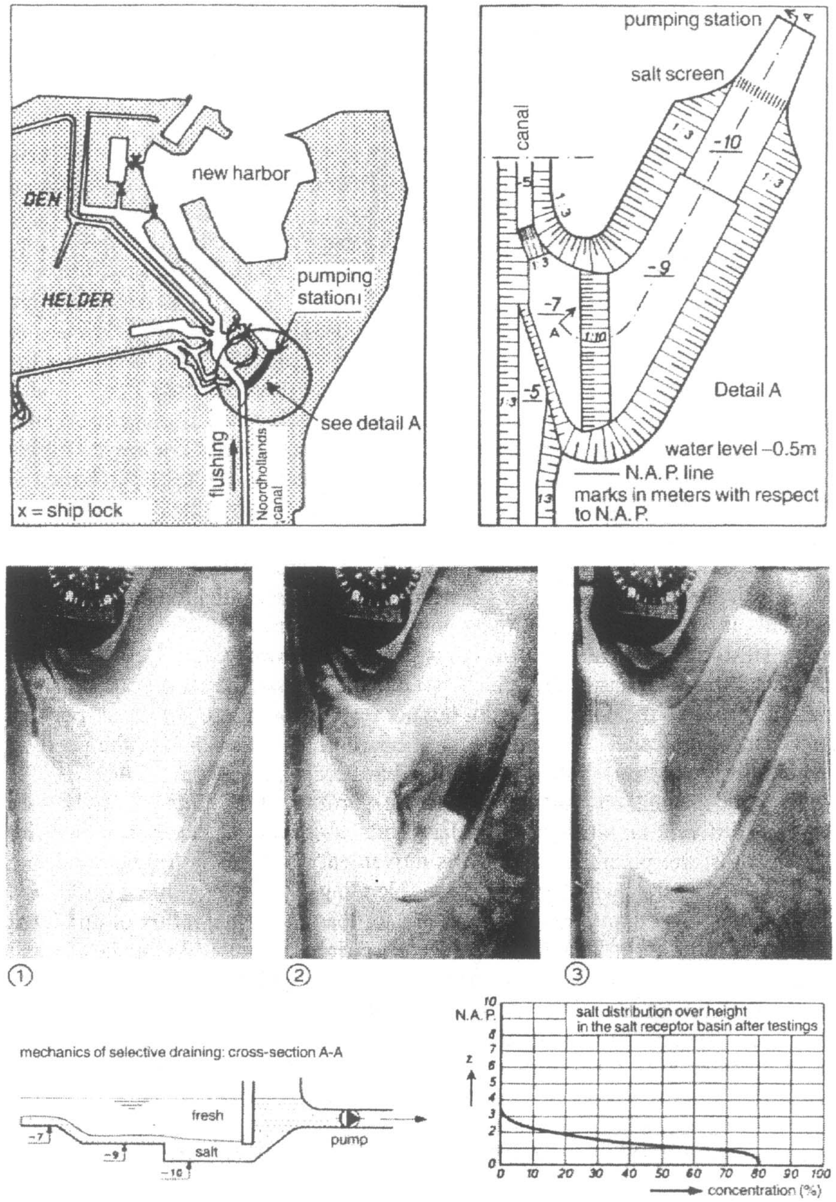


Figure A9 Model tests receptor basin Koopvaarder Lock, Den Helder (Blumenthal et al., 1976).

In conclusion: The system with salt water receptor basin is only suitable in case that sufficient fresh water is available. It requires the construction of a receptor basin, return conduits and control valves and the installation of a pumping station (in case that the sea water level can rise above the canal water level). The salt water intrusion can considerable be reduced but this requires quite a lot of fresh water (the fresh water quantity may be as high as the salt water quantity). The receptor basin may need a regular dredging.

A3.4 Direct withdrawal of salt water

As an alternative to the system presented in Section A3.2 the salt water can also directly pumped / flushed back, without the interposition of a receptor basin (see Figure A10). This is done through a drain that has its opening in the floor directly at the lock entrance. The capacity of the drain should be sufficient to drain immediately the intruded salt water and an additional quantity of fresh water.

The system is most effective with higher density difference between the salt water (under-layer) in the lock chamber and the water of the forebay. It is therefore that filling of the lock chamber (prior to opening of the gates) should occur with care, if possible, in order not to mix up the salt underlayer. A carefull operation will reduce the volume of salt water that needs to be flushed back, and also the amount of fresh water that will be lost.

The inlet of the drain can be in the floor of the lock chamber, near to the landside gates, or in the bottom of the forebay adjacent to the lock (Figure A10). When discharging the salt water, the interface between salt water and fresh water will lower, and fresh water will also flow into the drain. Also due to blending (Figure A11) a considerable amount of fresh water may be lost (up to about twice the quantity of intruded salt water). Sailing ships may temporarily disturb the proper action of the drain. Reversely, sailing ships may experience hindrance of the flows towards the drain, and special lock operation rules may be required to prevent unwanted forces on the ships.

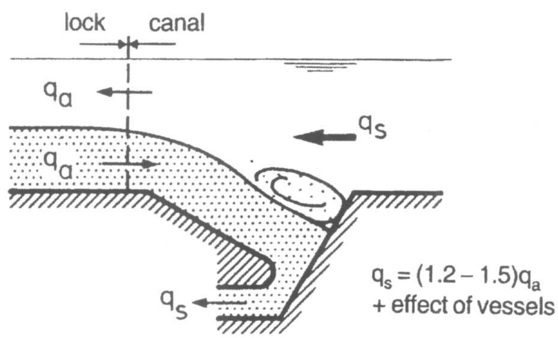


Figure A10 Direct flushing of salt water (Kerstma et al, 1994).

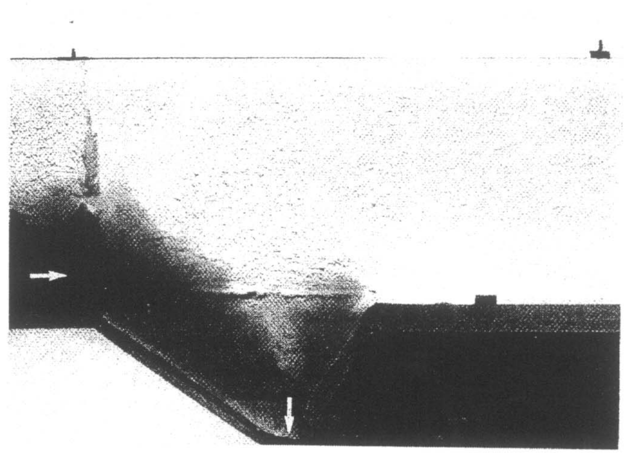


Figure A11 Scale model test of salt water drain, Lock Terneuzen (Kolkman and Slagter, 1976).

Applicability

At the upstream side of the Zandvliet sea lock (Antwerp, Belgium) a small salt water pit, connected to a pumping unit, has been constructed that is aimed to return the salt water to the salt access channel. This pit may also be used to return sediment laden water to the access channel. The efficiency of this system is not known.
In the Netherlands a salt water drain has only been installed at the Terneuzen lock complex in combination with a receptor basin. The inlet of the drain has been constructed directly underneath the floor of the new, big sea lock (see Figure A12).

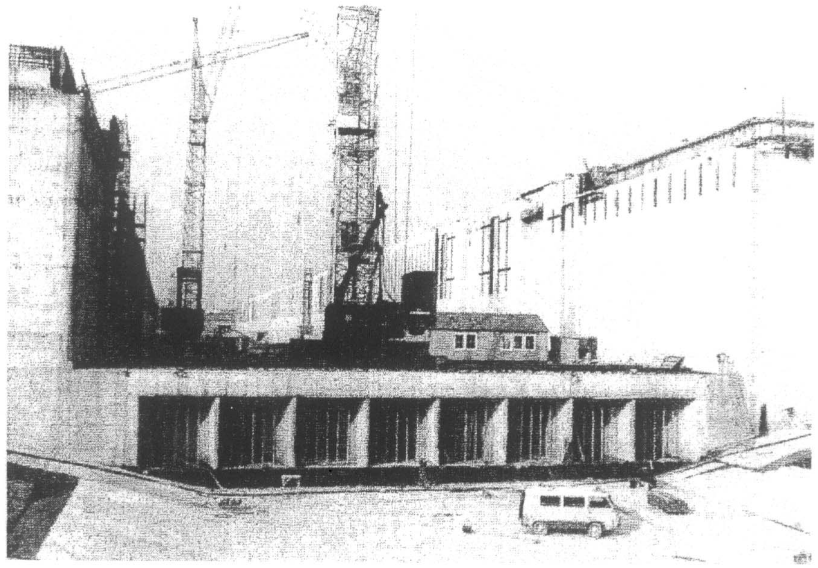


Figure A12 Inlet of drain at Terneuzen lock (Rijkswaterstaat, 2000).

In order to drain all the salt water and an additional amount of fresh water a capacity of about 350 m^3/s is required at Terneuzen lock. This spill flow causes a considerable blending of fresh water and salt water and limits also the navigation. For that reason, in practice only a 20% fraction of the intruded salt water is directly drained. The remaining portion is caught in the interception basin and drained back later. To sustain the action of the system air bubble screens have been installed in the lock chamber.

Measurements have been conducted in the connecting canal at a location 2200 m inland of the Terneuzen locks. Monthly averaged chloride contents have been analysed, see reference (Delft Hydraulics, 1988). The chloride content (salinity) in the canal depends on:

1. The drainage of fresh water from the hinterland. A reduction of the fresh water supply quickly results in an increase of the chloride content. This effect is related to seasonal variations.
2. The number of lockages at the Terneuzen locks. An increase of the number of lockages leads to an increase of the chloride content in the canal.

3. The chloride content in the seaside Westerschelde estuary. The chloride content of the Westerschelde depends on the discharge of the Schelde River. This varies with the season.

From the measurements the conclusion could be drawn that the average chloride content of the canal increased somewhat after the new, big sea lock at Terneuzen came into operation in 1968. The number of lockages per year in the new and existing locks increased considerable in the period 1974 to 1983. During that period also the fresh water supply increased and the average chloride content of the Schelde River decreased slightly. It appeared that the increase of fresh water supply was not sufficient to compensate for the increased number of lockages.

Although it was observed that the salinity level in the canal increased during time no adjustments have been made to the Terneuzen system. It was concluded that the installed salt-intrusion mitigation system worked satisfactory and the increase of the chloride content of the canal was accepted.

A4 Mitigation measures, lock gates closed

Systems are described in this section, which are aimed to mitigate the intrusion of salt water in the phase that the lock gates are closed, the ship is in the lock chamber or waiting outside, and the water level of the lock chamber is equalized with the water level of the adjacent higher or lower basin. Special provisions facilitate the drainage of salt water from the lock chamber and a simultaneous supply of fresh water, meaning that more fresh water is required for lock operations. In other systems the salt water is not drained but kept in a separate part of the lock chamber. The operation of locks which are provided with these facilities, is more complicated than the operation of a conventional lock and requires also more time.
Next systems are described into greater detail:

- System with salt water flow through openings in the floor and fresh water flow through openings in the lock walls near to the water surface.
- Systems with combined transverse outflow of salt water near the floor and longitudinal inflow of fresh water near the water surface, or reverse.
- Systems with the salt water in a separate part of the lock chamber.

A4.1 System with perforated floor and openings in lock walls

The system with a perforated lock chamber floor and openings in the lock walls is applied in the sea lock Dunkerque (France) and in the Kreekrak locks and Krammer Locks (Netherlands).
Figure A13 presents a longitudinal cross-section of the Krammer locks, Figure A14 presents a cross section. The several steps of the lockage process are shown in Figure A15 (left figures: sea level > canal level, right figures: sea level < canal level). During the 'uplockage' process (ship sails from sea to canal) the entire volume of salt water inside the lock chamber is drained and stored in a low reservoir. At the same time this water is replaced by water from a higher fresh water reservoir. The salt water is drained (or supplied) through the perforated floor of the lock chamber. The fresh water is supplied (or drained) through openings in the sidewall, which are constructed at a high elevation near the water suface.

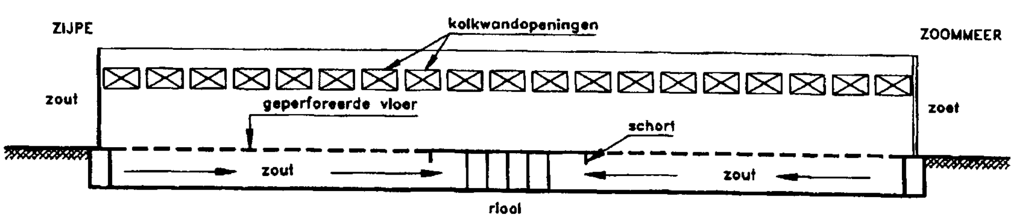


Figure A13 Longitudinal section of the Krammer locks (Rijkswaterstaat, 2000).

In the first step of the 'uplockage' process the water of the lock chamber is levelled with the canal water. This levelling process is always done with salt water through the lock chamber floor. Levelling is required because the openings in the lock walls are at an equal elevation as the canal water level. After levelling the replacement of the salt water with fresh water is carried out by pumping salt and fresh water to and from reservoirs. The salt-fresh water interface is moving downward during the exchange process. The lock gates can be opened after the salt-fresh water interface is below the floor level of the lock chamber.

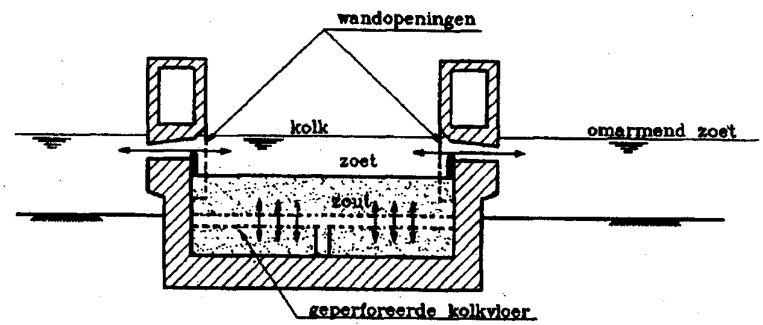


Figure A14 Cross-section of the Krammer locks (Rijkswaterstaat, 2000).

In the case that a ship sails from the canal to the sea ('downlockage') the fresh water in the lock chamber is replaced with salt water from a reservoir. The salt-fresh water interface is kept below the keel of the vessels so that the salt water is not drained through the openings in the lock walls. Than the water in the lock is levelled with the sea water. Consequently, some fresh water is lost when the lock gates are opened.
In the situation that enough fresh water is available the step in which fresh water in the lock chamber is replaced with salt water is not necessary. The omission of this step saves some time.

The required time for levelling and replacement of water is longer than with conventional locks. Although levelling through the floor of the lock chamber is faster than levelling through openings in the lock heads, extra time is needed for, in particular, a smooth and carefull replacement of the salt water with fresh water. This is needed to prevent too a strong blending of fresh and salt water (which reduces the efficiency of the mitigation system) and to limit the transverse forces on the ships in the lock chamber.

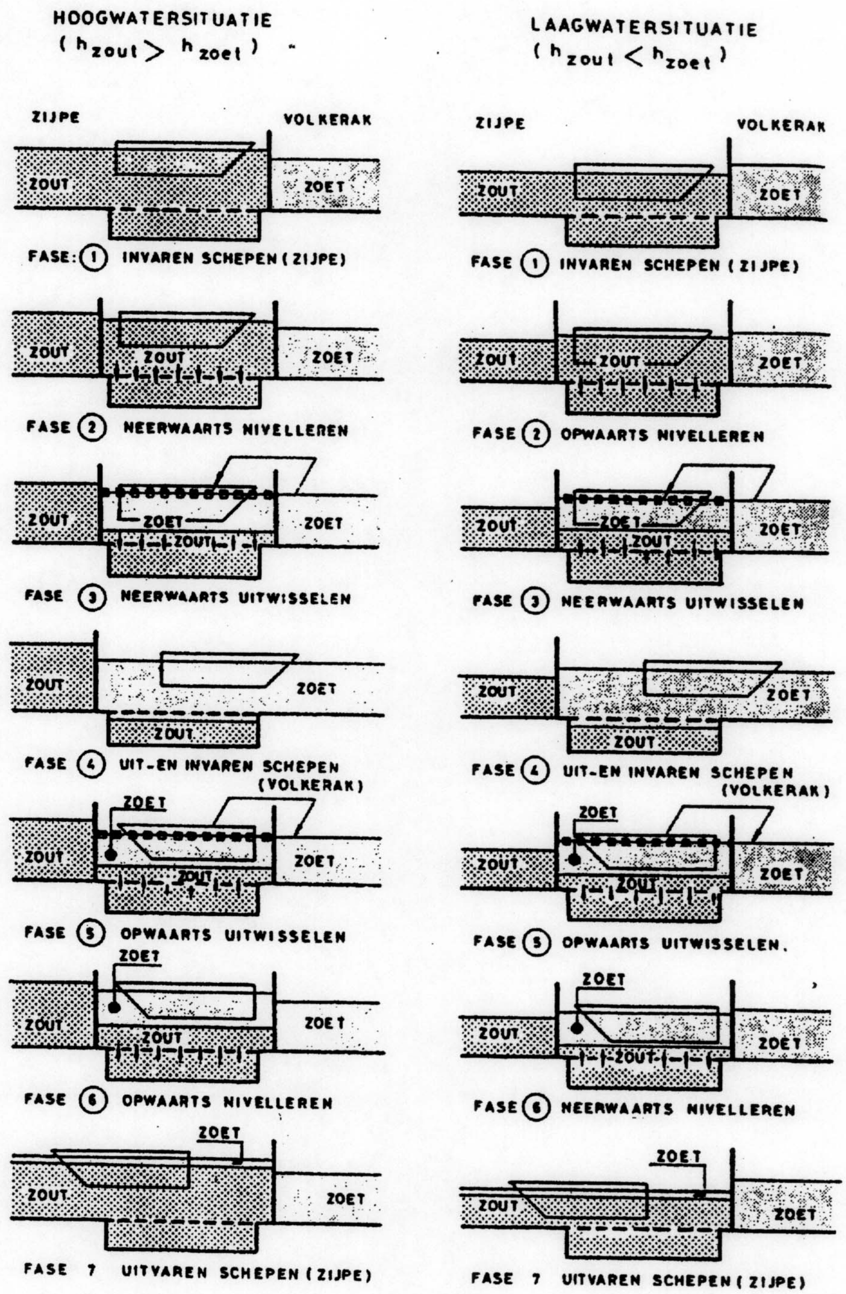


Figure A15 Phases in the lockage process, Krammer locks (Rijkswaterstaat, 2000).

Salt water - fresh water interface and blending

More salt water will intrude the fresh water canal when the salt water-fresh water interface in the lock chamber does not remain horizontal (the exchange flows can not be controled well) and when blending takes place (the salt water - fresh water interface becomes too thick and salt water may enter the fresh water reservoir. It is therefore that the exchange process must carefully be executed.

Openings in the lock chamber floor are provided over the full floor area. The openings in both lock walls are equally distributed in longitudinal direction of the lock chamber. The openings in the floor or the openings in both lock walls are all simultaneously used. As a result water is mainly flowing in a vertical, transverse plane during levelling and during exchange operations, not in a longitudinal direction. In this way the salt water - fresh water interface in the lock chamber can be kept at an equal elevation in longitudinal and transverse direction of the lock.
Ships inside the lock chamber disturb this horizontal salt water - fresh water interface to a certain extent. This is especially the case at the beginning of the downward exchange process.

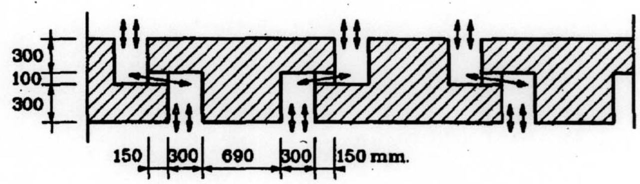


Figure A16 Longitudinal cross-section of floor of Krammer locks (Rijkswaterstaat, 2000).

The perforated floor has three main functions: (i) to equally distribute the inflow / outflow of salt water, (ii) to limit the vertical flow velocity of the salt water that passes the floor (this reduces blending), and (iii) to form a cover above the salt water - fresh water interface (to prevent mixing when ships sail in from or sail out to the forbay at the canal side).

The fresh water flows horizontally into the lock chamber through the openings in the lock walls (Figure A17). With the help of overflow lifting gates the actual flow openings are positioned just below the water level; the overflow discharge is controlled in such a way that blending at the water surface is limited and salt water does not flow into the fresh water culverts. Optimal inflow conditions exist when the so-called internal Froude number F_i is 1:

$$F_i = \frac{u}{\sqrt{\frac{\Delta\rho}{\rho} gd}} = 1$$

where:
- u = flow velocity (m/s)
- d = water depth above gate crest (m)
- $\Delta\rho$ = density difference between salt water and fresh water (kg/m^3)
- ρ = density of fresh water (kg/m^3)

The fresh water enters the lock chamber in the form of a fresh water wave that moves in transverse direction along the salt water surface. In the centre the waves from both sides reflect and return. In this way a fresh water layer is built up on top of the salt water. To prevent mixing ships are not allowed to use their propellers during levelling and exchange operations.

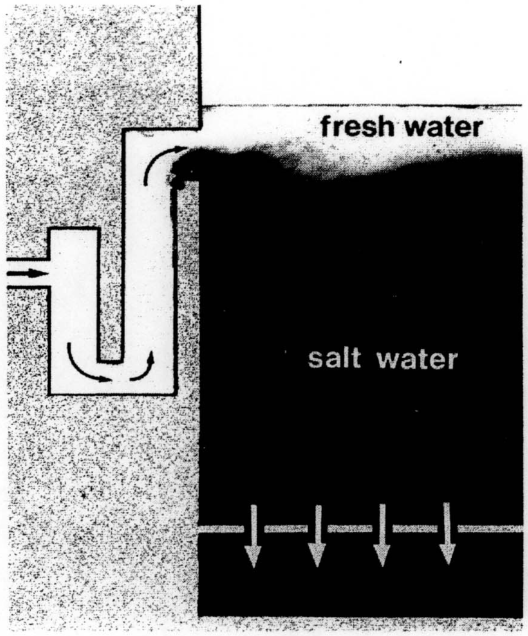


Figure A17 Model test of fresh water inflow (Kolkman and Slagter, 1976).

Supply and drainage system

The openings in the sidewalls of the lock chamber are connected by short culverts with the fresh water that surrounds the lock chamber. The real lock chamber floor is located at some distance under the perforated floor. The space between the perforated floor and the actual floor is connected by culverts with two salt water reservoirs. The reservoir with high water level is used to supply salt water to the lock, the reservoir with low water level is used for storage of salt water. The supply and drainage of salt water is controlled with the help of valves in the culverts. The water levels of the salt water reservoirs are controlled by pumps which connect to the seaside tailbay, but the tidal movement is optimally exploited so as to minimize pumping.

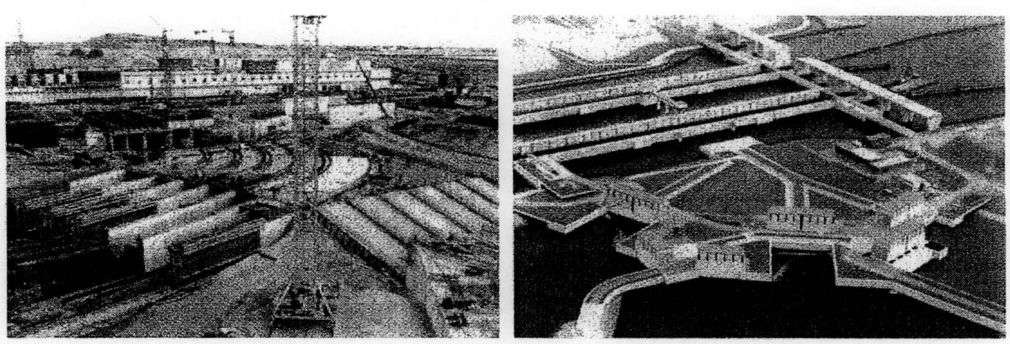


Figure A18 Supply and drainage system Kreekrak locks (Rijkswaterstaat, 2000).

A characteristic property of this system is that the drainage and supply of salt water is the leading activety, while the fresh water flows follow. A water level difference is maintained over the fresh water openings in the lock walls, which is sufficient to counteract the hydraulic resistance losses of the openings.

Fresh water loss

Fresh water losses occur mainly when a ship sails from the canal to the sea. During 'downlockage' the salt water - fresh water interface is kept just below the keel of the ship in the lock chamber. This is done so to prevent the flow of salt water through the openings in the lock walls to the fresh water basin, which especially may occur when a ship is positioned near to one lock wall, in front of the openings in the wall.
The fresh water that remains in the lock chamber after levelling with the water in the seaside tailbay flows out after opening of the gates and is than lost. This loss of fresh water is accepted as it prevents salt water to enter the fresh water forebay.

Transverse forces on ships

Fenders have been constructed in front of the openings in the lock walls. This is done to prevent a blockage of the openings by vessels that are positioned beside the openings (see Figure A19).

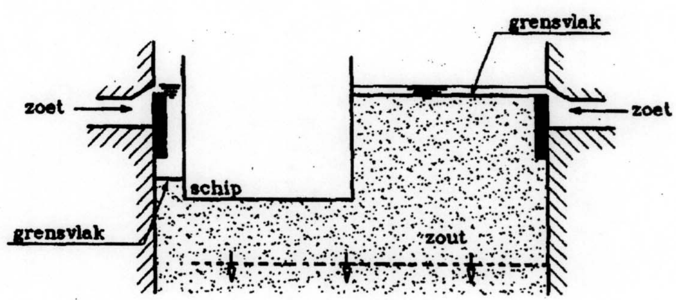


Figure A19 Salt-fresh water interface at both sides of a ship (Rijkswaterstaat, 2000).

With an asymmetrical position of the ship and an equal inflow / outflow of fresh water at both sides, an uneven level of the salt water - fresh water interface results. This occurs especially in the case of a downward exchange of water (inflow of fresh water, Figure A19). Due to an uneven water level at both sides of the ship and density differences transverse forces arise which push the ship away from the lock wall. Additional blending of fresh and salt water occurs when the fresh water flows underneath the ship towards the side with salt water. Initially, the exchange operation should therefore carefully be executed.

A contrary situation occurs when the upward exchange is continued too long. At the side where the ship is positioned the salt water reaches the openings in the sidewalls earlier than at the other side of the lock chamber. Salt water can thus flow into the fresh water reservoir. The ship is pushed towards the sidewall in this situation. To prevent these effects the interchange operation should be stopped when the salt-fresh water interface reaches the bottom of the ship.

Measurements without ships, executed in scale models and in the Krammer locks, have shown that the thickness of the salt water – fresh water interface generally increases when the exchange operations are faster executed. Blending occurs mainly when the interface passes the perforated floor.
Measurements with ships were also carried out in the Krammer locks. It appeared that the ships in the lock chamber are the cause of mixing, when sailing, and may have some thickness-increasing effect on the salt water – fresh water interface. Both effects are the cause of a somewhat reduced efficiency of the mitigation system.

Rijkswaterstaat (1989) carried out salinity measurements in the forebay of the Krammer locks. The Department concluded that the salinity level in the forebay was almost negligible. Just above the bottom and within a short distance of the lock small salinity values were observed. These measurements show that salt water intrusion is for the greater part prevented with the Krammer locks system.

Applicability

This system has been applied at several locations, but some details differ significantly. The first lock where the system was applied, is the shipping lock at Dunkerque (France). In the Dunkerque lock the salt water that is drawn from the lock chamber, is pumped back through salt water culverts towards the salt water tailbay, without making use of salt water reservoirs. The system at Dunkerque is less expensive than the system of the Krammer locks; the salt water intrusion is somewhat higher but the loss of fresh water is smaller.
The Kreekrak locks (Netherlands) have a more or less similar system as applied in the Krammer locks. The salt water that is supplied to the lock chamber is not drained from a salt water reservoir, but from the salt tailbay. Due to the present small density differences between forebay and tailbay there is no need to fully utilize the system.

It can be concluded that the system has a good hydraulic performance. The salt water intrusion is considerably reduced (reduction up to 95%). Fresh water losses are 30% to 80% of the lock chamber volume per lockage cycle. The system has also several disadvantages: it is technically complicated, requires a longer lockage time than conventional locks, may cause transverse forces on the ships, while also the operation is difficult.

A4.2 Systems with longitudinal and transverse inflow / outflow

This section describes two systems with longitudinal and transverse inflow / outflow. In fact these systems are simplifications of the system applied in the Krammer locks.

The following two systems can be distinguished in the interchange of water:

System 1: Transverse inflow of fresh water and longitudinal outflow of salt water. Fresh water enters the lock chamber through openings in one lock wall (near the water surface), which are distributed over the entire length of the lock chamber. At the same time the salt water leaves the lock chamber through an opening near the bottom at the sea side of the lock.

System 2: Longitudinal inflow of fresh water and transverse outflow of salt water. The fresh water enters the lock chamber through openings just below the water surface, near the inner lock gates and forms an internal fresh water wave that protrudes in longitudinal direction. The salt water leaves the lock chamber at the same time through openings in one lock wall (just above the floor), which are distributed over the entire lock chamber length.

The systems are designed to reduce the salt water intrusion, but are not aimed to reduce the fresh water loss. In view of the longitudinal flows in the lock chamber the systems can best be applied in short lock chambers (they are not applicable for large sea locks).

System 2 has been applied in the Hansweert lock and the Bergsediep lock (Netherlands). System 1 has been applied in Krammer yacht locks. These lock systems will be described hereafter.

System 1: Transverse inflow of fresh water and longitudinal outflow of salt water (Krammer yacht locks)

Inflow and outflow of the salt water is done through openings near the seaside gates just above the floor of the lock chamber (see Figure A20). Fresh water is supplied through openings at high elevation which are distributed along one of the two lock walls.

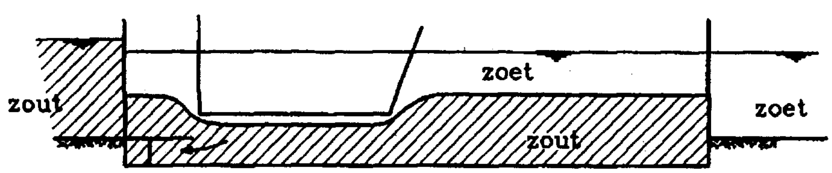


Figure A20 Drainage of salt water during downward exchange of salt and fresh water, system 1 (Rijkswaterstaat, 2000).

The subsequent steps of the lockage process are shown in Figure A21 (left figures: sea level > canal level, right figures: sea level < canal level).

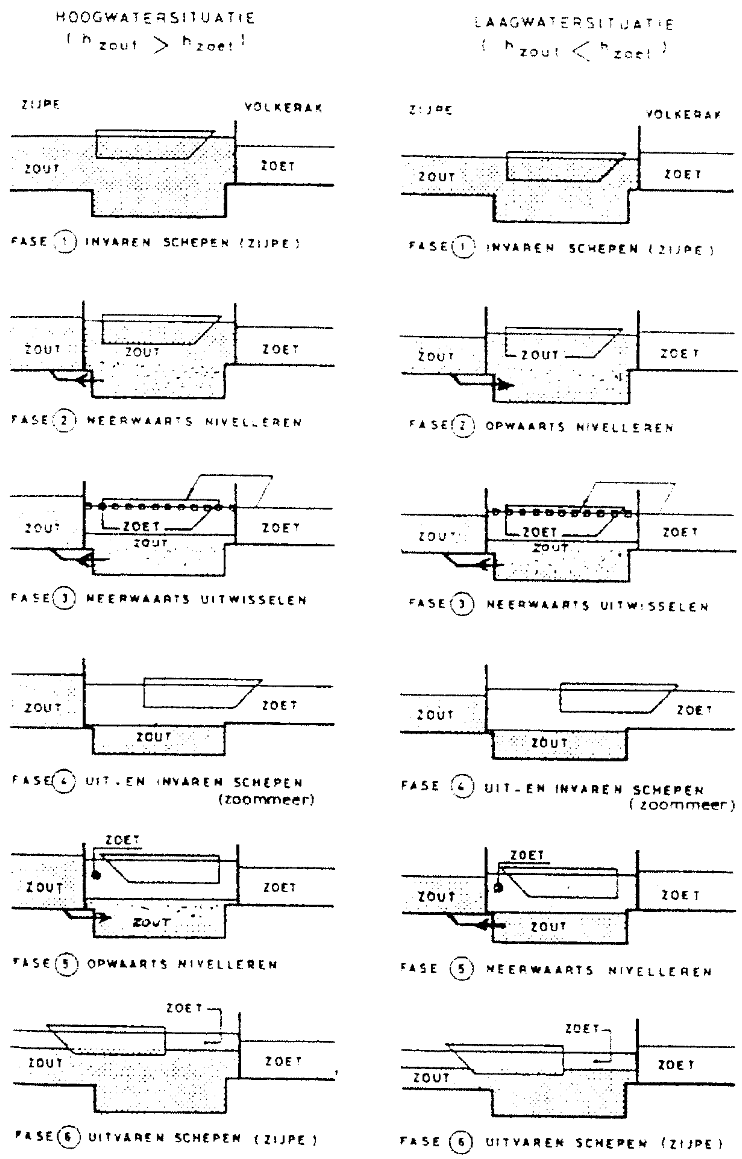


Figure A21 Lockage steps of the Krammer yacht locks, system 1 (Rijkswaterstaat, 2000).

In order to prevent a strong blending at the salt water - fresh water interface the velocity of the salt water flowing in longitudinal direction must be small. For that reason the floor of the lock chamber is designed at a much lower elevation than the bottom of the salt tailbay (this provides a deep lock chamber basin and facilitates small longitudinal flow velocities). The process of transverse inflow of fresh water near the water surface should also be carried out with care (initially a low flow velocity is required).

System 2: Longitudinal inflow of fresh water and transverse outflow of salt water (Hansweert / Bergsediep locks)

In this system fresh water is supplied through openings in the landside gates; an adjustable sill in front of these openings (see Figure A22) is used to spread and regulate the inflow of fresh water. The fresh water flow forms an internal wave that moves in longitudinal direction of the lock. The drainage of salt water occurs through openings in one of the lock walls, close to the floor of the lock. The flow of salt water mainly occurs in transverse direction of the lock. In the seaside gates normal openings have been constructed for levelling.

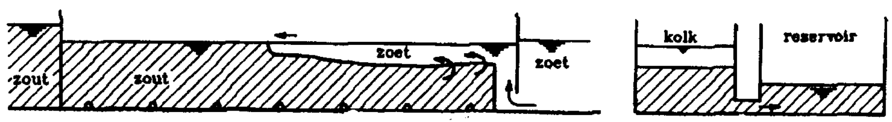


Figure A22 Schematised longitudinal and perpendicular cross-section Bergsediep lock, System 2 (Rijkswaterstaat, 2000).

The salt water is drained through the openings in the lock wall into a reservoir that has been constructed beside the lock. This reservoir has a volume that is equal to the lock chamber volume, and has also an equal floor elevation. The water from the reservoir is pumped continuously at low speed towards the salt tailbay. The system is controlled with valves in the lock wall openings.

Comparison of systems 1 and 2

The characteristic properties and the differences between the systems 1 and 2 can be summarized as follows:

- Both systems result in a large reduction of the salt water intrusion in the landside forebay. Measurements have shown that system 2 facilitates a reduction of the salt water intrusion up to about 80% at a fresh water loss of 100% of the lock chamber volume. Although the reduction of the salt water intrusion is smaller than obtained with the Krammer lock system (see Section A4.1), systems 1 and 2 are less complicated.
- When a large ship blocks the longitudinal flow in the lock chamber it will have a negative impact on the reduction of the salt water intrusion. This is especially true for system 2 (longitudinal inflow of fresh water). In the Netherlands systems 1 and 2 are used for recreational boats only. In that case blockage rarely occurs.
- Both systems are only effective if the lock is not too long.
- System 1 causes transverse forces on the ship and system 2 longitudinal forces. Moored ships can better be handled in case of longitudinal forces than in case of transverse forces. This implies that exchange flow velocities can be higher in system 2 than in system 1, which results in shorter lockage times with system 2.
- The lay out and operation of system 2 is, generally, less complex than that of system 1. System 2 has been installed in the existing Bergsediep lock; this was not possible with system 1.

Lock systems with a longitudinal inflow of water are generally not suited for locks that handle big seagoing ships.

A4.3 Systems with the salt water in a separate part of the lock chamber

The salt intrusion mitigation system in which the salt water is kept in a separate part of the lock chamber, has been developed starting from the design demands: (i) minimize the salt water intrusion and (ii) simultaneously minimize the loss of fresh water. The system was developed for a fairway crossing of a dam that separates salt water and fresh water (Netherlands). The system has not been applied in prototype.

The first idea was to construct a lock with a height that was twice the normal height and a fixed sill in the middle of the chamber (see Figure A23). Salt water is present at the seaside of the sill, below the crest level of the sill. Fresh water is present in the other lock compartment. By pumping additional fresh water into the fresh water compartment, the fresh water level rises above the sill, flows over the sill and forms as a fresh water layer on top of the salt water. When, initially, a ship is in the salt water compartment ('uplockage') it is lifted and can, after some time, sail from the salt water compartment to the fresh water compartment. The fresh water is now drained and the water in the fresh-water compartment is levelled with the water of the landside forebay. In the 'downlockage' operation the reverse sequence is followed. The relative high construction costs and the huge amount of water to be pumped during each lockage, in combination with the long lockage time has led to the abandonment of this idea.

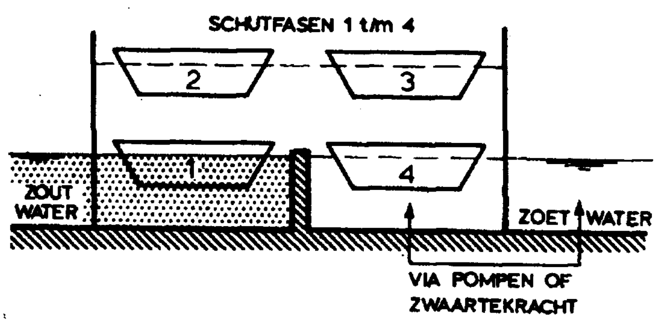


Figure A23 Lock with a high mid-chamber sill (Van der Kuur, 1985).

From this idea the salt lift trough has been developed. In this system a trough with salt water is moved in vertical direction in a lock that is filled with fresh water, see Figure A24. The lock chamber is deepened so that the entire salt trough can be lowered below the sill of the lock. The lock is wider than the salt trough, which enables the flow of fresh water over the sides of the salt trough during vertical movement of the trough. The length of the salt trough is equal to the lock chamber length.

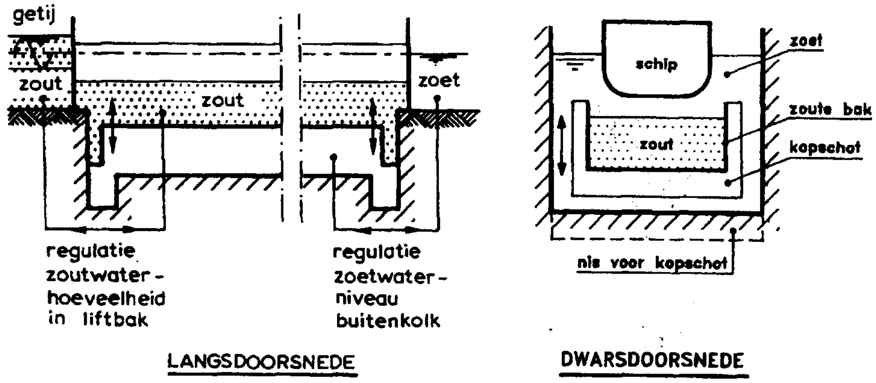


Figure A24 Longitudinal and perpendicular cross-section of salt lift trough (Rijkswaterstaat, 2000).

The different phases of the operation of a lock with a salt lift trough are presented in Figure A25. From the hydraulic point of view it can be seen that the action of the salt lift trough system is very similar to the system with the fixed salt compartment. Instead of the fresh water compartment the salt water compartment is active.

The fresh water can be pumped or drained by gravity to or from the landside forebay, when levelling. The volume of salt water in the salt lift trough is variable as this depends on the size of the ship. This variability should be adjusted by pumping salt water from the seaside forebay to the salt lift trough (or the other way around).

Some blending of salt and fresh water occurs when vessels move over the salt-fresh water interface. Additional blending occurs during the vertical movement of the salt lift trough. The ship will experience transverse forces in the case that it is asymmetrical positioned in the salt lift trough.

This system can at this moment be considered as the most efficient system to prevent salt intrusion. It hardly requires extra lockage time. With the salt lift through system salt penetration percentages are expected to be very low. These estimations were assessed on the basis of results of computations and studies conducted in a scale model. The system has never been realised due to high construction costs.

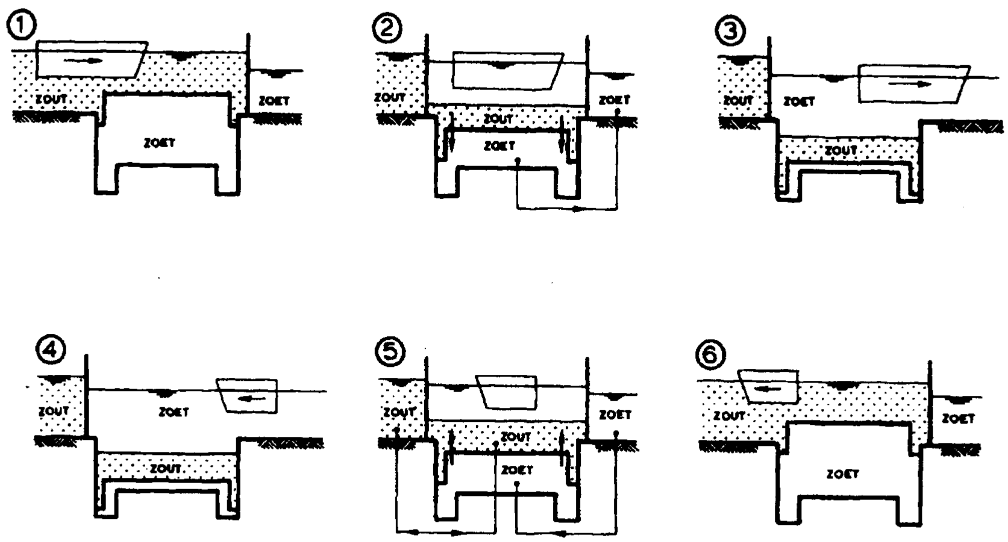


Figure A25 Operation of a lock with salt lift trough system (Van der Kuur, 1985).

A5 Efficiency of different mitigation systems

Kolkman (1986) and Kerstma et al (1994) compared the efficiency of different systems to mitigate the intrusion of salt water at navigation locks in delta areas. These systems have been developed for single-lift locks; tidal fluctuations occur and are the reason that the sea water level can temporarily be higher than the canal water level.
The comparison is based on 1) the amount of additional fresh water that is lost during each lockage cycle (additional to the normal lockage losses) and 2) the salt water intrusion per lockage cycle expressed as a percentage of the lock chamber volume. The comparison is presented in Figure A26. The following practical conclusions can be drawn:

- If no fresh water is available to repel salt-water intrusion, air bubble screens combined with an optimal operation of the locks may be the first option.
- If a high reduction of the salt water intrusion is needed, and little fresh water is available, then a system that replaces the salt water in the lock chamber with fresh water in the phase that the gates are closed, or a system comparable with a salt lift trough system, may be a good, but expensive option.
- When adequate fresh water volumes are available good results can be obtained by draining the salt water tongue after it has entered the canal (system Terneuzen).

These conclusions are valid for delta areas with relative small water level difference between sea and canal (up to about 5 m), and tidal fluctuations which may exceed the canal water level. The systems can also be applied to multiple lift locks or high-head locks, but a further study is needed into the perfomance under these different conditions.

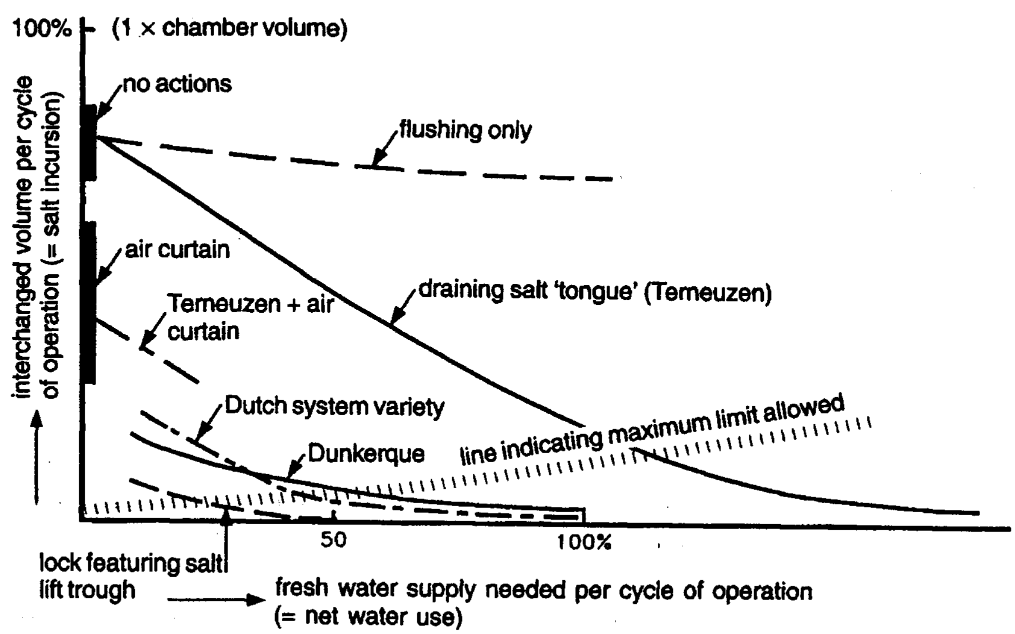


Figure A26 Quality comparison of the various systems (Kerstema et al., 1994).

Literature

Abraham, G., 1976. Density currents due to differences in salinity. Rijkswaterstaat Communications no. 26, Delft Hydraulics Publication No. 169b.

Abraham, G., 1972. Theoretical considerations on salt mitigation at ship locks by air curtains (in Dutch). De Ingenieur, 84, March 1972, number 2. Delft Hydraulics Publication No. 138N.

Abraham, G., and P. van der Burgh, 1964. Pneumatic reduction of salt intrusion through locks. Journal of Hydraulics Division, ASCE, Vol. 90, No. HY1, 83-119. Delft Hydraulics Publication No. 28.

Abraham, G., Van der Burgh, P., and P. Vos, 1973. Pneumatic barriers to reduce salt intrusion through locks, Rijkswaterstaat Communications No. 17. Delft Hydraulics Publication No. 126.

Abraham, G., Van der Burgh, P., and P. Vos, 1975. Pneumatic barriers to reduce salt intrusion through locks. Land and Water International. No. 27, pp. 14-27.

Abraham, G., and P. van der Burgh, 1962. Reduction of salt water intrusion through locks by pneumatic barriers. Delft Hydraulics Publication No. 28.

Abraham, G., Van der Burgh, P., and P. Vos, 1965. Means to reduce salt intrusion through new and existing locks. Delft Hydraulics Publication No. 38.

Abraham, G, Jong, P. De, and F.E. van Kruiningen, 1986. Large-scale mixing processes in a partly mixed estuary. Physics of Shallow Estuaries and Bays, Lecture notes on Coastal and Estuarine Studies Vol. 16, ed. Springer, Berlin.

Batterink, L. and T.J. Boon, 1986, The compartmentalisation dams - How the barrier helps work wonders. Dredging and port construction, Vol. 13, no.9, pp.43, 45-46.

Blumenthal, K.P., et al., 1976. Salt distribution in estuaries. Rijkswaterstaat Communications no. 26, Delft Hydraulics Publication No. 169.

Bogess, D.H., 1968. A test of flushing procedures to control salt-water intrusion at the W.P. Franklin Dam near Ft. Myers, Florida.

Bogess, D.H. and H. Durward, 1970. A test of flushing procedures to control salt-water intrusion at the W.P. Franklin Dam near Ft. Myers, Florida. Florida Bureau of Geology, Information Circular No. 62, Part 1, pp. 1-15.

Burgh, van der, P., 1967. De ontzilting van diepe putten. Rijkswaterstaat, Deltadienst.

Burgh, van der, P., 1965. Salz- und Schlickbekämpfung mit druckluft in den Niederlanden. Deutsche Gewässerkundlichen Mitteilungen, Sonderheft, S., pp. 8-16.

Burgh, van der, P., 1964. Reduction of salt water intrusion through locks by pneumatic barriers. Int. Abwasser Konferenz, Tokio, paper 16.

Burgh, van der, P., 1963. Zoutbestrijding bij de schutsluis in de Haringvlietdam. Rijkswaterstaat, Deltadienst.

Burgh, van der, P., 1963. Zoutbezwaar van schutsluizen te Terneuzen. Rijkswaterstaat, Dienst voor de Waterhuishouding.

Burgh, van der, P., 1963. Het effekt van kunstmatig beluchten van oppervlaktewater. Rijkswaterstaat, Dienst voor de Waterhuishouding.

Burgh, P. van der, 1962. Zoutbestrijding door luchtschermen. Proeven in de grote schutsluis te Kornwerderzand. Rijkswaterstaat, Dienst voor de Waterhuishouding.

Burgh, P. van der, 1961. Zoutbestrijding door luchtschermen. Proeven in de middensluis te Middelburg. Rijkswaterstaat, Dienst voor de Waterhuishouding.

Burgh, P. van der, 1959. Proeven met betrekking tot de zoutbestrijding in het Kanaal door Voorne. Rijkswaterstaat, Dienst voor de Waterhuishouding.

Burgh, P. van der, 1958. Proeven inzake de zoutbestrijding door middel van samengeperste lucht. Rijkswaterstaat, Dienst voor de Waterhuishouding.

Burgh, P. van der, and P. de Vos, 1962. Luchtbellenschermen in schutsluizen. Rijkswaterstaat.

Burgh, P. van der, and P. de Vos, 1961. Zoutbestrijding door luchtschermen. Proeven in de middensluis te Middelburg. Rijkswaterstaat, Dienst voor de Waterhuishouding.

Cole, T.M. and E.M. Buchak, 1995. CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model, Version 2.0 User Manual. Draft Instruction Report, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Committee on Tidal Hydraulics, 1963. Salt water intrusion lake Washington ship canal, Seattle, WA, U.S. Army Corps of Engineers.

Davies, P.A., Charlton, J.A. and G.H.M. Bethune, 1988. A laboratory study of primary saline intrusion in a circular pipe. Journal of hydraulic research, IAHR, Vol. 26, no.1, 1988, pp.33-48.

Delft Hydraulics, 1970. Zoutbestrijding door uitwisseling bij gesloten deuren. Delft Hydraulics Report S57.

Delft Hydraulics, 1963. Zoutbezwaar bij schutsluizen aan zee. Oorzaken en mogelijke bestrijdingswijzen. Delft Hydraulics report M 0772 A.

Ding Xingrui, and Zhou HuaXing, 1988. Design and test of the salt prevention system at Haihe lock, Technical report No. 3, Tinjan Research Institute of Water Transport Engineering, Tinjan, China.

Ding Xingrui, and Zhou HuaXing, 1987. Design and test of the salt prevention system at Haihe lock. Port Engineering in Developing Countries, Second International Conference, Beijing, China, September 7-11, 1987, Vol. II, pp.1739-1744.

Dock and Harbor Authority, 1999. Shiplift and transfer systems, Vol. 79, January/February, No. 893, p. 213.

Elzerman, J.J., 1954. Het "zoutscherm" als middel tot ontzilting van het Noordzeekanaal. IJmuiden. Rijkswaterstaat, Arr. Noordzeekanaal.

Engineering Hydraulics Incorporated , 1987. Feasibility study of a pneumatic salinity barrier for structure 21A-canal 102 : phase 1 monitoring report.

Environmental and Hydraulics Laboratory, 1986. CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model, User Manual. Draft Instruction Report E-86-5, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Eysink, W.D., 1973. Dealing with the design of outlet works for cooling water and waste water, abatement of salt intrusion by proper design of shiplocks, design of inlet works for cooling water. Conference on Hydraulics serving the industry and the environment, May 24-25, 1973, Paper no.11, 23 pp., Delft, The Netherlands., Delft Hydraulics Publication No. 110N.

Glerum, A. and A. Vrijburgt, 2000. Design of Navigation Locks (in Dutch.), Part I and II. Ministry of Transport, Public Works and Water Management. Bouwdienst.

Haan, F.S., de, 1992. Zout/zoet-scheidingssysteem Bergsediepsluis. Programma van eisen. Rijkswaterstaat, BDS.A-R-91015.

Hillen, J.G., Ockhuysen, C.P., and P. Kuur, 1984. The technical and economic aspects of the water separation system of the Krammer locks. Water Science Technology, Rotterdam, Vol. 16, 131-140.

Jianqiu, G., Senpei, L. and T. Yunfang, 1987. Sea lock with a membrane to reduce salt water intrusion and save fresh water. Port Engineering in Developing Countries, Second Int. Conf., (Beijing, China: Sep. 7-11, 1987), Vol.II, Nanjing, China, China Ocean Press, 1987, Group F, p.1807-1812.

Kerstma, J., Kolkman, P.A., Regeling, H.J., and W.A. Venis, 1994. Water quality control at ship locks. Prevention of salt- and fresh water exchange, A.A. Balkema, Rotterdam

Kerstma, J., Kolkman, P.A., Regeling, H.J., and W.A. Venis,1991: Zout-zoetscheiding bij schutsluizen. Delft Hydraulics, Rijkswaterstaat DWW. Deel A en B.

Keulegan, G.H., 1957. An experimental study of the motion of saline water from locks into fresh water channels. Thirteenth progress report on model laws for density currents, National Bureau of Standards, Report No. 5168.

Keulegan, G.H., 1966. The mechanism of an arrested saline wedge, Chapter 11 in Estuary and Costline Hydrodynamics, A.T. Ippen, ed. McGraw Hill Inc.

Kiamco, C. 1999. Note on saltwater intrusion, Panama Canal Commission, unpublished manuscript.

Kolkman, P.A., 1986. Methods employed to limit saltwater-freshwater exchange in locks. Delft Hydraulics Publication No. 364.

Kolkman, P.A., 1982. Salt-fresh water interchange at ship locks (in Dutch). Polytechnisch Tijdschrift, civiele techniek 37 (2) and (3).

Kolkman, P.A., 1976. The use of hydraulic models for the study of salt-fresh water currents in aid of measures to prevent salt water penetration. Rijkswaterstaat Communications no. 26, Delft Hydraulics Publication No. 169e.

Kolkman, P.A., 1973. Low-head navigation lock, door filling and emptying systems developed by hydraulic investigations. Land and Water Int. 193, No. 16.

Kolkman, P.A. and J.C. Slagter, 1976. The Kreekrak locks on the Scheldt-Rhine Connection. Rijkswaterstaat Communication No. 24, Delft Hydraulics Publication No. 160.

Kraaijenbrink, B.H., 1966. Resultaten van een proef inzake de kunstmatige ontzilting van een diepe stroomgeul in het Veerse Meer. Rijkswaterstaat, Deltadienst.

Kuur, van der, P., 1985. Locks with devices to reduce salt intrusion. Journal for Waterway, Port Coastal, Ocean Engineering, Proceedings of the American Society of Civil Engineers, Vol. 111, No. 6, 1009-1021.

Lesleighter, B.E., 1962. Salt water intrusions and the use of pneumatic of similar barriers with special application to Newcastle harbour. Manly Vale New South Wales Department of Public Works, Harbours and Rivers Branch.

Long, G.L., Eiland, R.G., and L.A. Mullnix, 1957. Occurrence and control of salt intrusion through navigation locks, U.S. Army Committee on Tidal Hydraulics, Paper presented at the ASCE Jackson Convention, February 1957.

Mausshardt, Sherill, and Singleton, Glen., 1995. Mitigation of salt-water intrusion through Hiram M. Chittenden Locks, Journal of Waterway. Port, Coastal, and Ocean Engineering, American Society of Civil Engineers, July/August 1995. Vol. 121, No. 4, pp. 224-227.

Monadier, P., 1981. Probleme de la remontee des eaux par les ecluses miritimes, example de l'ecluse de Mardyck a Dunekerque. La Huille Blanche, Vol. 36/2-3, 121-127.

Ockhuysen, C.P., 1983. A mathematical advection-dispersion model to optimize the freshwater and salt-water intrusion due to the exchange in navigation locks. Proc. XX IAHR Congress, Moscow, September 5-9, 1983, Vol. 5, pp. 431-439.

Parchure, T.M., S.C. Wilhelms, Soraya Saruff, W.H. McAnally, 2000. Salinity intrusion in the Panama Canal. US Army Corps of Engineers, ERDC – Coastal and Hydraulics Division, February 2000

PIANC, 1982. Final report of the international commission for the study of locks, Salt water penetration control devices. Permanent International Association of Navigation Congress (PIANC), Supplement Bulletin No. 55, Chapter 12, p. 366-375.

PIANC, 1993. Problems created by saltwater infiltration. Permanent International Association of Navigation Congress (PIANC), Report of working group No. 6, Supplement to Bulletin No. 80.

Postma, R., 1991. Maatregelen ter bestrijding van de zoutlast van de Bergsediepsluis. Rijkswaterstaat, AX 91.043.

Ribes, G., and C. Blanchet, 1965. Les courants de densitee et le project de l'ecluse de Mardyck a Dunqerque. La Houlle Blanche, 20:48.

Roelfsema, A., 1991. Guidelines on the study of seawater intrusion into rivers. UNESCO, IHP-III project, 4.4.b, Paris, France.

Roelfsema, A., 1980. Salt intrusion in canals through ship locks. 2nd International Symposium on Stratified Flows. Trondheim, June 24-27, 1980, pp. 553-561.

Roelfsema, A., and A.G. van Os, 1978. Effect of harbours on salt intrusion in estuaries. 16th Int. Conf. on Coastal Eng., Hamburg. Delft Hydraulics Publication No. 204.

Rijkswaterstaat, 2000. Ontwerp van schutsluizen (Design of shipping locks, in Dutch). Rijkswaterstaat, Bouwdienst.

Rijkswaterstaat, 1989. Results of the prototype salinity measurements near the Krammer locks (in Dutch). Rijkswaterstaat, Directie Zeeland, Memo (Nota) ZLMD-89.N.090.

Rijkswaterstaat, 1988. Evaulation of desalinization, period 17 april 1987 until 1 February 1988 (in Dutch). Rijkswaterstaat, Directie Zeeland, Memo (Nota) AX 88.120, August 1988.

Rijkswaterstaat, 1964. Combating salt intrusion by air curtains in the shipping locks of IJmuiden, the Netherlands. (Zoutbestrijding door luchtschermen in de sluizen te IJmuiden). Rijkswaterstaat / Directie Noord Holland / Arrondissement Noordzeekanaal.

Schonfeld, J.C., 1952. Zoutbezwaar van een zeesluis. Rijkswaterstaat, Centrale Studiedienst.

Schultz, E.A. and Simmons, H.B., 1957. Fresh water-salt water density currents. a major cause of siltation in estuaries. USACE, Committee on Tidal Hydraulics, Technical bulletin, no. 2.

Shabrin, A.N., 1975. Interchange of water of different densities through a navigation lock. <Journal title> ,Vol. 8, PP. 37-40.

Thabet, R.A.H., Verboom, G.K. and G.J. Akkerman, 1985. Two-dimensional modelling of tidal motion for harbour studies. Delft Hydraulics Publication No. 344.

Tran, D. and J.L. Merveille, 1986. Problemes de penetration des eaux sales dans les voies d'eau interieures, PIANC Bulletin No. 53, 79-95.

Uwland, J., Kolkman, P.A., and K.W. Pilarczyk, 1985. Prototype measurements on discharge sluices in the Netherlands. Contribution to the 21st Congress IAHR, Aug. 1985, Melbourne, Australia.

Vrijburcht, A., 1991. Vertical motions of ships sailing into or out of locks and the related water motions. Delft Hydraulics Publication No. 461.

Vrijburcht, A., 1991. Forces on ships in a navigation lock induced by stratified flow. DSc. Thesis, Delft University of Technology, Delft Hydraulics Publication No. 448.

Ward, G.H., 1983. The effect of deepdraft ship channels on salinity intrusion in shallow bays. Ports 83, Speciality Conference on Port Modernization, Upgrading and Repairs, New Orleans, U.S.A., March 21-23, 1983. In: Wong, K. 1983, New York, U.S.A., ASCE, 1983, Session 16, p.532-542.

Delft Hydraulics, 1993. Besturing zoutbestrijding-systeem Bergsediepsluis. Delft Hydraulics Report Q1595.

Delft Hydraulics, 1992. Zoutbestrijding-systeem Bergsediepsluis. Delft Hydraulics Report Q1472.

Delft Hydraulics, 1989. Onderzoek naar zoutbestrijding volgens systeem Duinkerken. Delft Hydraulics Report Q281.2.

Delft Hydraulics, 1988. Onderzoek naar het zoutbestrijdingssysteem volgens het systeem Terneuzen. Delft Hydraulics Report Q281.

Delft Hydraulics, 1988. Onderzoek naar zoutbestrijding volgens systeem Terneuzen (in Dutch). Delft Hydraulics Report R1860.

Delft Hydraulics, 1988. Prototypemetingen Krammer- en Kreekraksluizen 1986-1988, measurement series 2000 and 3000 (in Dutch). Delft Hydraulics Report Q373, Part IV.

Delft Hydraulics, 1988. Prototypemetingen Krammer- en Kreekraksluizen 1986-1988 (in Dutch). Delft Hydraulics Report Q373, Part V.

Delft Hydraulics, 1986. Zout / zoetscheidingssystemen bij schutsluizen. Delft Hydraulics Report R1860.

Delft Hydraulics, 1982. Duwvaartsluizen in de Philipsdam. Twee-dimensionaal onderzoek naar menging en zout-zoet verliezen (in Dutch). Deel II. Delft Hydraulics Report M1529.

Delft Hydraulics, 1982. Philipsdam yacht locks. Analyses of the flow in the culvert during different phasis of the lockage (in Dutch). Delft Hydraulics Report R1650-3.

Delft Hydraulics, 1981. Duwvaartsluizen in de Philipsdam. Twee-dimensionaal onderzoek naar menging en zout-zoet verliezen (in Dutch). Deel I. Delft Hydraulics Report M1529.

Delft Hydraulics, 1979. Duwvaartsluizen in de Philipsdam. Twee-dimensionaal onderzoek vormgeving kolkwand (in Dutch). Deel II. Delft Hydraulics Report M1431.

Delft Hydraulics, 1977. Duwvaartsluizen in de Philipsdam. Twee-dimensionaal onderzoek vormgeving kolkwand (in Dutch). Deel I. Delft Hydraulics Report M1431.

Delft Hydraulics, 1977. Zoutbestrijding Volkerak schutsluizen. Vooronderzoek. Delft Hydraulics Report M1432.

Delft Hydraulics, 1974. Theoretische beschouwingen over zoutbestrijding bij schutsluizen door luchtbellengordijnen. Delft Hydraulics Report

Delft Hydraulics, 1973. Outlet sluice Noordland in the Eastern Scheldt barrage (in Dutch). Report M1204.

Delft Hydraulics, 1972. Zoutbestrijding schutsluizen Hansweert. Modelonderzoek over zoutbestrijding volgens systeem met uitwisseling bij gesloten deuren en in langsrichting van de sluis. Delft Hydraulics Report M1128.

Delft Hydraulics, 1967. Zoutbestrijding Kreekraksluizen (in Dutch). Delft Hydraulics Report M865.

Delft Hydraulics, 1960. Theoretische beschouwingen over invloed van luchtbellengordijn op voortplantingssnelheid van zouttong. Delft Hydraulics Report M703.

Whitehead R.H., 1915. Hydraulics of the locks of the Panama Canal. Engineering Congress, held in San Francisco, CA, USA.

Zhou HuaXing, Wang Bingzhe, Zhang Furan, and Sun Yuping, 1989. A study on the lock with the exchange system to reduce salt-water intrusion, Technical Report No. 13, Tianjin Research Institute of Water Transport Engineering, Tianjin, China.

Appendix B: Pneumatic barriers to reduce salt intrusion through locks

RIJKSWATERSTAAT COMMUNICATIONS

PNEUMATIC BARRIERS TO REDUCE SALT INTRUSION THROUGH LOCKS

by

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The views in this article are the authors' own.

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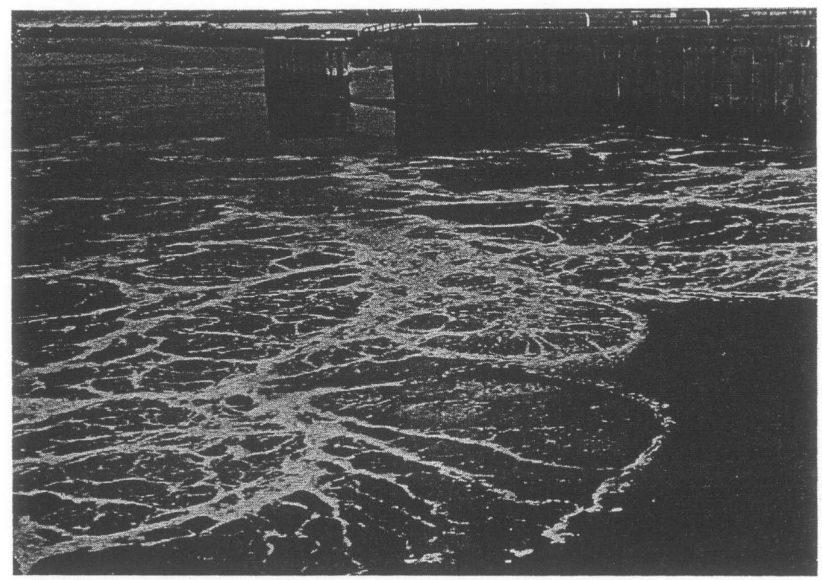


Photograph 1. Northern Lock, IJmuiden; seaward gate; pneumatic barrier

Photograph 2. Northern Lock, IJmuiden; ore-carrier 'CETRA CARINA', 73,700 DWT, puts into port and crosses pneumatic barrier near seaward gate

1. Introduction

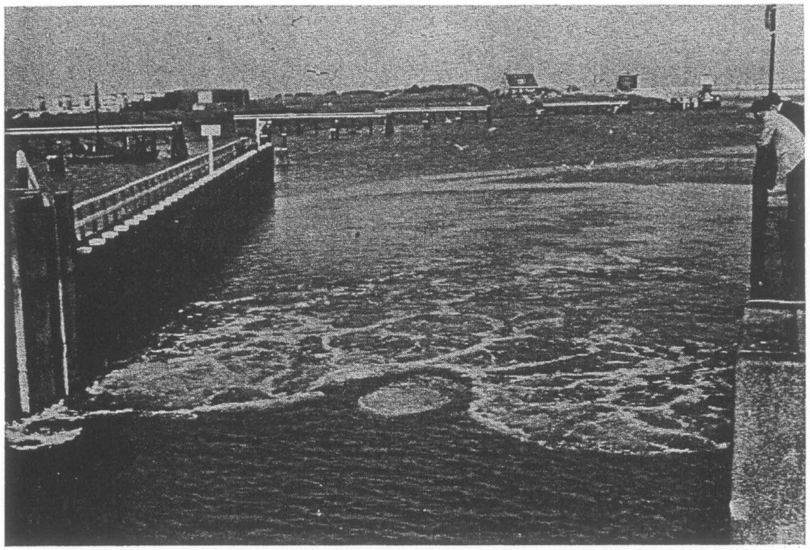
Extensive areas in the low-lying parts of the Netherlands are below average sea level. They are divided up into polders in which the water levels are controlled by pumping. The water that seeps upwards in the soil together with surplus rain water is pumped into canals encircling the polders; the canals are linked and serve as collectors, the water level in most of which are a few decimetres below average sea level. Formerly, the water in the 'collector' canals was discharged into the sea through sluices which were opened for the purpose while the tide was running out. This natural method of getting rid of the surplus water has now been partly replaced by pumping.

The 'collector' canals have always served more than one purpose. Their function as waterways is second only to that of disposing of surplus water. Constant improvement of the drainage side of the system has led to the increased use of the canals as waterways, which in turn has necessitated keeping the water in the canals up to a certain level; to achieve this, the polder water in the canals has to be supplemented from some other source. The increasing density of the population, more intensive use of the soil and industrialisation have been making water management in the 'collector' canal regions an increasingly exacting task in the last few decades. One of the criteria by which the quality of the water in the canals is judged is its salt content. The canal water is in danger of becoming saline because the salt water seeping up through the polder soil is pumped into the canals so that it may run along them into the sea. Salt water also reaches the canals from the sea; it comes in through the locks as ships enter. Any sea water that gets into a canal can spread over a wide area because of the difference between the density of sea water and that of the water pumped from the polders into the canal. The means by which this intrusion of sea water through locks can be controlled and their efficacy are dealt with in this issue. The 'pneumatic barrier' is the chief expedient described.

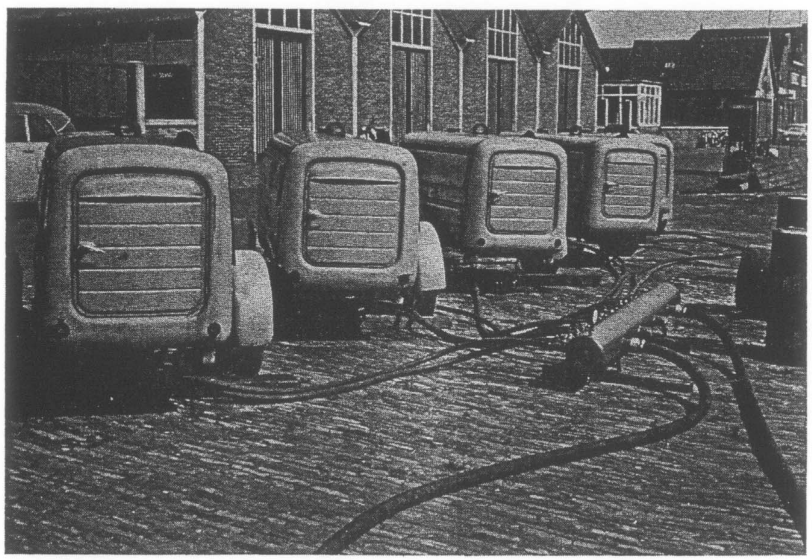
The pneumatic barrier is the outcome of several sets of experiments carried out in locks. The first set was conducted in the middle Lock at IJmuiden in April 1961. The next was carried out in a lock in the Zuyder Zee Barrier Dam at Kornwerderzand in September 1961. Lastly there were experiments in the Southern Lock at IJmuiden, in the middle Lock at IJmuiden a second time and in the Western Lock at Terneuzen.

The experiments were most useful in that they provided material for treatises on the hydrodynamic aspects of pneumatic barriers for locks (see Chapter 6) and on the design criteria (see Chapter 7).

The experience gained with pneumatic barriers at IJmuiden over a period of years is described in Chapter 8.



Photograph 3. Kornwerderzand; seaward gate; experimental pneumatic barrier



Photograph 4. Compressor battery supplying air for pneumatic barrier experiments

2. Salt intrusion through locks in the Netherlands

2.1. History and geography

As early as 1667 Hendric Stevin drew attention to the salinization of the surface water in the low-lying parts of the Netherlands [18]. Stevin regarded the locks between the salt water in the sea and the fresh water inland as the main sources of salt and described how the quantity of salt water intruding during the locking process could be reduced by pumping the water out of the lock chamber. Stevin also proposed that the Zuyder Zee be closed off and that the sea arms in the south-west be dammed off to create large reservoirs containing fresh water. It was not until this century that his ideas were put into effect. Various steps have been taken down the centuries, however, to reduce as much as possible the salt bugbear attaching to locks. Salt-intrusion and wastage of fresh water due to leaks were lessened by taking increasing care to seal the walls of locks and associated structures. Sets of sluices were built next to locks to facilitate discharging the intrusive salt water back into the sea before it could affect the water in the 'collector' canals.
Ships became bigger and the canal locks had to be enlarged to accommodate them. In many instances larger locks were built beside the ones that had become too small so that in many places there are now three or four locks of varying dimensions side by side. The increased size of ships, locks and canals has aggravated the salination problem. It is gradually becoming impossible to draw fresh water for various purposes from the 'collector' canals in many places, whereas the demand for fresh water is constantly increasing. The problem has prompted the search in the last few decades for more effective ways of reducing the salinification hazard at locks and improving the quality of the water in the 'collector' canals.

2.2. Present position

Figure 1 shows the average salinity of the canals in the low-lying parts of the Netherlands at the present time. Although the quantities of salt indicated spring from both the salt seepage pumped up from the polders and the water intruding through the locks, the figure shows clearly that it is near the locks that salinification is greatest. It is often noticeable dozens of miles away from the locks and prevents the canal water from being utilised for a number of purposes over a wide area.

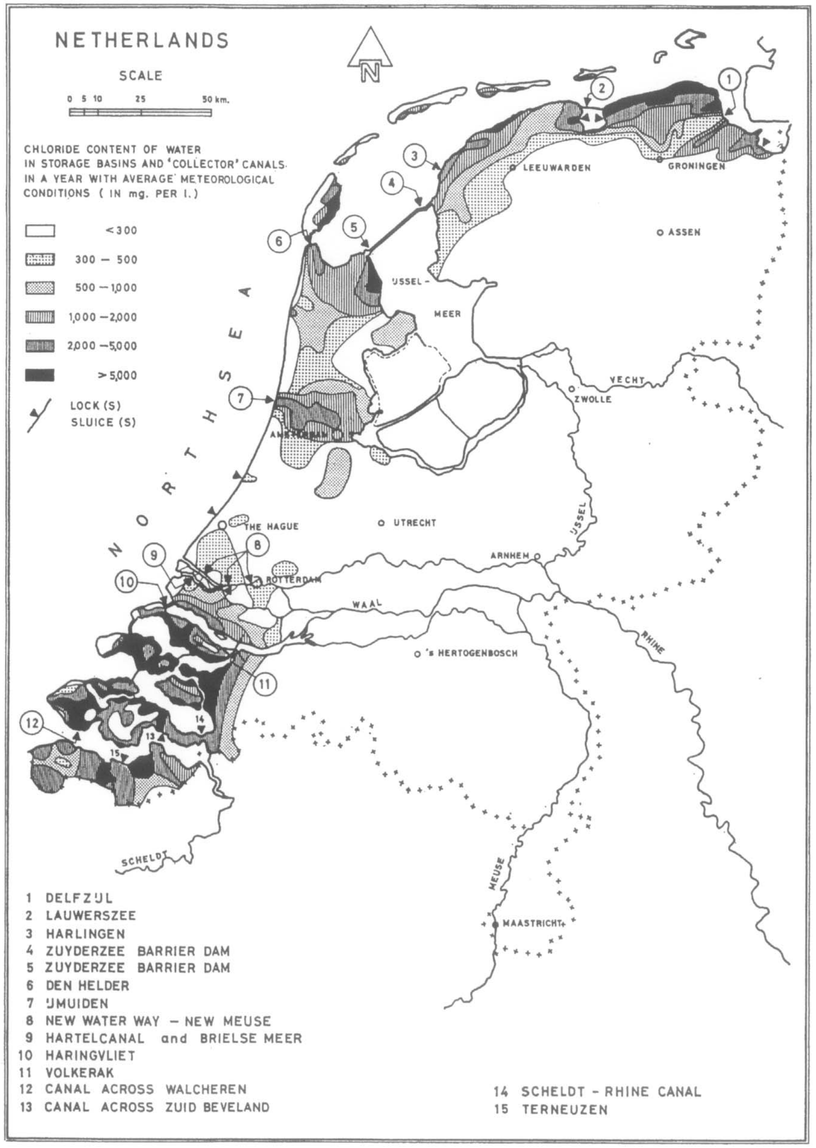


Figure 1. Chloride content of water in 'collector' canals in the Netherlands and location of locks

3. Mechanism of salt intrusion through locks

3.1. Salt intrusion due to equalization of levels

If the water level outside a lock is higher than that in the canal when the lock is being used, a quantity of water must inevitably reach the canal from the outside when the levels are equalized and the lock gates are opened.
The quantity of chlorine reaching the canal after each complete locking cycle is

$$A_s \cdot h_s \cdot Cl$$

A_s being the area of the lock chamber, Cl the chlorine content of sea water and h_s the difference between water level on seaward side and that on canal side of lock. No chlorine will reach the canal if the water level outside the lock is lower than that in the canal.

3.2. Salt intrusion due to exchange of salt and fresh water

Figure 2 shows the current pattern produced when lock gates separating salt and fresh water are opened. A tongue of salt water will slip into the fresh water near the bottom and a tongue of fresh water will slide across the salt water near the surface; in effect there will be two currents moving in opposite directions, the one over the other. The fresh water in front of the salt water tongue will be at rest; the salt water in front of the fresh water tongue will also be at rest. A quantity of salt water equal to the volume of the lock chamber can penetrate into the basin filled with fresh water behind a lock bordering on the sea as a consequence of this exchange process if the gates are kept open long enough (see [4] and [5]).
The mechanism occasioning the exchange converts potential energy into kinetic energy; the salt water sinks, raising the fresh water. Water that was at rest is set in motion. A formula for the rate of movement of both the salt water tongue and the fresh water tongue can be obtained by expressing the conversion of energy as an equation.
Assume that the two tongues cover a distance of $L = c \cdot \Delta t$ in a Δt period of time. The potential energy converted into kinetic energy in that time will correspond with the energy released as the salt water sinks from 1 to 4 and the fresh water is raised from 4 to 1. The potential energy, which is converted into kinetic energy, is

$$E_p = \tfrac{1}{4}\, ch^2\, \Delta\varrho\, g\, \Delta t \qquad (1)$$

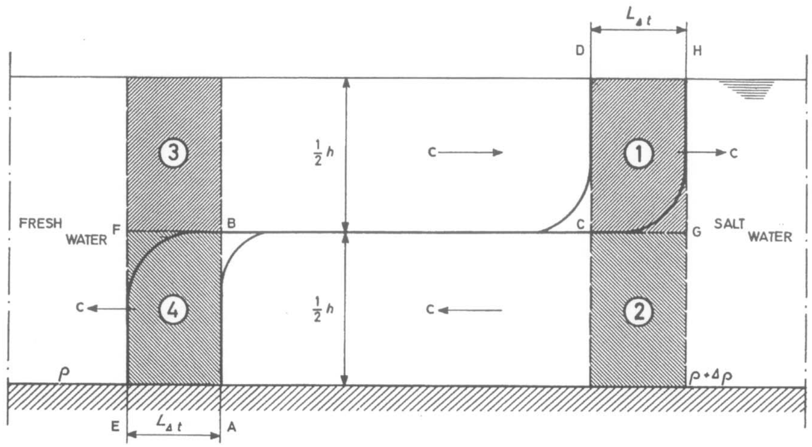


Figure 2. Exchange currents

The kinetic energy released can be arrived at by bearing in mind that water that was originally at rest in positions 1 and 4 starts moving during the Δt period. The following formula emerges:

$$E_k = c^3 h\, \varrho\, \Delta t \tag{2}$$

In formulating equation (2) the density of salt water was in the first instance regarded as being the same as that of fresh water.
In view of the fact that

$$E_p = E_k \tag{3}$$

it follows that

$$c = \tfrac{1}{2}\left(\frac{\Delta\varrho}{\varrho} \cdot g \cdot h\right)^{\frac{1}{2}} \tag{4}$$

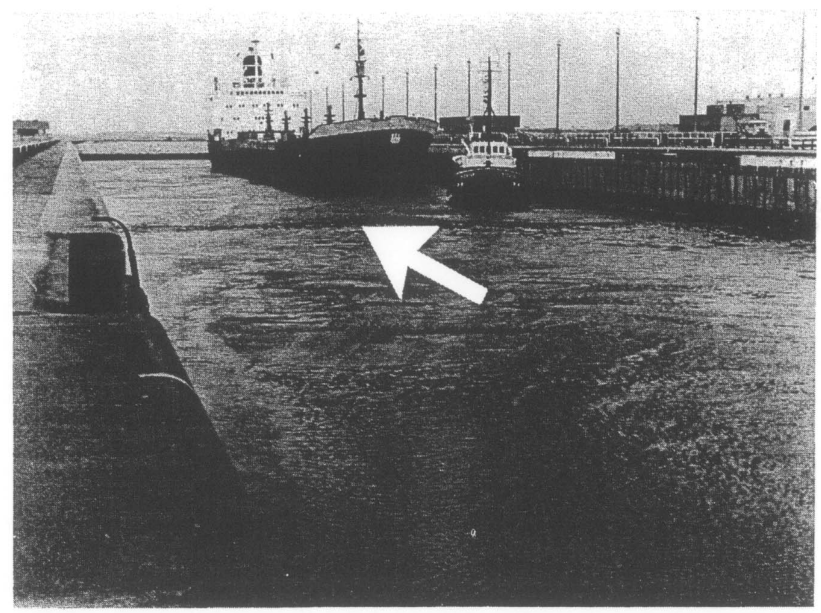
and

$$q_{in,}{}^{0} = \tfrac{1}{4}\left(\frac{\Delta\varrho}{\varrho} \cdot g \cdot h\right)^{\frac{1}{2}} \cdot h \tag{5}$$

Equation (5) gives the quantity of salt water that penetrates into a lock chamber filled with fresh water immediately after the outer gates have been opened. It may not be used after the salt water has rebounded from the inner gates.

3.3. Effect of displacement of ships

The exchange of water in a lock chamber is usually upset by the presence of ships. As they pass in and out, their displacement accounts for a certain volume, so the volume of water contained in the lock chamber without ships does not in its entirety participate in the exchange process.
The effect of shipping on the exchange of water is very complex indeed. It depends not only on the amount of shipping and the shape of the lock chamber but also on the locking process.
The time factor (T) and the presence or absence of a curtain of air bubbles also determine the extent to which shipping upsets the exchange process.
If a lock chamber has to handle a large number of vessels, their effect on the salinization process should be taken into account.



Photograph 5. IJmuiden; Ore-carrier 'ANITA TYSSEN', 15,600 DWT, coming into port through Northern Lock in the days when there were no pneumatic barriers to reduce the exchange between salt and fresh water; the front of the fresh-water coming from the canal advanced almost as far as the tug (see arrow)

4. Ways of reducing salt intrusion through locks

4.1. Flushing canal with fresh water

A repressive method of combating salinization through locks is to flush the 'collector' canal with fresh water in the direction of the sea; this is not very effective, however. The difference in density allows a comparatively large volume of salt water to enter the canal through the lock and a comparatively large volume of fresh water would be required to mix with it and carry it away.
Tests have shown that the dimensions of canals very greatly affect the degree of salt intrusion. A small increase in depth causes a comparatively large rise in the salinity of the water in a canal.

4.2. Pneumatic barriers

Pneumatic barriers are curtains of air bubbles rising from perforated pipes placed on the bottom of a lock chamber perpendicular to the axis of the chamber. The rising bubbles create a vertical current of water which reduces the magnitude of any exchange currents passing over it, provided the volume of air is adequate. Pneumatic barriers reduce salt intrusion caused by density exchange currents. This is important, as salt intrusion is largely due to exchange currents. For further information on pneumatic barriers see Chapters 6 ff.

4.3. Water barriers

Theoretically, a vertical current could also be induced by pumping water, thus creating a water barrier which would also reduce the magnitude of the exchange currents. Initial experiments with this method have been carried out on models.

4.4. Selective withdrawal of salt water during intrusion

The salt water tending to run into the canal when the inner gates of a lock are opened

can be withdrawn and discharged back into the sea during the exchange process through a slot in the bottom of the lock located at the point where the lock meets the adjoining fresh water basin. The volume of fresh water wasted corresponds to the quantity of water withdrawn through the slot. If withdrawal cannot be entirely selective, the amount of fresh water wasted during each complete locking cycle will exceed the volume of the lock chamber.

4.5. Selective withdrawal of salt water after intrusion

This is accomplished in the following manner. The intrusive salt water is collected in a sump of adequate volume made by deepening part of the canal, is selectively withdrawn from it and discharged in a steady stream. The volume of fresh water wasted corresponds to the quantity of water withdrawn from the sump. Since the salt water is diluted as it enters and while it remains in the sump, more fresh water will be wasted than when using the method described in 4.4.
A drawback of this method is that not all the intrusive salt water is trapped in the sump; some of it passes on into the canal and has to be removed by flushing, large volumes of fresh water being required to expel even small quantities of salt water.

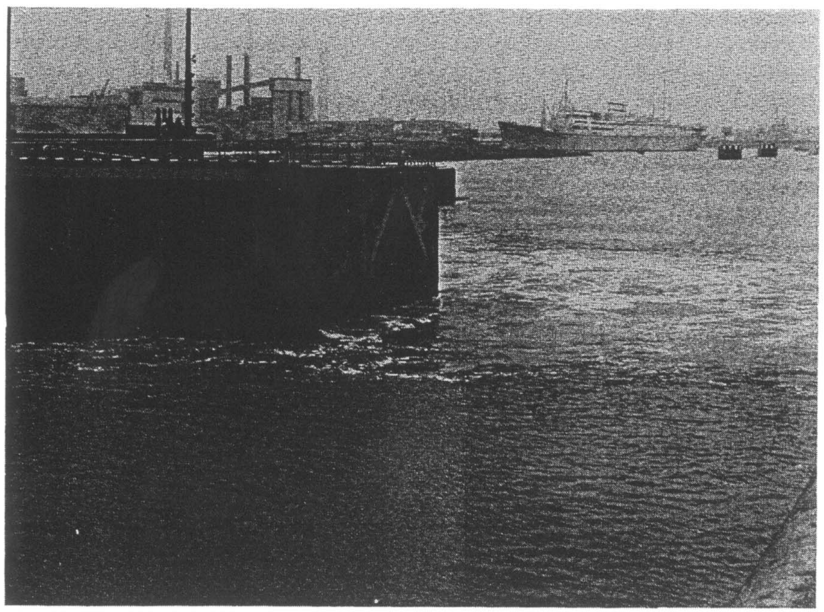
4.6. Equalization by pumping instead of gravity

If there is a considerable difference between average canal level and high water on the seaward side of the lock, salt intrusion can be greatly reduced by pumping the water in the lock chamber referred to in 3.1. back into the sea instead of allowing it to reach the canal. Large-capacity pumps would be required to remove in a short time the large quantities of water in lock chambers having a large area. The pumping capacity required could be reduced by storing the water in a basin between the lock and the sea and artificially keeping the level in the basin lower than that in the lock chamber. This method may be the one to adopt, because there would be more time in which to pump the water out of the basin.

4.7. Exchanging while gates are closed

The salt water can be withdrawn from the lock chamber through orifices near the bottom and replaced by letting fresh water into the chamber through orifices near the surface of the water. Fresh water can be replaced by salt water in like manner, the

salt water being admitted near the bottom and the fresh water being withdrawn near the surface.
If this exchange process is completed before the gates are opened, waters of different density are prevented from meeting, thus obviating exchange currents.
There would be a certain amount of mixing while the exchange is being effected; the vessels in the lock chamber would also cause some fresh water to be wasted due to mixing. The fresh water could be withdrawn and admitted through the wall of the chamber or through the gates at the fresh-water end. Both systems were tested.



Photograph 6. Northern Lock, IJmuiden; landward gate being opened while pneumatic barrier is working

5. Selecting the method

5.1. For existing and projected locks

Existing locks

A method that might be considered for canals linked with existing locks is to flush them daily with copious quantities of fresh water. The quantity of water required to flush wide, deep canals is considerable; it would not always be possible to satisfy the maximum salinity requirements in certain places (see 4.1.). If flushing does not produce the desired result, a stretch of canal close to the lock could be deepened and used as a sump in which the salt water would collect (see 4.5.). A pumping station operating with a deep suction nozzle would withdraw the salt water and pump it into the sea. If necessary, a wall could be built between the pumping station and the sump with orifices near the bottom of the latter. Alternatively, the salt water could be removed by gravity if the water level in the canal were either temporarily or permanently higher than that of the sea.
The quantity of salt water intruding into an existing canal owing to exchange flow caused by differences in density can be reduced by means of an air-bubble curtain placed near the lock gates (see 4.2.). This expedient could be combined with the sump method described above. Whether a single method or a combination of methods is adopted depends on their local feasibility.

Projected locks

Installing water curtain equipment (see 4.3.) in existing locks is hardly feasible because of the size of the pipes required. It is even questionable whether this method would be so much better than the other expedients as to warrant its adoption for new locks. The qualitative control of fresh water is constantly having to be stepped up and it is essential to be economical with fresh water for many reasons. Accordingly, there are three methods in addition to the three already described for existing locks that may be considered for new locks, viz. constructing a sump next to the lock on the landward side from which the intrusive salt water can be selectively withdrawn (see 4.4.) and the two methods by which either the salt water in the lock chamber is replaced by fresh water while the lock gates are closed (see 4.7.) or the water required for equalization is pumped back into the sea (see 4.6.).

5.2. Current practice in the Netherlands

The location of locks between the sea and inland waters is shown in figure 1. The flushing method is used for all locks; water from the canal is flushed through openings placed as low as possible in the lock or sluice structures. The velocity of the current passing through the openings may not exceed a certain figure to ensure that the water discharged will contain the maximum amount of salt. Since the salt water pumped from the polders in various places as well as that coming in through the locks reaches the canals, the fresh water flowing towards the locks also helps to overcome the salinization of the country's water and soil. It should be noted that it will always be necessary to flush the systems with a certain quantity of fresh water, no matter how effective any steps taken to reduce the wastage of fresh water through locks may be.

Air curtain equipment has already been installed in a number of locks and others are to be equipped with the system in the near future. Supplementary systems are being considered for certain locks. The most important locks and the methods being employed in them are described below.

1. DELFZIJL

Salinization of the canals running from the locks is countered by replacing the water in the canals at regular intervals by rainwater and by water drawn from Lake IJssel. The locks are provided with apertures located well below the water line so as to make the replacement process as effective as possible.

2. LAUWERSZEE

Damming off the Lauwerszee has very greatly reduced the salinity of the adjoining parts of the provinces of Friesland and Groningen. Sluices are incorporated in the dam through which excess water may be discharged. Provision has been made for the comparatively small lock to be fitted with air-curtain equipment, if required.

3. HARLINGEN

Salt intrusion through the locks is countered by replacing the water in the canals at regular intervals by rainwater and by water drawn from Lake IJssel. Air-curtain equipment is also used to further reduce salinization.

4 AND 5. ZUYDER ZEE BARRIER DAM

There are locks in the dam beside the two sets of sluices with which the water in Lake IJssel is controlled. Arrangements are being made to equip all the locks with pneumatic barriers.

6. DEN HELDER

Salt intrusion through the three locks and the sea dock lock is countered by replacing the water in the canals at regular intervals by rain water and by water drawn from

Lake IJssel. Arrangements are being made to replace gravity discharge by pumping. A sump is to be built near to the pumping station in which to store the salt water from the locks prior to its being pumped into the sea. The most important lock is equipped with a pneumatic barrier.

7. IJMUIDEN

Salt intrusion through the North Sea Canal is countered by replacing the water at regular intervals by water from the adjoining regions and from Lake IJssel. The four locks are equipped with a pneumatic barrier. Arrangements are being made to install a pumping station to supplement gravity discharge through a sluice. The construction of a deep sump to collect the salt water is also being contemplated together with a salt baffle to maximize the salinity of the water discharged into the sea.

8. NEW WATERWAY – NEW MAAS

There are a number of locks along the New Waterway and the New Maas, both of which are open to the sea. Salt intrusion in the canals running from the locks is countered by replacing the water by rain water and water drawn from the River Rhine. The quantity of river water required could be somewhat reduced by installing pneumatic barriers in the locks but there are as yet no plans to make any such provisions.

9. HARTEL CANAL AND BRIELSE MEER

The Hartel canal is the landward shipping link between Europoort and the Old Maas. There are pneumatic barriers in the two locks that give access to the Old Maas to reduce salinization of the latter. The canal is also flushed with river water which runs out through the locks, which are also equipped with pneumatic barriers.

The Brielse Meer is a fresh-water lake south of the Hartel canal; a lock links it with the Old Maas. The lake must be protected as well as possible against salinization if the salt intrudes beyond the lock when the Rhine is low. Consequently, a great deal has been done to counter salt intrusion at this point. There are two pumps in two culverts by means of which water can be pumped out of the lock chamber. There is air-curtain equipment and a deep sump in the canal next to the lock to which the pumps can be connected to remove any salt water that may get through the lock.

10. HARINGVLIET

The Haringvliet lock is fitted with pneumatic barriers. There are deep culverts in the sluice next to the lock connected with a sump from which any salt water can be withdrawn.

11. VOLKERAK

There are two locks linking the rivers with Zeeuwse Meer. The water south of the dam will be strongly saline until the Eastern Scheldt dam is finally closed in 1978; mean-while, salt intrusion through the locks is being reduced by means of pneumatic barriers.

12. CANAL ACROSS WALCHEREN
Salt intrusion through the locks at Flushing will have to be tackled when the fresh-water lake north of the island is completed in 1978. Experiments are being carried out to discover whether a canal flushing system would be effective or whether the locks will have to be equipped with pneumatic barriers at both ends.

13. CANAL ACROSS SOUTH BEVELAND
For observations on the existing locks see 12. Plans for the rebuilding of the canal and locks are being prepared. A modern system of countering salt intrusion is being considered; the salt water in the lock chambers would be replaced by fresh before opening the gates giving access to the fresh-water lake. The fresh water used would serve to clean the adjoining canal.

14. SCHELDT-RHINE CANAL
Two locks are being incorporated in the canal linking Antwerp with the Rhine. Salt intrusion will be countered by replacing the salt water in the lock chambers by fresh water flowing in through apertures in the walls while the gates are closed. As in the new system described in 13, the fresh water used would serve to clean the adjoining stretch of the fresh-water lake.

15. TERNEUZEN
There are one old and two new locks in the canal between Terneuzen and Gent. Pneumatic barriers reduce salt intrusion through the new inland-waterways lock. A sump has been constructed next to the new sea lock with deep culverts the orifices of which are built into the lock to carry the salt water trapped in the basin towards the sea. The level of the water in the canal is almost always above that of the high tides, so discharge is by gravity. Moreover, salt intrusion is further reduced by means of pneumatic barriers.

Accordingly, one or more locks in seven places in the Netherlands are equipped with pneumatic barriers, viz. at Harlingen, Den Helder, IJmuiden, Hartel canal/Brielse Meer, Haringvliet, Volkerak and Terneuzen.

6. Hydrodynamics of pneumatic barriers

6.1. Pneumatic barrier in homogeneous water

6.1.1. *Analogy with two-dimensional jet*

When air is blown into a body of water through a tube at the bottom perforated at equal distances throughout its length, the air combines with the water above the tube to form a mixture the density of which is lower than that of the surrounding water. This causes the mixture to rise (figure 3). The upward current is maintained because the surrounding water is entrained by it. The process can be compared to the convection currents set up around a central-heating radiator.

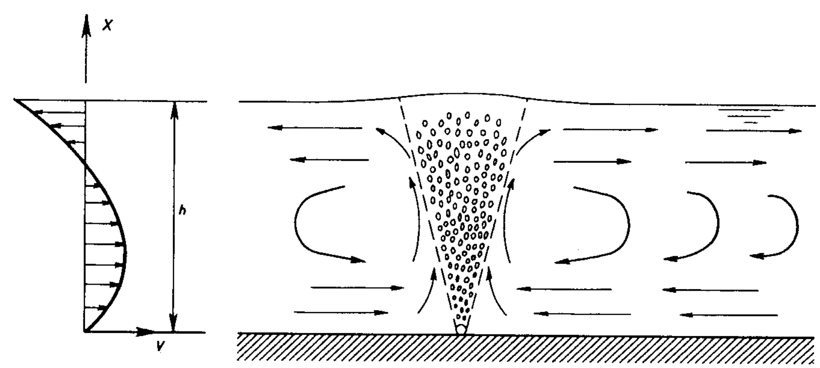


Figure 3. Pneumatic barrier in homogeneous, still water

Most of the air escapes into the atmosphere when the mixture reaches the surface. The water then flows horizontally (figure 3). Tests carried out in water to a depth of about 10 metres have shown that the depth of the horizontal current thus set up is about 1/4 of the total depth and that the velocity of the current increases linearly from zero at the lower boundary to $v_{opp.}$ at the surface. The upward movement of the mixture below the horizontal current may be regarded as being unaffected by the surface. In that zone the movement of the mixture may be looked upon as a two-

dimensional jet with a negligible initial momentum, a phenomenon the theory underlying which is known (see [8], [9] and [10]).
In the light of the underlying theory we may say that both the upward velocity of the water in the mixture and the concentration of air bubbles accords with a Gauss function (figure 4).
This can be expressed as:

$$u = u_m \, e^{-k(y/x)^2} \tag{6}$$

and:

$$n = n_m \, e^{-\mu k(y/x)^2} \tag{7}$$

The number of bubbles n per unit of horizontal area comprises all the bubbles of radius r the centres of which are less than r above or below the horizontal plane. If the bubbles are equally distributed vertically at a certain spot, we count the average area of their intersection by the horizontal plane, which is:

$$\bar{A} = \frac{I}{2r} = \tfrac{2}{3}\pi r^2 \tag{8}$$

6.1.2. *Continuity equation*

The velocity of the air in the air/water mixture is not the same as that of the water. The difference in velocity must be taken into account when we consider the continuity of the flow of air.
By analogy with a two-dimensional jet, the continuity of the flow of air may be expressed as:

$$q_L = 2\int_0^\infty (u + u_{rel.})\, n \, \bar{A} \, dy \tag{9}$$

The term $n\bar{A}$ in equation (9) is the aggregate area of each unit of horizontal area occupied by air.

6.1.3. *Momentum equation*

According to the relevant boundary layer approximations for two-dimensional jets [11], the distribution of pressure within the air/water mixture is the same as that in the surrounding water. In other words, the pressure at level x in the mixture is the same as the hydrostatic pressure at level x next to the mixture. This brings an upward force dK to bear upon the mixture per unit of volume, per unit of horizontal area and per

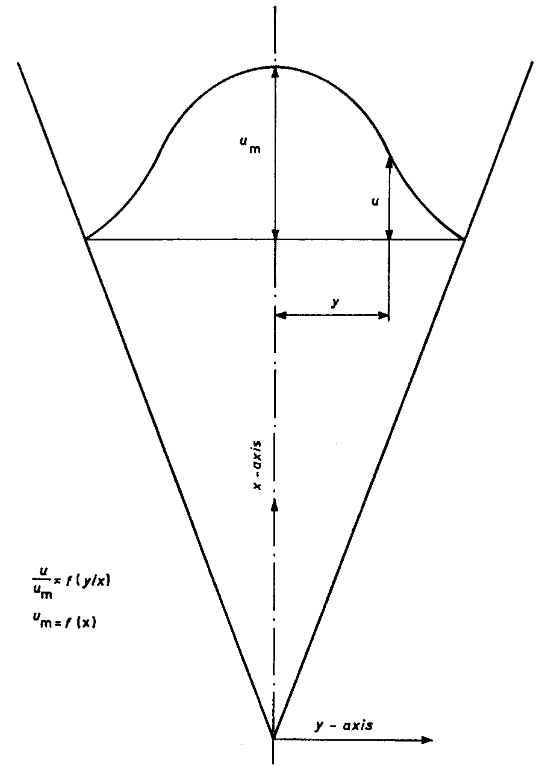


Figure 4. Similarity of velocity distributions within barrier

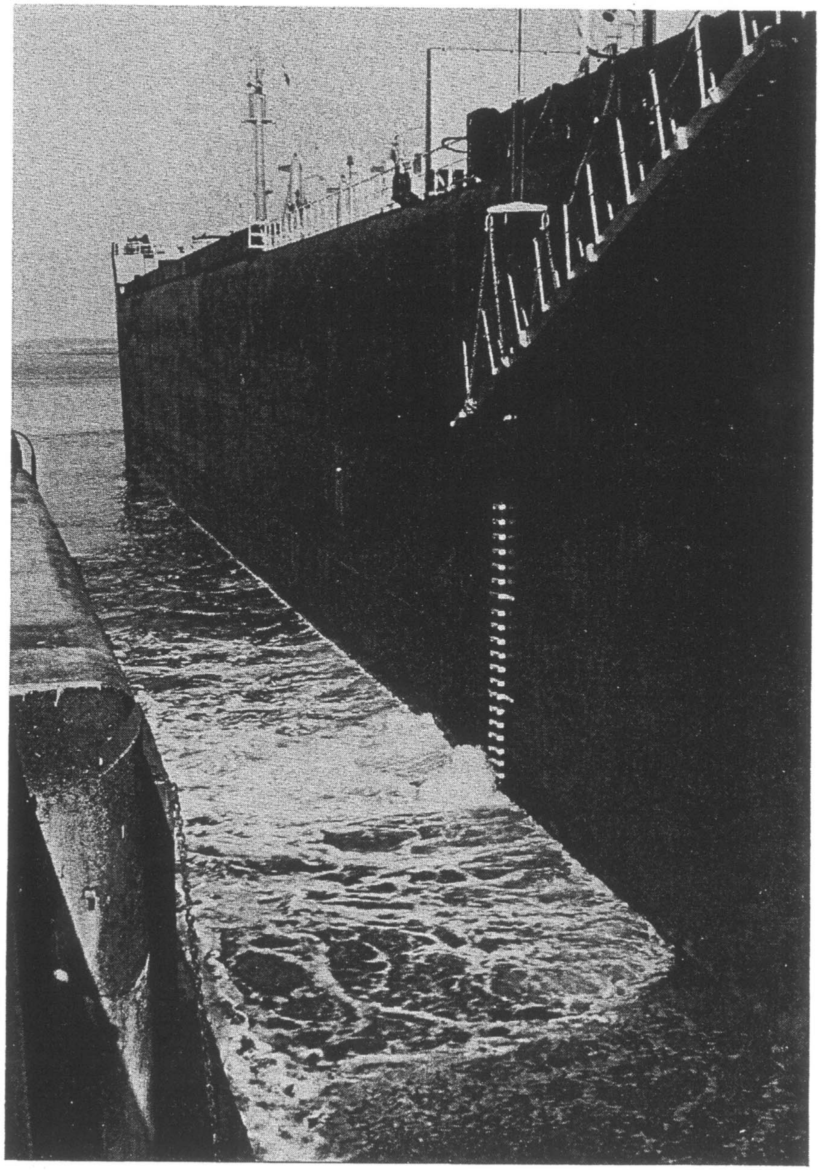
unit of height dx, viz.:

$$dK = n\bar{A}(\rho_w - \rho_L) g \, dx \tag{10}$$

In view of this, the equation for the vertical flow of the water in the mixture can be expressed as:

$$d\left(2\varrho_w \int_0^\infty u^2 \, dy\right) = 2\int_0^\infty dK \, dy \tag{11}$$

If we disregard the volume occupied by the water, the lefthand side of equation (11)



Photograph 7. Northern Lock, IJmuiden; seaward gate; sea-bound ore-carrier 'FRIGGA', 37,500 DWT, crossing pneumatic barrier

expresses the increase in momentum in distance dx. The right-hand side of equation (11) expresses the force exerted on the water in distance dx.

6.1.4. *Mathematical solution*

The current pattern may be expressed in its entirety by substituting equations (6), (7) and (10) in equations (9) and (11); we then get:

$$q_L = \frac{\pi^{\frac{1}{2}}}{k^{\frac{1}{2}}}\left\{\frac{1}{(1+\mu)^{\frac{1}{2}}}u_m + \frac{1}{\mu^{\frac{1}{2}}}u_{rel.}\right\} n_m \bar{A} x \tag{12}$$

and

$$\frac{d\left\{\dfrac{\pi^{\frac{1}{2}}}{(2k)^{\frac{1}{2}}}\varrho_w u_m^2 x\right\}}{dx} = \frac{\pi^{\frac{1}{2}}}{(\mu k)^{\frac{1}{2}}}(\varrho_w - \varrho_L)\, g n_m \bar{A} x \tag{13}$$

On eliminating $n_m \bar{A} x$ from equations (12) and (13) and bearing in mind that $\rho_L \ll \rho_w$, we get:

$$\frac{d(u_m^2 x)}{dx} = \left(\frac{2k}{\mu\pi}\right)^{\frac{1}{2}} \frac{q_L g}{\dfrac{1}{(1+\mu)^{\frac{1}{2}}}u_m + \dfrac{1}{\mu^{\frac{1}{2}}}u_{rel.}} \tag{14}$$

The term q_L in equation (14) is a quantity dependent on x; it is the quantity of air measured at the pressure obtaining at the relevant level (see explanation of equation (9)). In view of the compressibility of air:

$$q_L = \frac{H_a}{H_a + (h - x)} q_a \tag{15}$$

Substituting equation (15) in equation (14), we get:

$$\frac{d(u_m^2 x)}{dx} = \left(\frac{2k}{\mu\pi}\right)^{\frac{1}{2}} \frac{1}{\left\{1 + \dfrac{(h-x)}{H_a}\right\}} \frac{q_a g}{\left\{\dfrac{1}{(1+\mu)^{\frac{1}{2}}}u_m + \dfrac{1}{\mu^{\frac{1}{2}}}u_{rel.}\right\}} \tag{16}$$

Experiments with two-dimensional jets with negligible initial momentum [9], [12] show that:

$$k = 32;\ \mu = 1.27 \tag{17}$$

Accordingly, u_m is the only term dependent on x in equation (16). Therefore u_m could be obtained by solving equation (16). Before we can do so, however, we must know the value of u_m, which is established a short distance above the tube. But we know too little about what is happening close to the tube to be able to determine this. Nevertheless, we can give some approximate solutions for equation (16).

To obtain an anlytical solution we must disregard the compressibility of air. Consequently, the term $\dfrac{1}{1 + \dfrac{h - x}{H_a}}$ in equation (16) is taken as equalling 1, which turns equation (16) into:

$$\frac{d(u_m^2 x)}{dx} = \left(\frac{2k}{\mu\pi}\right)^{\frac{1}{2}} \cdot \frac{q_a \cdot g}{\left\{\dfrac{1}{(1+\mu)^{\frac{1}{2}}} \cdot u_m + \dfrac{1}{\mu^{\frac{1}{2}}} u_{rel.}\right\}} \tag{18}$$

This equation has been taken as the basis for the two solutions given below.

Solution No. 1

We assume that the velocity of the bubbles relative to that of the water is small, viz.:

$$u_m >> u_{rel.} \tag{19}$$

In the light of this assumption we may simplify equation (18) to read:

$$\frac{d(u_m^2 x)}{dx} = \left(\frac{2k}{\mu\pi}\right)^{\frac{1}{2}} \cdot \frac{q_a \cdot g}{\left\{\dfrac{1}{(1+\mu)^{\frac{1}{2}}} \cdot u_m\right\}} \tag{20}$$

Alternatively:

$$(u_m^2 x)^{\frac{1}{2}}\, d(u_m^2 x) = \left(\frac{2k}{\mu\pi}\right)^{\frac{1}{2}} (1+\mu)^{\frac{1}{2}}\, q_a g x^{\frac{1}{2}} dx \tag{21}$$

The solution to equation (21) is:

$$\tfrac{2}{3}(u_m^2 x)^{\frac{3}{2}} = \tfrac{2}{3}\left(\frac{2k}{\mu\pi}\right)^{\frac{1}{2}} (1+\mu)^{\frac{1}{2}} q_a g x^{\frac{3}{2}} + C_e \tag{22}$$

We know too little about what is happening close to the tube to be able to determine the integration constant C_e, but we are justified in stating that the integration constant may be disregarded, provided the value of x is large enough, because the integration constant is independent of x and the two other terms in equation (22) are proprotional to $x^{\frac{3}{2}}$. If the value of x is large enough, we may therefore infer from equation (22) that:

$$u_m = \left[\frac{2k}{\pi\mu}(1+\mu)\right]^{\frac{1}{6}} \cdot (g q_a)^{\frac{1}{3}} \tag{23}$$

The quantity of water rising in the air/water mixture satisfies the equation:

$$q_{opw.} = 2\int_0^\infty u\, dy \tag{24}$$

On substituting equation (6), equation (24) reads:

$$q_{opw.} = \left(\frac{\pi}{k}\right)^{\frac{1}{2}} u_m x \tag{25}$$

Substitution of equation (17) in equations (23) and (25) gives us the final solution:

$$u_m = 1.8\,(g\, q_a)^{\frac{1}{3}} \tag{26}$$

and

$$q_{opw.} = 0.31\, u_m x \tag{27}$$

Solution No. 2

Now let us assume that the velocity of the bubbles relative to that of the water is great, viz.:

$$u_{rel.} >> u_m \tag{28}$$

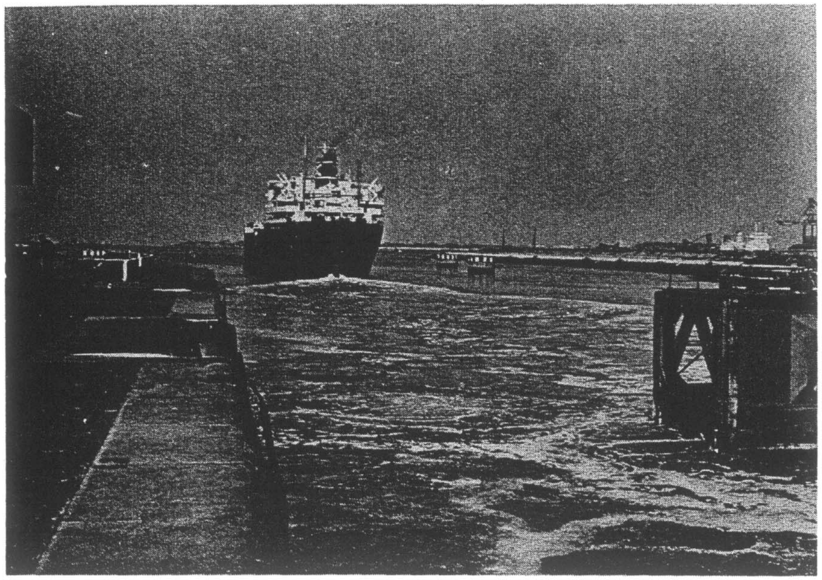
Equation (18) can now be reduced to:

$$\frac{d(u_m^2 x)}{dx} = \left(\frac{2k}{\mu\pi}\right)^{\frac{1}{2}} \frac{q_a g}{\mu^{-\frac{1}{2}} u_{rel.}} \tag{29}$$

which can be converted into:

$$d(u_m^2 x) = \left(\frac{2k}{\mu\pi}\right)^{\frac{1}{2}} \mu^{\frac{1}{2}} \frac{q_a g}{u_{rel.}}\, dx \tag{30}$$

Solving equation (30), we get:



Photograph 8. Northern Lock, IJmuiden; seaward gate; lock gate being closed after passage of ore-carrier 'FRIGGA'

$$u_m^2 x = \left(\frac{2k}{\mu\pi}\right)^{\frac{1}{3}} \mu^{\frac{1}{3}} \frac{q_a g}{u_{rel.}} x + C_e \qquad (31)$$

Here, too, the integration constant may be disregarded if the value of x is large enough; in that event:

$$u_m = \left(\frac{2k}{\pi}\right)^{\frac{1}{3}} \cdot \left(\frac{q_a g}{u_{rel.}}\right)^{\frac{1}{3}} \qquad (32)$$

6.1.5. *Outcome of experiments*

At the beginning of 6.1.1. it is stated that tests carried out in water to a depth of about 10 metres have shown that the depth of the horizontal current thus set up (see figure 3) is about $\frac{1}{4}$ of the total depth and that the velocity of the current increases linearly from zero at the lower boundary to $v_{opp.}$ at the surface [6], [7], [13]. Accordingly:

$$\tfrac{1}{4}\, v_{opp.} \cdot h = q_{opw.,\frac{3}{4}} \qquad (33)$$

Using equation (33) we can now arrive at the value of $q_{opw.,\frac{3}{4}}$ derived from the tests described in the literature on the subject. The tests show that $v_{opp.}$ decreases as the distance from the pneumatic barrier increases and that it is reasonable to assume that the maximum value of $v_{opp.}$ must be taken when using equation (33). Bulson's tests [6] will then give us:

$$q_{opw.,\frac{3}{4}} = (0.40 \ldots 0.47)\left(1 + \frac{h}{H_a}\right)^{-\frac{1}{3}} \cdot (g q_a)^{\frac{1}{3}} \cdot h \qquad (34)$$

(for method of deduction see [14]).
Tests carried out by the Hydraulics Laboratory in collaboration with the Department of Water Control [7] show that:

$$q_{opw.,\frac{3}{4}} = 0.30\,(g q_a)^{\frac{1}{3}} \cdot h \qquad (35)$$

(for method of deduction see [14]).

6.1.6. *Theory and outcome of experiments compared*

Substitution of $x = \frac{3}{4}h$ in equation (27) enables us to deduce from the theoretical equations (26) and (27) that:

$$q_{opw.,\frac{3}{4}} = 0.42 (g q_a)^{\frac{1}{3}} \cdot h \qquad (36)$$

Formula context	$\frac{q_{opw.,\frac{3}{4}}}{(g q_a)^{\frac{1}{3}} \cdot h}$		
Depth	Experiments		Theory
	Bulson	Hydr. Lab.	
(m)	Equ^n. (34)	Equ^n. (35)	Equ^n. (36)
5	0.35 . . . 0.41	0.30	0.42
7.5	0.33 . . . 0.39	0.30	0.42
10	0.32 . . . 0.37	0.30	0.42
12.5	0.31 . . . 0.36	0.30	0.42
15	0.29 . . . 0.35	0.30	0.42

Table 6.1.6. Theory and outcome of experiments compared

This formula accords broadly with the outcome of the experiments. Consequently, the latter should be dealt with by the method described in Solution No. 1.
In table 6.1.6 the solution based on equation (19) (Solution No. 1) is compared with the outcome of the experiments. We see that theory and Bulson's experiments both give higher values for $q_{opw.\frac{1}{2}}$ than the experiments described by the Hydraulics Laboratory. Moreover, the shallower the water the more nearly theory accords with the upper limit given by Bulson's tests. This is not surprising since the effect of disregarding the compressibility of air as in Solution No. 1 becomes greater as the depth increases. The extent to which theory accords with the tests must be regarded as satisfactory in view of the fact that the compressibility of air is disregarded.

6.2. Effect of pneumatic barrier on salt intrusion

6.2.1. *Introduction*

Figure 5 is the basis of the following observations. On one side of a sluice-gate there is salt water with a density of $(\rho + \Delta\rho)$ and depth h_1; on the other side there is fresh water with a density of ρ and depth h_2. Air is blown into the water on either side of the gate at a rate of $\frac{1}{2}q_a$. The bubbles cause the water on either side to move upwards. As stated at the beginning of 6.1. we should distinguish between zone I in which the volume of water rising ($q_{opw.}$) increases as the distance x from the air tube increases

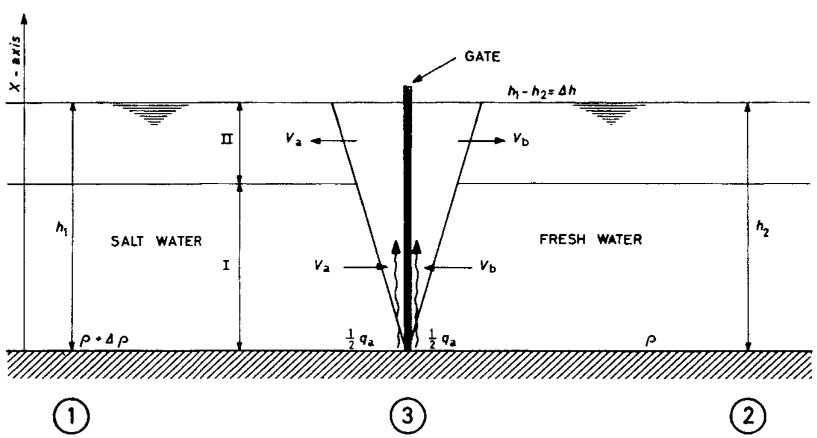


Figure 5. Basis of observations on effect of pneumatic barrier on salt intrusion

and zone II in which the volume of water rising decreases as the distance from the air tube increases.
The movement of the salt water on the one side of the gate satisfies the following equations:

$$\text{[Zone I]} \quad (dq_{opw.}/dx) > 0; \quad p_1 = p_3 + (\varrho + \Delta\varrho)v_a^2 \tag{37}$$

$$\text{[Zone II]} \quad (dq_{opw.}/dx) < 0; \quad p_1 = p_3 - (\varrho + \Delta\varrho)v_a^2 \tag{38}$$

The movement of the fresh water on the other side of the gate satisfies equations:

$$\text{[Zone I]} \quad (dq_{opw.}/dx) > 0; \quad p_2 = p_3 + \varrho v_b^2 \tag{39}$$

$$\text{[Zone II]} \quad (dq_{opw.}/dx) < 0; \quad p_2 = p_3 - \varrho v_b^2 \tag{40}$$

We now assume that the gate is removed when the water movement has become steady. The difference between the depth of the salt water and that of the fresh water $(h_2 - h_1)$ should then adjust itself so that the net flow across the cross-section of the chamber is zero; this involves satisfying the equation:

$$\int_{\text{zone I}} |v_a|\,dx = \int_{\text{zone II}} |v_a|\,dx \tag{41}$$

(If it did not, there would be disequilibrium.)
The quantity of salt water that would then pass through the pneumatic barrier would be:

$$q_{in} = \int_{\text{neg. zone I}} |v_b|\,dx \tag{42}$$

(neg. zone I: part of zone I with $v_a < 0$.)
We should have to know the velocities v_a and v_b as functions of x before we could use (42). To ascertain this we shall use the momentum equation and the continuity equation.

6.2.2. *Momentum equation*

The difference between the density of fresh water and that of salt water is small compared with the difference between the density of the air/water mixture on the one hand and that of fresh or salt water on the other. It may therefore be assumed that p_3 will have the same value over the entire width of the upward current of water when the gate is removed. It is also assumed that the pneumatic barrier will be powerful enough to prevent the intrusion of salt water. Under these conditions and because $\Delta\rho \ll \rho$ it follows from equations (37), (38), (39) and (40) that:

$$[\text{Zone I}] \quad (\mathrm{d}q_{opw.}/\mathrm{d}x) > 0; \quad p_1 - p_2 = \varrho(v_a^2 - v_b^2) \tag{43}$$

$$[\text{Zone II}] \quad (\mathrm{d}q_{opw.}/\mathrm{d}x) < 0; \quad p_1 - p_2 = -\varrho(v_a^2 - v_b^2) \tag{44}$$

in which $p_1 - p_2$ is the difference in pressure at level x.
From now on the difference in depth after the gate has been removed will be expressed as:

$$h_2 = h_1\left(1 + \tfrac{1}{2}\frac{\Delta\varrho}{\varrho}\right) + \Delta h \tag{45}$$

in which Δh replaces $(h_2 - h_1)$ as defined in equation (45).
In view of the hydrostatic distribution of p_1 and p_2, we then see that:

$$p_1 - p_2 = -\Delta\varrho\, g\left(x - \tfrac{1}{2}h + \frac{\varrho}{\Delta\varrho}\Delta h\right) \tag{46}$$

6.2.3. *Continuity equation*

According to figure 5, the continuity equation is:

$$v_a + v_b = \frac{\mathrm{d}q_{opw.}}{\mathrm{d}x} \tag{47}$$

It is assumed that $\mathrm{d}q_{opw.}/\mathrm{d}x$ may be deduced from the description of the upward current of water set in motion by blowing air into still, homogeneous water given in 6.1. The grounds for this assumption become firmer the more salt water the pneumatic barrier excludes.
It follows from the experiments described at the beginning of 6.1. [6], [7] and [13] that:

$$(\mathrm{d}q_{opw.}/\mathrm{d}x) > 0 \text{ for } x < \tfrac{3}{4}h \tag{48}$$

According to equations (26) and (27) and the experiments described in 6.1.5., we see that:

$$(\mathrm{d}q_{opw.}/\mathrm{d}x) \approx C_1 \text{ for } x < \tfrac{3}{4}h \tag{49}$$

in which C_1 is a constant velocity.
It follows from equation (49) that

$$q_{opw.\frac{3}{4}} \approx \tfrac{3}{4}C_1 h \tag{50}$$

Experiments with a pneumatic barrier in still, homogeneous water have shown that

the velocity of the horizontal current near the surface (see figure 3) is a straight line running from zero at level $x = \frac{3}{4}h$ to a maximum value of $v_{opp.}$ at level $x = h$ [6], [7] and [13]. Using this, we can plot $\mathrm{d}q_{opw.}/\mathrm{d}x$ against various values of $x > \frac{3}{4}h$. However, using the curve for $\mathrm{d}q_{opw.}/\mathrm{d}x$ plotted in this manner gives infinite values for v_a and v_b. For this reason, the $\mathrm{d}q_{opw.}/\mathrm{d}x$ curve will henceforth be plotted on the basis of linear velocity of horizontal current from a value of $\frac{1}{6}v_{opp.}$ at level $x = \frac{3}{4}h$ up to a value of $\frac{5}{6}v_{opp.}$ at level $x = \frac{3}{4}h$. Accordingly, continuity arguments based on equations (33) and (50) show us that:

$$(\mathrm{d}q_{opw.}/\mathrm{d}x) \approx -C_1 - 16\frac{C_1}{h}(x - \tfrac{3}{4}h) \quad \text{for } x > \tfrac{3}{4}h \tag{51}$$

Theoretical and experimental values of C_1 can be deduced from equation (50) in conjunction with equations (34), (35) and (36). They will show us that Bulson's experiments [6] give:

$$C_1 = \tfrac{4}{3}(0.40 \ldots 0.47)\left(1 + \frac{h}{H_a}\right)^{-\frac{1}{3}} \cdot (gq_a)^{\frac{1}{3}} \tag{52}$$

According to the tests carried out by the Hydraulics Laboratory in collaboration with the Department of Water Control [7]:

$$C_1 = 0.40(gq_a)^{\frac{1}{3}} \tag{53}$$

It follows from the theory on the subject that:

$$C_1 = 0.56(gq_a)^{\frac{1}{3}} \tag{54}$$

6.2.4. *Effect of volume of air on salt intrusion*

Equations (47), (49) and (51) give $(v_a + v_b)$ as a function of x and the volume of air q_a (see equations (52), (53) and (54)). Equations (43), (44) and (46) give $(v_a + v_b)\cdot(v_a - v_b)$ as functions of x and the difference in level Δh. Therefore v_a and v_b can be represented as functions of x, q_a and Δh.
The term Δh can then be worked out with equation (41).
We get:

$$[\text{Zone I}] \quad (\mathrm{d}q_{opw.}/\mathrm{d}x) > 0; \quad x < \tfrac{3}{4}h$$

$$v_a = \frac{C_1}{2} - \frac{1}{2C_1}\frac{\Delta\varrho}{\varrho}g\left(x - \tfrac{1}{2}h + \frac{\varrho}{\Delta\varrho}\Delta h\right) \tag{55}$$

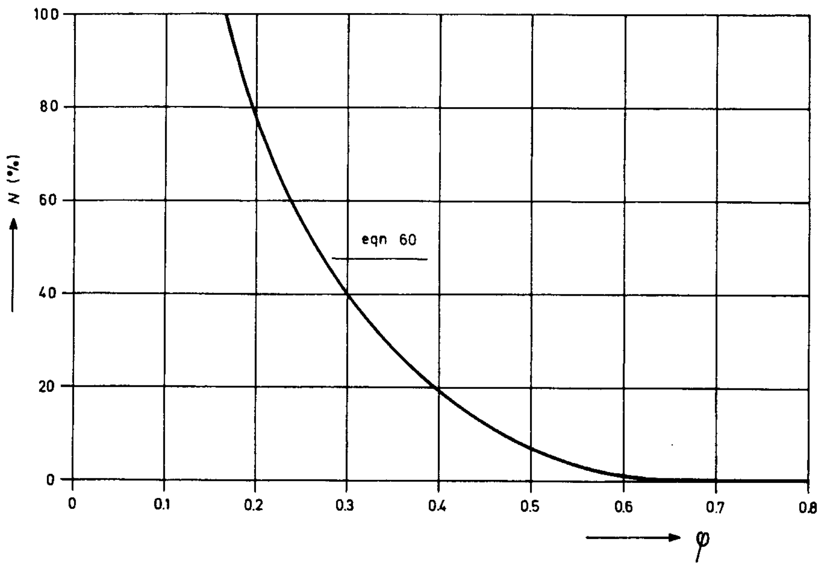


Figure 6. Salt intrusion as function of volume of air in accordance with the theoretical solution

$$v_b = \frac{C_1}{2} + \frac{1}{2C_1}\frac{\Delta\varrho}{\varrho}g\left(x - \tfrac{1}{2}h + \frac{\varrho}{\Delta\varrho}\Delta h\right) \tag{56}$$

[Zone II] $(dq_{opw.}/dx) < 0;\quad x > \tfrac{3}{4}h$

$$v_a = \tfrac{1}{2}\left[C_1 + 16\frac{C_1}{h}\left(x - \tfrac{3}{4}h\right) + \frac{\Delta\varrho}{\varrho}g\left(x - \tfrac{1}{2}h + \frac{\varrho}{\Delta\varrho}\Delta h\right)\cdot \frac{1}{C_1 + 16\frac{C_1}{h}(x - \tfrac{3}{4}h)}\right] \tag{57}$$

$$v_b = \tfrac{1}{2}\left[C_1 + 16\frac{C_1}{h}\left(x - \tfrac{3}{4}h\right) - \frac{\Delta\varrho}{\varrho}g\left(x - \tfrac{1}{2}h + \frac{\varrho}{\Delta\varrho}\Delta h\right)\cdot \frac{1}{C_1 + 16\frac{C_1}{h}(x - \tfrac{3}{4}h)}\right] \tag{58}$$

$$\Delta h = 0.07\frac{\Delta\varrho}{\varrho}h \tag{59}$$

Using equations (5) and (42), we get:

$$N = \frac{q_{in}}{q_{in.0}} = -0.86\varphi + \frac{0.185}{\varphi} + \varphi^3 \text{ (as percentages)} \tag{60}$$

with

$$\varphi = \frac{C_1}{\left(\frac{\Delta\varrho}{\varrho}gh\right)^{\frac{1}{3}}} \tag{61}$$

Equation (60) is shown as a graph in figure 6. Equations (60) and (61) give salt intrusion as a function of C_1 and therefore, together with equations (52), (53) and (54), as a function of q_a. These equations show that we should distinguish between a solution based on Bulson's lower limit, one based on Bulson's upper limit, one based on the Hydraulics Laboratory experiments and one based on the jet theory.

6.2.5. *Limitations of theoretical solution*

When the continuity equation is used, the values of $dq_{opw.}/dx$ are equated with those pertaining to a pneumatic barrier in homogeneous, still water. This assumption would seem less reasonable as the value of N increases.

A greatly simplified conception of the flow pattern around the pneumatic barrier was adopted when elaborating the underlying theory. The actual flow pattern is shown diagrammatically in figure 7a. Salt water is carried upwards by the curtain of bubbles. Some of it runs back into the sea along the surface. Some of it is caught in an eddy with a horizontal axis on the landward side of the bubble curtain from where it reaches the lock chamber.

Salt and fresh water mix in the eddy. The salt water reaching the lock chamber from the eddy must of necessity displace fresh water. The fresh water has to traverse the eddy to leave the lock chamber. The currents will alternately exhibit the patterns shown in figures 7b and 7c, provided the line of bubbles is powerful enough.

It follows from the foregoing that equation (60) only affords an initial impression of the reduction in salt intrusion brought about by the curtain of bubbles. The extent to which the experiments described below accord with theory is nevertheless encouraging.

The mixing of salt and fresh water that takes place in the current of water flowing upwards from the bubble curtain was disregarded when working out the underlying

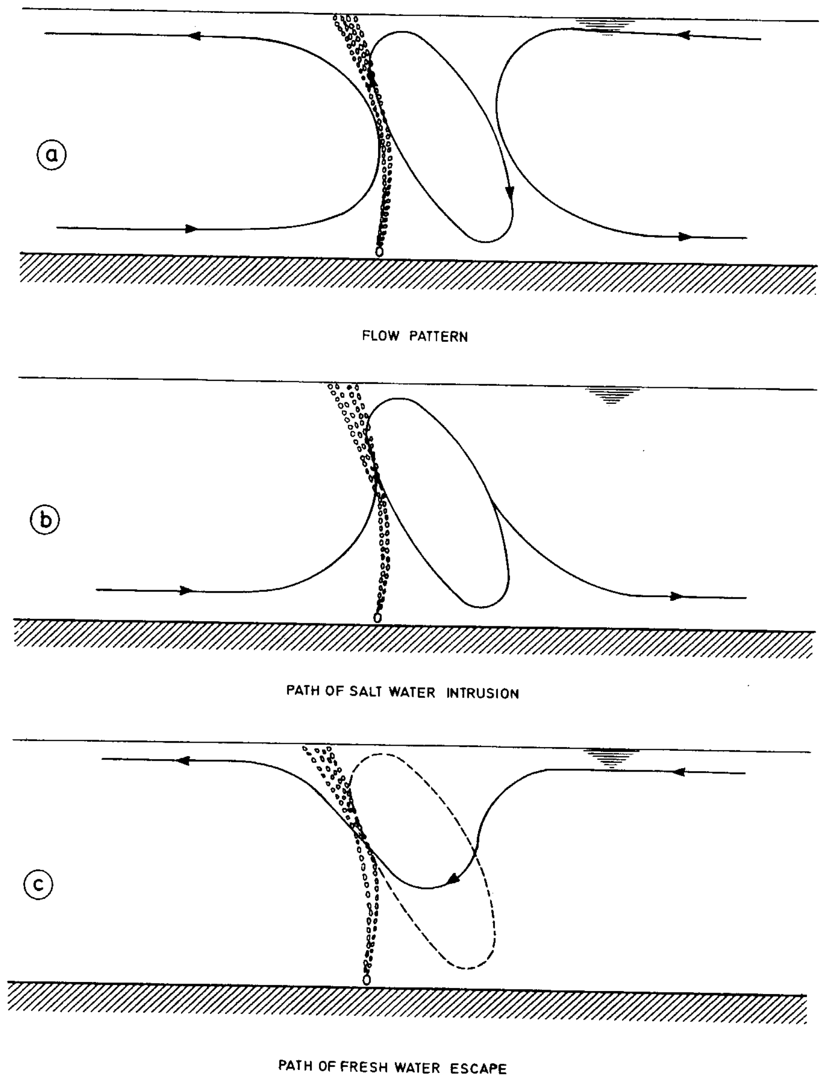


Figure 7. Flow pattern around pneumatic barrier

theory. Consequently, the theoretical process may not be used to discover how much air would have to be blown into the water to reduce salt intrusion to zero ($N = 0$). What the underlying theory can show us, however, is that a rational volume of air will be assured if we observe the condition (see figure 6) that

$$0.16 < \varphi < 0.65 \qquad (62)$$

$v_{opp.} = c$ in the lower limit set in equation (62).
Equation (60) may only be used if the process around the bubble curtain is not affected by the salt tongue being thrown back from the closed end of the lock chamber.

6.2.6. *Outcome of experiments*

Experiments were carried out in the locks at Kornwerderzand and IJmuiden [1], [2] before the pneumatic barriers at IJmuiden were permanently installed. The experiments are summarised in [14]. The lock chamber at Kornwerderzand is much wider at the bottom than it is at the surface of the water. As a result, the outcome of the experiments carried out at Kornwerderzand accord less well with theory than do the tests carried out at IJmuiden. Consequently, the experiments conducted at IJmuiden are the only ones dealt with here.
The outcome of the tests in Southern Lock, Middle Lock and Northern Lock at IJmuiden is shown in figures 8, 9 and 10 respectively. It should be noted that the measuring points in Northern Lock and some of those in Middle Lock were determined after pneumatic barriers had been installed in these locks [15].

6.2.7. *Theory and outcome of experiments compared*

Figures 8, 9 and 10 show that the outcome of the experiments accords satisfactorily with the theory on the subject. Theory and practice approach each other closest in the matter of the theoretical solution founded on the lower and upper limits established by Bulson's tests. This might mean that Bulson's formula (equation 34) would present a better picture of the behaviour of a pneumatic barrier in homogeneous, still water than the one derived from the experiments described by the Hydraulics Laboratory (equation 35).
The theoretical solution derived from the jet theory expounded in 6.1. is not based on readings pertaining to the flow pattern engendered by a curtain of bubbles in homogeneous, still water. The extent to which it accords with the outcome of the experiments conducted with a view to reducing salt intrusion is nevertheless satisfactory.

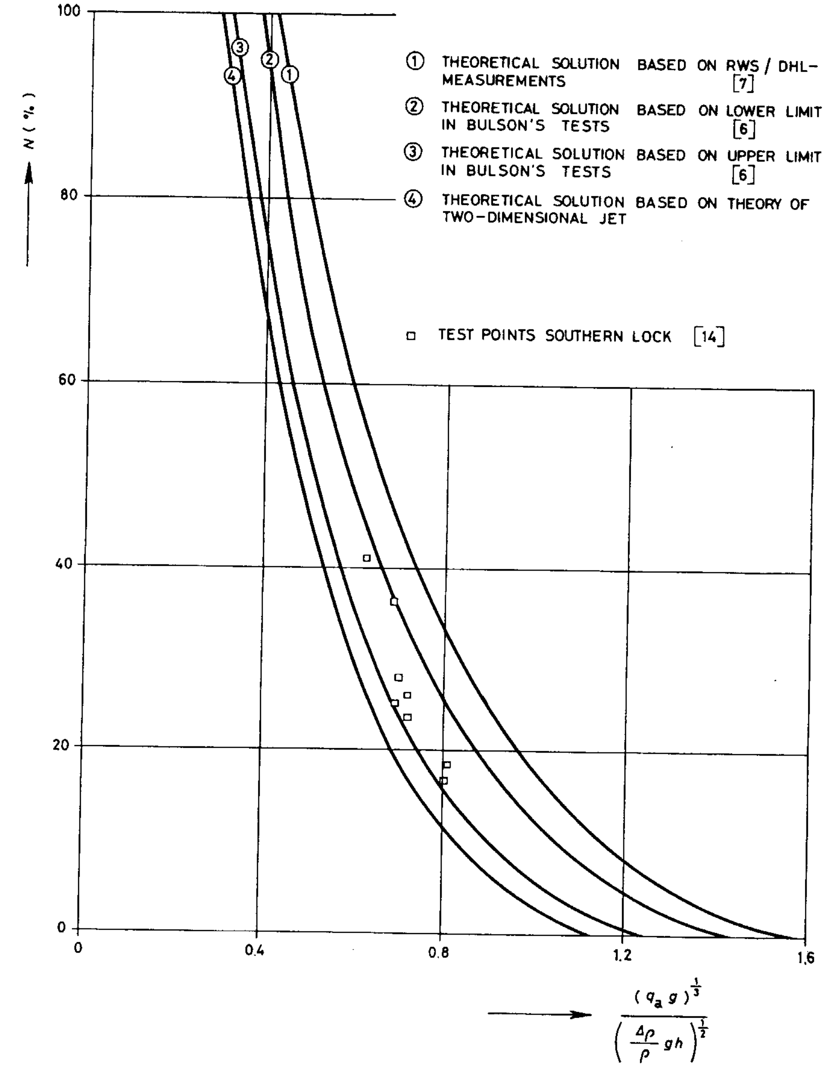


Figure 8. Theory and outcome of experiments compared (h = 7.5 m.)

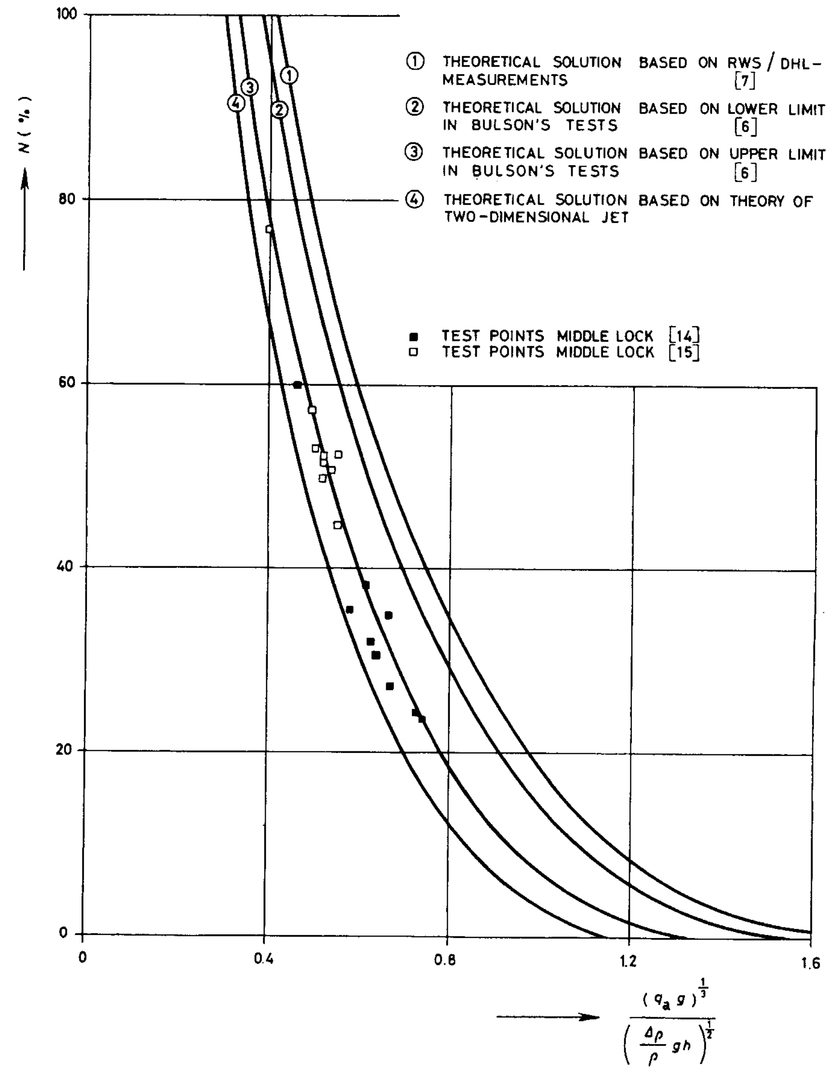


Figure 9. Theory and outcome of experiments compared (h = 10 m.)

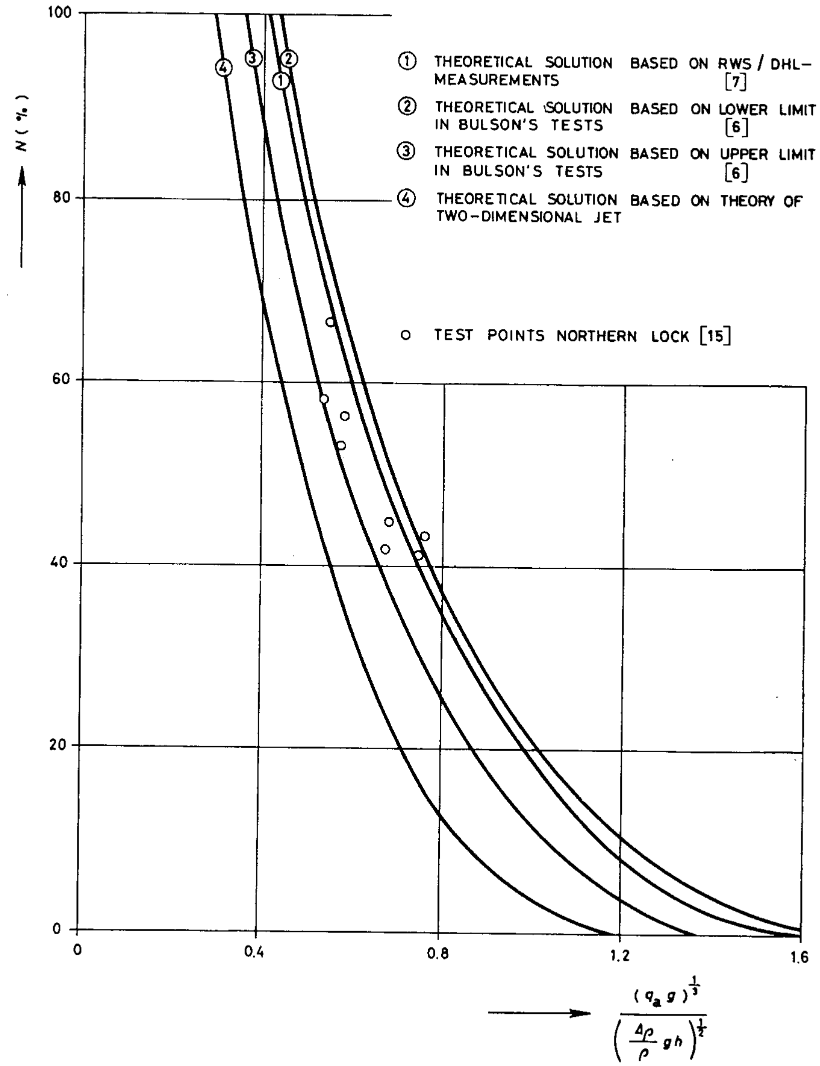


Figure 10. Theory and outcome of experiments compared (h = 15 m.)

7. Design criteria for pneumatic barriers in locks

7.1. Calculating air supply

7.1.1. *Extent to which water is exchanged in a lock chamber*

Figures 8, 9 and 10 give theoretical figures and those obtained from tests carried out in three of the locks at IJmuiden.

At the end of 6.2.5 it is stated that the theory on the subject only holds if the process around the bubble curtain is not affected by the salt tongue being thrown back by the closed end of the lock chamber.

The extent of the exchange after the rate of exchange has been affected by the rebound differs from lock to lock; only tests will reveal this. The figures for Middle Lock and Northern Lock are given in figures 11 and 12.

The following dimensionless quantities were used to give a quantitative picture of the extent of the exchange both with and without a pneumatic barrier: – U = extent of exchange, i.e. the ratio of intrusive salt (or fresh) water (taken as undiluted salt or fresh water) to the entire volume of water in the lock chamber at a certain moment.

time factor

$$T = \frac{t}{4 \cdot L} \cdot \left(\frac{\Delta\rho}{\rho} \cdot g \cdot h \right)^{\frac{1}{2}} \tag{63}$$

volume of air factor

$$Q = \frac{(q_a \cdot g)^{\frac{1}{3}}}{\left(\frac{\Delta\rho}{\rho} \cdot g \cdot h \right)^{\frac{1}{2}}} \tag{64}$$

It follows from the definition of U, from the definition of T (63) and from equation (5) that the exchange $U = T$ up to the moment of rebound ($T < \frac{1}{2}$) in any lock of uniform cross section.

It is clear from the exchange-test figures given in figures 11 and 12 for Middle Lock and Northern Lock that when the exchange curves have changed direction at point

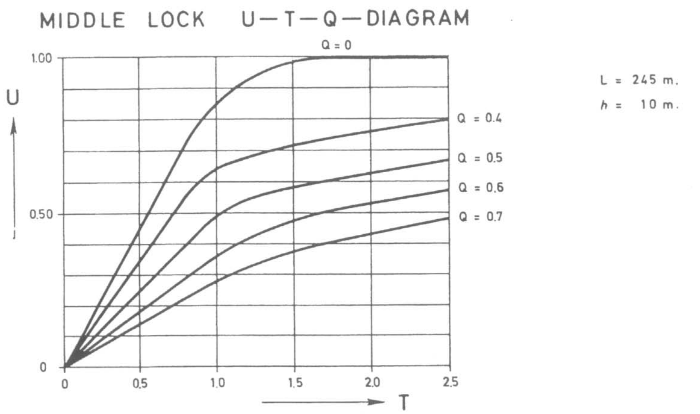
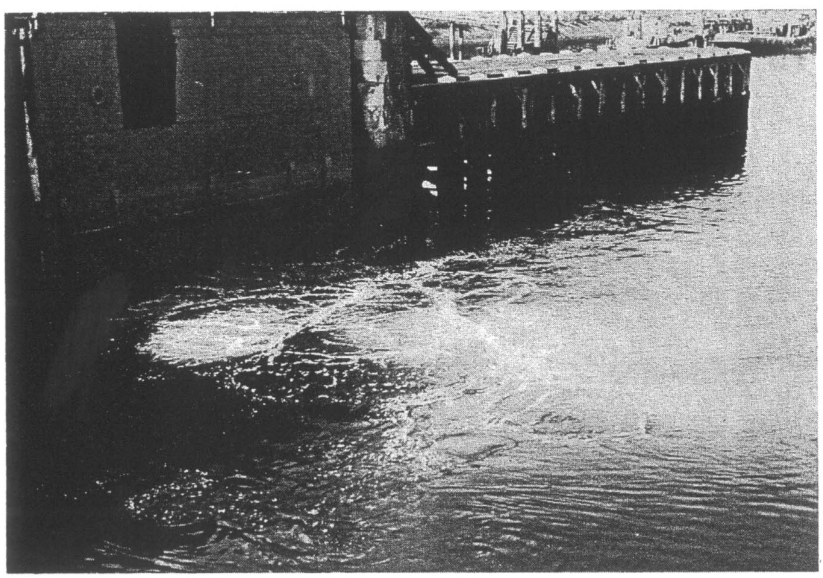


Figure 11. Extent of water exchange *U* in lock chamber of Middle Lock at IJmuiden (one pneumatic barrier)



Photograph 9. Southern Lock, IJmuiden; seaward gate; pneumatic barrier

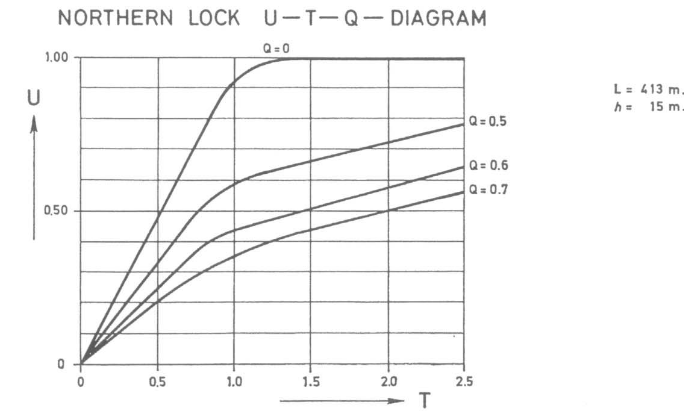
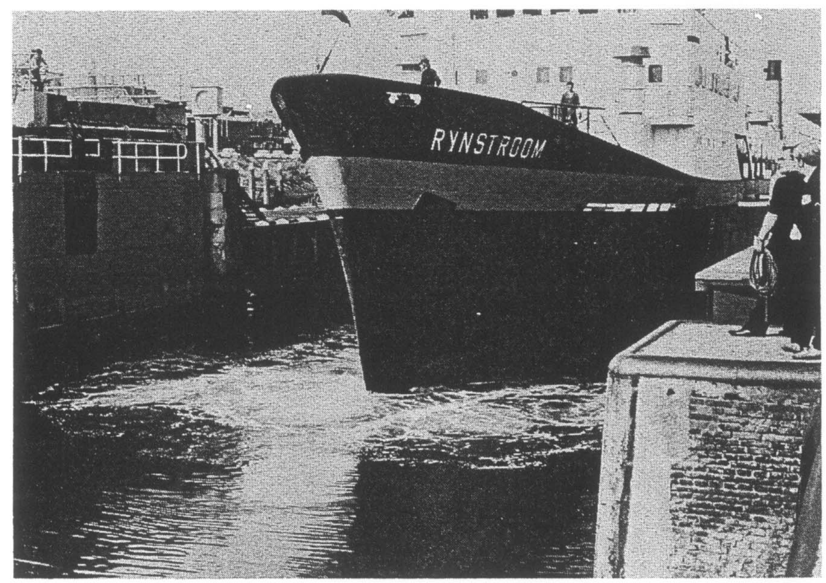


Figure 12. Extent of water exchange *U* in lock chamber of Northern Lock at IJmuiden (one pneumatic barrier)



Photograph 10. Southern Lock, IJmuiden; seaward gate; general cargo ferry 'RIJNSTROOM', 500 BRT, puts into port and cuts across the pneumatic barrier without impairing the barrier's protective action

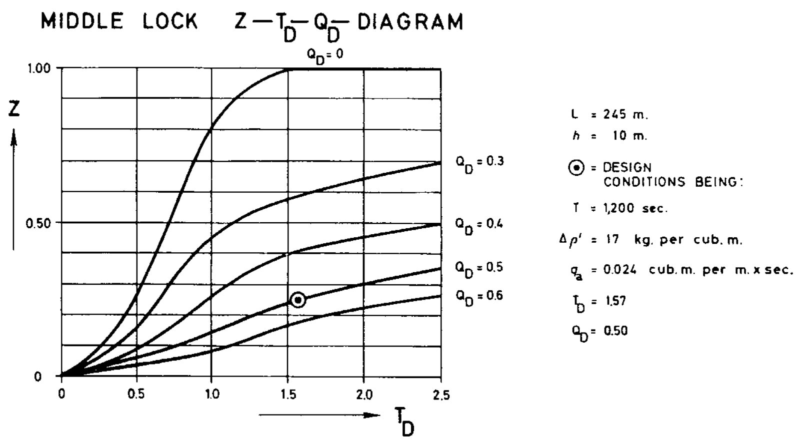


Figure 13. Parameter Z for quantity of salt water intruding through Middle Lock at IJmuiden during one locking cycle (pneumatic barrier at both ends of lock)

T = approximately 1, they almost become straight lines; on altering Q the straight sections are seen to remain virtually parallel as they shift.

7.1.2. *Two pneumatic barriers in one lock*

We have hitherto concerned ourselves with the exchange of water in a lock chamber fitted with a single pneumatic barrier.
It is nearly always an advantage to have two barriers, one next to the outer gates and one next to the inner gates. Since a pneumatic barrier need only function while the relevant lock gates are open and since the gates at either end of a lock chamber are never open at the same time, a single compressor unit can supply each barrier in turn. The U-T-Q diagram for single-barrier exchange (figures 11 and 12) can be converted into a Z-T_D-Q_D diagram showing the overall effect of two barriers on salt intrusion (figures 13 and 14), in which Z (see key) is a parameter for the quantity of salt water passing through the lock in a complete cycle in the same manner as U is a parameter for the extent of exchange in a lock chamber with a single barrier.
There is a single exchange with the sea and a single exchange with the canal in a single cycle. It is assumed that the water both inside and outside the lock chamber will have mixed and become completely homogeneous before each exchange takes place.
When many cycles have been completed, a symmetrical state of balance will have been reached in which the density in the lock chamber will constantly change by $Z \cdot \Delta\rho'$, $\Delta\rho'$ being the difference between the density of the water on the seaward side

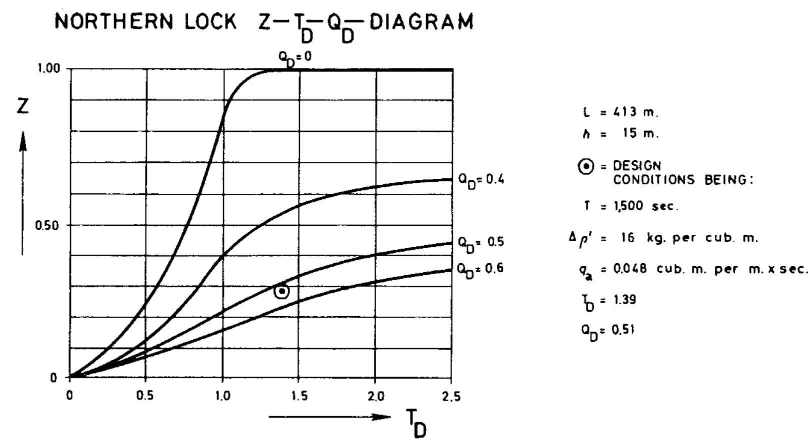


Figure 14. Parameter Z for quantity of salt water intruding through Northern Lock at IJmuiden during one locking cycle (pneumatic barrier at both ends of lock)

and that of the water on the landward side of the lock. The density of the water in the lock chamber before the exchange with the sea takes place is $\rho + \frac{1-Z}{2} \cdot \Delta\rho'$ and before the exchange with the canal $\rho + \frac{1+Z}{2}\,\Delta\rho'$.

It follows that the difference between the density of the water in the chamber on the one hand and that in the sea or the canal on the other will be $\frac{1+Z}{2} \cdot \Delta\rho'$ before the commencement of a single exchange in a system equipped with two pneumatic barriers; the single exchange will then reduce the difference in density by $Z \cdot \Delta\rho'$.
Consequently, for a single exchange and in accordance with the definition of U (see key):

$$\frac{U \cdot Z \cdot \Delta\rho'}{\frac{1+Z}{2} \cdot \Delta\rho'} = \frac{2 \cdot Z}{1+Z} \tag{65}$$

or

$$Z = \frac{U}{2-U} \tag{66}$$

Since

$$T = \frac{t}{4 \cdot L}\left(\frac{\Delta\rho}{\rho} \cdot g \cdot h\right)^{\frac{1}{2}} \qquad (63)$$

and

$$T_D = \frac{t}{4 \cdot L} \cdot \left(\frac{\Delta\rho'}{\rho} \cdot g \cdot h\right)^{\frac{1}{2}} \qquad (67)$$

we get

$$T_D = \left(\frac{\Delta\rho'}{\Delta\rho}\right)^{\frac{1}{2}} \cdot T \qquad (68)$$

from

$$\frac{\Delta\rho'}{\Delta\rho} = \frac{2}{1 + Z} \qquad (69)$$

we get

$$T_D = \left(\frac{2}{1 + Z}\right)^{\frac{1}{2}} \cdot T \quad \text{or} \quad T_D = (2 - U)^{\frac{1}{2}} \cdot T \qquad (70)$$

Since

$$Q = \frac{(q_a \cdot g)^{\frac{1}{3}}}{\left(\frac{\Delta\rho}{\rho} \cdot g \cdot h\right)^{\frac{1}{2}}} \qquad (64)$$

and

$$Q_D = \frac{(q_a \cdot g)^{\frac{1}{3}}}{\left(\frac{\Delta\rho'}{\rho} \cdot g \cdot h\right)^{\frac{1}{2}}} \qquad (71)$$

we see by analogy that

$$Q_D = \left(\frac{1}{2 - U}\right)^{\frac{1}{2}} \cdot Q \qquad (72)$$

The Z-T_D-Q_D combination corresponding to any U-T-Q combination can be calculated by means of equations (66), (70) and (72).
If the extent to which it is desired to reduce salt intrusion and the basic data pertaining to the lock are known, the volume of air required can be calculated from the Z-T_D-Q_D diagram.

7.1.3. *Twin pneumatic barriers in two or more locks serving one canal*

There are a number of places where two or more locks link a single canal with the sea Determining the quantities of air required for the various locks and distributing the air in such a manner that disproportionately large sums are not spent on preventing salt intrusion through any one lock are two of the major problems to be solved.
The distribution of air adopted for the system of locks at IJmuiden is such that the cost price per kg. of salt prevented from intruding is the same for all the locks.

7.1.4. *Determining air supply for locks at IJmuiden*

There are four locks serving a single canal at IJmuiden and pneumatic barriers have been used in them for some considerable time. The wide experience gained there is the main subject of the next few sections.
Local conditions are given in figures 15 and 16.
Salt intrusion through the locks at IJmuiden used to cause the salt content of the water in Amsterdam docks to be high. The Amsterdam-Rhine canal links Amsterdam with the Rhine. Contamination of the canal must be prevented as it will be used to supply the western part of the Netherlands with fresh water. It is therefore essential that the salt content of the water in Amsterdam docks be kept as low as possible.
IJmuiden and Amsterdam are linked by the North Sea Canal; the latter is connected with Lake IJssel by locks and a sluice. The North Sea Canal has been flushed with water from Lake IJssel for many years; the water reaches the sea through the sluice at IJmuiden.
The volume of water available for flushing cannot be expected to increase to any very great extent, because the amount of fresh water reaching Lake IJssel is limited.
In view of the forogoing, the four locks at IJmuiden were equipped with pneumatic barriers.
The chloride content of the water in the North Sea Canal had been recorded for many years, so its salinity and the effect of various factors was known [16].
The system was designed to supply enough air to lower the chloride content of the water in the canal by 50%, the postulated reduction [3].
The volumes of air required for the four locks were calculated by the methods described in the foregoing. The design figures ultimately arrived at for Middle Lock and Northern Lock are given in figures 13 and 14.
The calculated volumes for the four locks were:

Little Lock	0.083 cub. m. per sec.
Southern Lock	0.267 cub. m. per sec.
Middle Lock	0.650 cub. m. per sec.
Northern Lock	2.50 cub. m. per sec.
Total	3.50 cub. m. per sec.

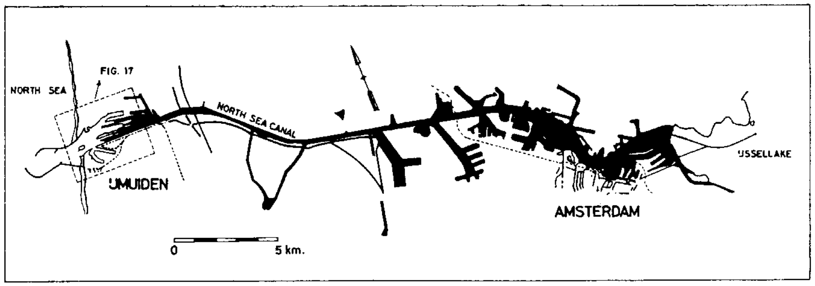
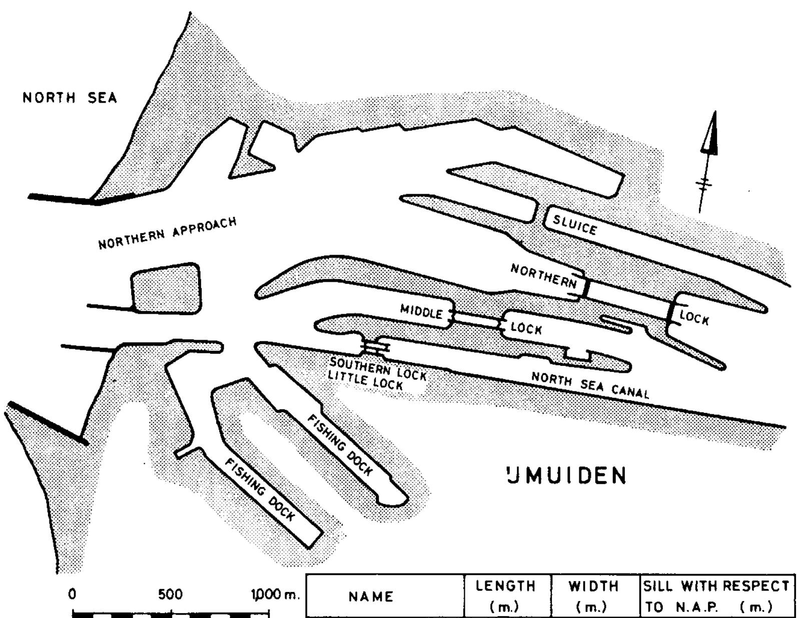


Figure 15. North Sea Canal connecting Amsterdam with the North Sea



NAME	LENGTH (m.)	WIDTH (m.)	SILL WITH RESPECT TO N.A.P. (m.)
LITTLE LOCK	78	12	5.24
SOUTHERN LOCK	130	18	8.00
MIDDLE LOCK	245	25	10.00
NORTHERN LOCK	413	50	15.00

Figure 16. Location of IJmuiden locks

The effect of the pneumatic barriers on the salinity of the water in the North Sea Canal can be assessed by comparing readings taken during a short period before the equipment was installed with readings taken during a short period after the barriers were put into operation. This method of assessing their efficacy minimizes the effect on the hydraulic behaviour of the canal of the widening operations being carried out at the time.

The figures for the years 1963 and 1964 (i.e. before installation) and for the year 1966 (i.e. after installation) are given in figures 17 and 18. The readings were taken at points near the surface of the water 3 km. and 24 km. from the locks. The efficacy of the system is evident.

7.2. Aerodynamic features of pneumatic barrier plants

7.2.1. *Designing air supply pipes*

Each lock has its own air supply mains and sets of perforated pipes.

Comprehensive treatises on the theory regarding the behaviour of air flowing through pipes and perforations and on experiments with pipes and perforations will be found in the literature on the subject [17].

One of the formulae for straight compressed air mains is:

$$\frac{P_1^2 - P_2^2}{L_b} = \frac{2 \cdot P \cdot \Delta P}{L_b} = 10 \cdot C \cdot \frac{q_a^{1,85}}{d^5} \qquad (73)$$

The diameter d can be calculated from P_1, P_2, L_b and q_a.

7.2.2. *Designing perforated pipes*

The holes must be distributed throughout the length of the pipe in such a manner that the escaping air will produce an even curtain of bubbles. If this requirement is satisfied, a quantity of air equal to $\frac{\Delta L_b}{L_b} \cdot q_a$ will escape from the holes in a length of pipe equal to ΔL_b. Equation (73) applied to a length of pipe equal to ΔL_b gives us:

$$p_{L_b}^2 - p_{L_b+\Delta L_b}^2 = 10 \cdot C \cdot \Delta L_b \cdot \frac{q_a^{1,85}}{d^5} \cdot \left\{1 - (n_L - 1)\,\frac{\Delta L_b}{L_b}\right\}^{1,85} \qquad (74)$$

Aggregating for the entire length of pipe, we get:

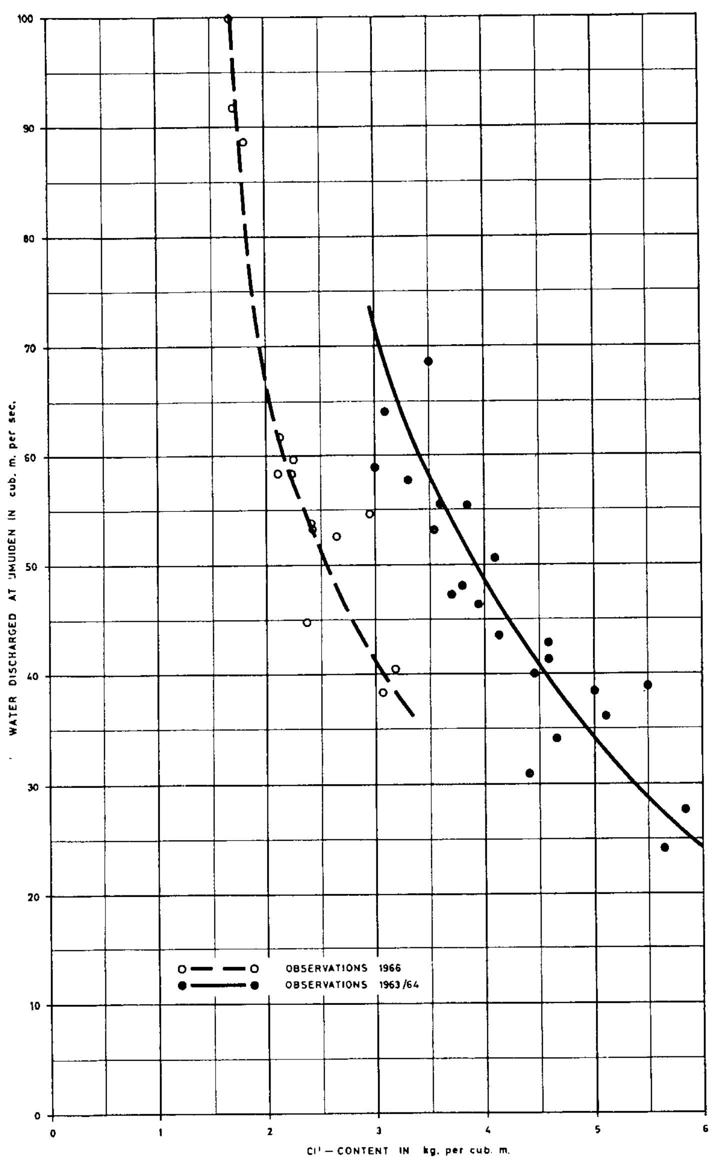


Figure 17. Chloride content of North Sea Canal near water surface 3 km. from IJmuiden locks

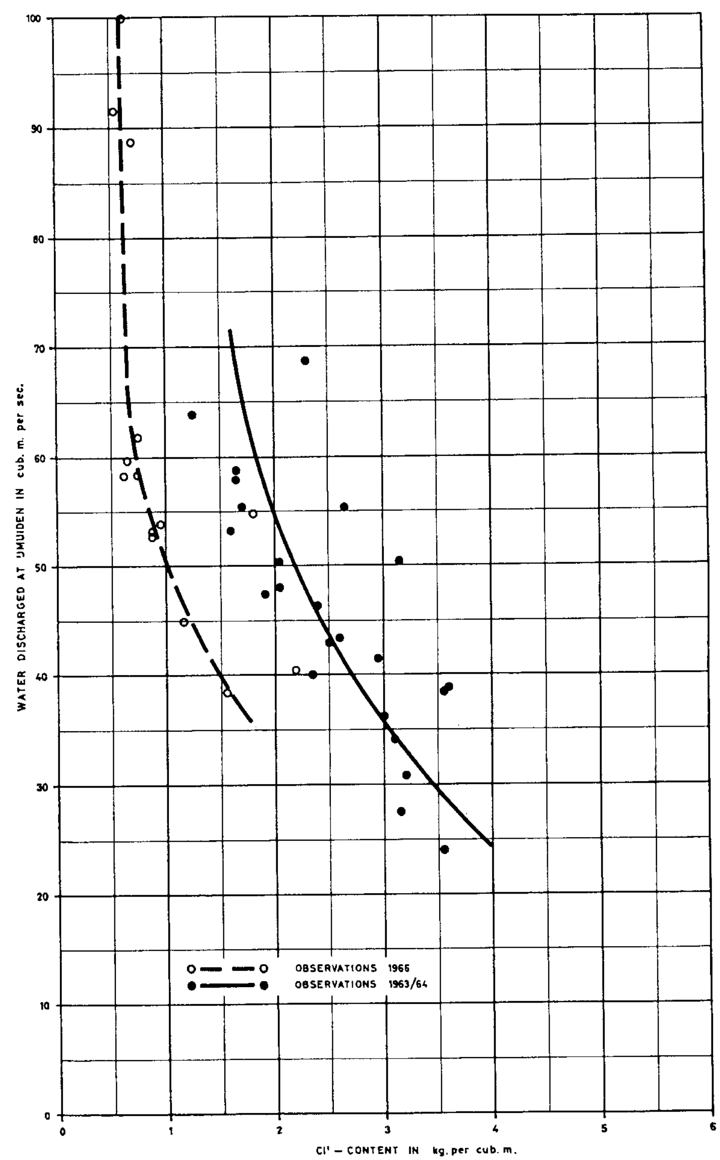


Figure 18. Chloride content of North Sea Canal near water surface 24 km. from IJmuiden locks

$$p_1^2 - p_2^2 = 10 \cdot C \cdot \frac{\Delta L_b}{d^5} \cdot q_a^{1.85} \cdot \sum_{n_L = 1}^{n_L = \frac{L_b}{\Delta L_b}} \left\{1 - (n_L - 1)\frac{\Delta L_b}{L_b}\right\}^{1.85} \qquad (75)$$

If ΔL_b approaches zero the equation becomes:

$$p_1^2 - p_2^2 = 10 \cdot C \cdot \frac{q_a^{1.85}}{d^5} \cdot \lim_{\Delta L_b \to 0} \Delta L_b \sum_{n_L = 1}^{n_L = \frac{L_b}{\Delta L_b}} \left\{1 - (n_L - 1)\frac{\Delta L_b}{L_b}\right\}^{1.85} \qquad (76)$$

The limit is difficult to solve.

A reasonable approximation can be obtained by determining the sum in equation (75) for $L_b = 10 \cdot \Delta L_b$ as follows:

$$\sum_{n_L = 1}^{n_L = \frac{L_b}{\Delta L_b}} \left\{1 - (n_L - 1)\frac{\Delta L_b}{L_b}\right\}^{1.85} = \sum_{n_L = 1}^{n_L = 10} \left(\frac{11 - n_L}{10}\right)^{1.85} =$$

$$= 1 + (\tfrac{9}{10})^{1.85} + (\tfrac{8}{10})^{1.85} + \ldots + (\tfrac{1}{10})^{1.85} = 4.02 \qquad (77)$$

Equation (75) then becomes:

$$p_1^2 - p_2^2 = 4.02 \cdot C \cdot \frac{L_b}{d^5} \cdot q_a^{1.85} \quad \text{(approximation)} \qquad (78)$$

7.2.3. *Size of holes in pipes*

The quantity of air that will escape through a small round hole is:

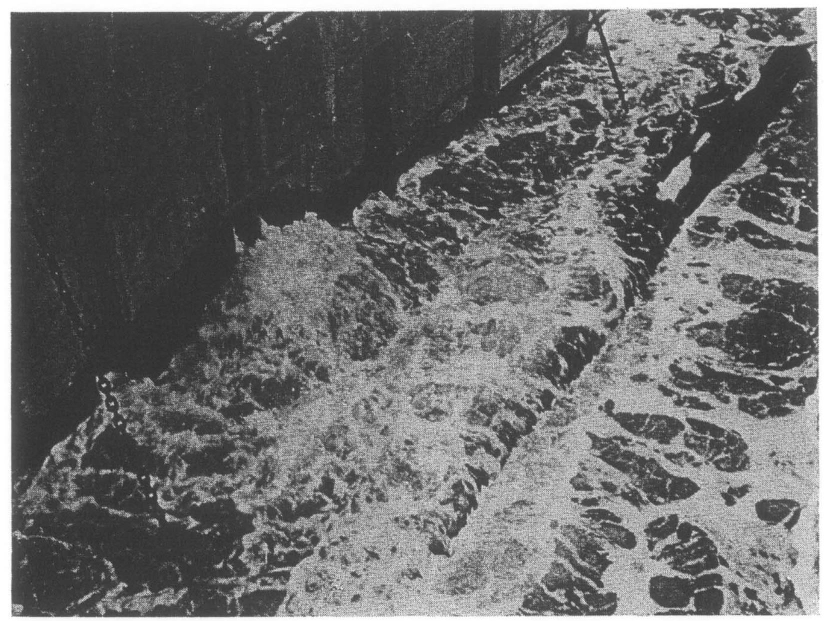
$$q_h = 3.07.\ 10^{-2} \cdot \eta \cdot d^2 \cdot \sqrt{P_u \cdot (P_i - P_u)} \qquad (79)$$

if

$$1.11 < \frac{P_i}{P_u} < 1.89$$

Accordingly, the minimum drop in pressure in the holes at the end of the pipe will be: $P_i = 1.11 \cdot P_u$.

The escape coefficient η may be somewhere between 0.6 and 0.9; η should not be assumed to be more than 0.6 because allowance must be made for obstruction of the holes with dirt and for the gradual closing of the holes due to deposits of foreign matter.
Since P_i changes throughout the length of the pipe, it is desirable that the number of holes should increase progressively so as to ensure that the quantity of air escaping per running metre remains the same.



Photograph 11. Northern Lock, IJmuiden; landward gate; pneumatic barrier with air main in wall

8. Upkeep of pneumatic barriers; experience gained at IJmuiden

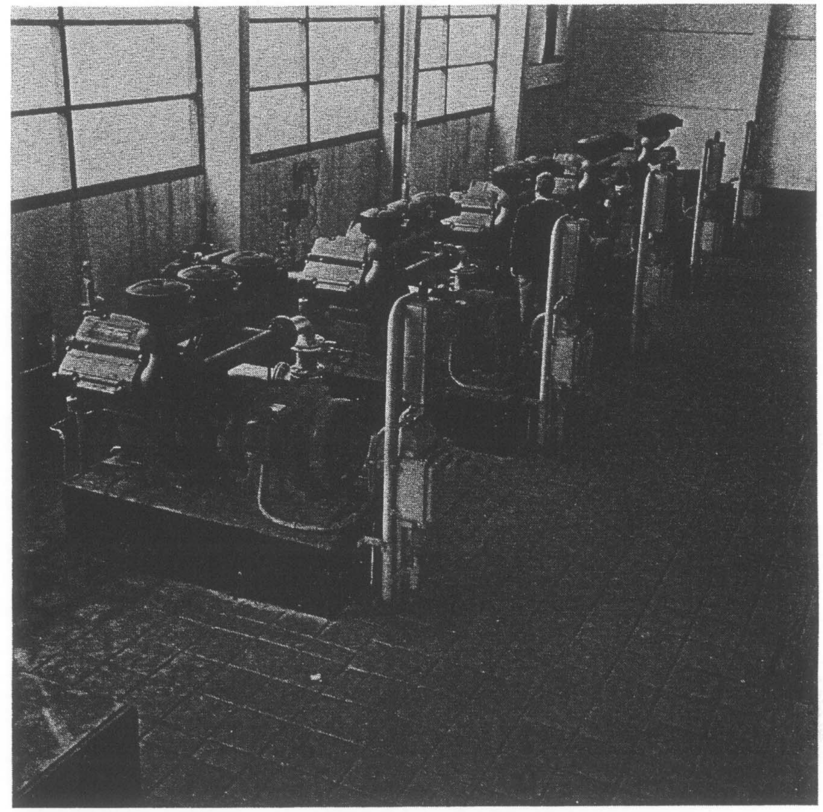
8.1. Air compressors

As all the locks at IJmuiden were already being supplied with electricity, each lock was provided with its own compressor room. Low-pressure, air-cooled, reciprocating compressors with air after-cooling were considered the best. Their dimensions are given in table 8.1.

compressors	Northern Lock	Middle Lock	Southern Lock	Little Lock
cap. per unit in cub. mtrs per sec.	0.53	0.23 and 0.45	0.10	0.10
no. of units	5	2	3	1
total vol. of air in cub. mtrs per sec.	2.65	0.68	0.30	0.10
operating press. in ato	2.5	2.0	1.7	1.4
total h.p. of motors	800	60 and 120	90	30
after-cooling	air	air	air	air
oil filter	no	yes	no	no
vol. measured	recorded	recorded	no	no

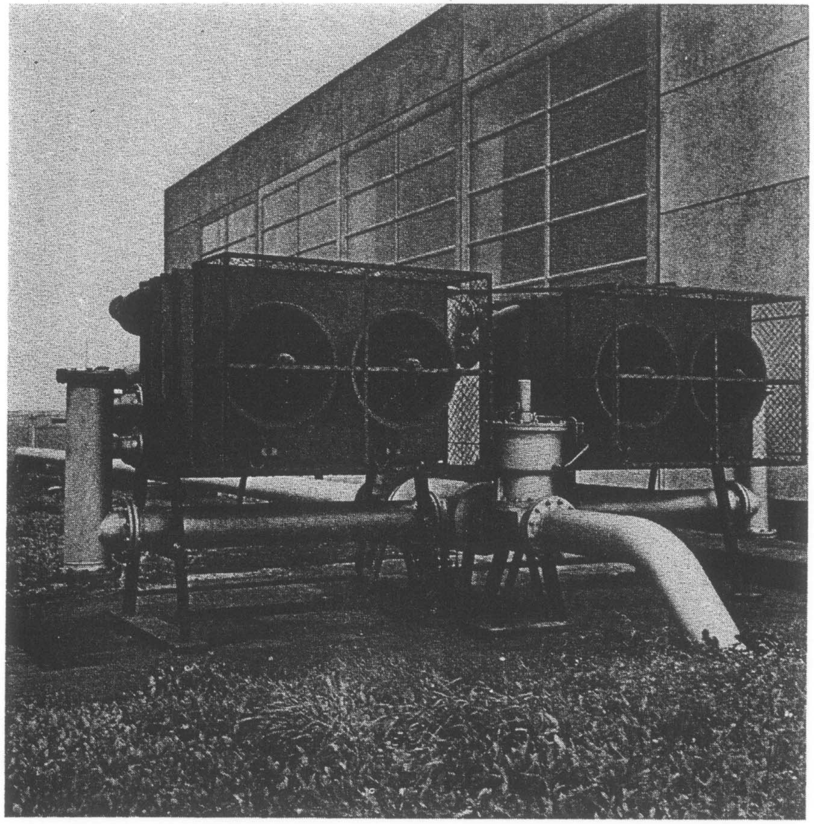
Table 8.1. Air compressors for pneumatic barriers in IJmuiden locks

The entire system is automatic. The compressors are switched on and off by the movements of the lock gates. Slight pressure is maintained in the perforated pipes in the Northern Lock even when the gates are closed; this is done to prevent sand and sediment from entering the holes and to keep the area near the pipes clear.
While one of the gates is being opened (the whole operation takes about two minutes) the compressors start up at intervals of 20 sec.
The Northern Lock compressor hall is large, this in view of the volume of air used and the temperatures. The hall is 22 mtrs long, 7.5 mtrs wide and 6 mtrs high. There is room for a sixth compressor unit.
Extra ventilation is provided by four fans in the roof which come into action when the temperature rises above 20 °C. The motors are heat-proof up to 60 °C.



Photograph 12. Northern Lock, IJmuiden; reciprocating compressors in compressor room

Steps must be taken to reduce noise for the benefit of the staff; covering the walls with fibreboard has been considered.
When designing the air after-cooling system, account was taken of the fact that the temperature of the air drawn in may be anything between − 10 °C. and + 25 °C. The air is cooled down to 15 °C. above the temperature of the surrounding air; the cooler does not operate until the temperature of the air drawn in exceeds 25 °C.
All the equipment in the three other locks is much smaller. The compressors have no reserve capacity. Overhauling and repairing the Northern Lock and Middle Lock installations are time-consuming operations; consequently, the systems cannot always work at full capacity. For this reason, these two locks are to be provided with stand-by compressors.



Photograph 13. Northern Lock, IJmuiden; air cooling compressed air outside compressor room

8.2. Number of holes

Each lock has a system of main pipes terminating in perforated pipes. The mains running to the inner and outer abutments may vary in length. The lengths of the mains running to the outer abutments are given in table 8.2.

The diameters of the perforations and their spacing are the same at either end of each lock chamber.

The methods and formulas in 7.2 were used to determine the diameters of the pipes and holes. Allowance was made for losses in bends and valves and for losses in pres-

pipes and holes	Northern Lock	Middle Lock	Southern Lock	Little Lock
mains				
length in mtrs	303	184	80	79
diameter in mm.	240	141	97	59
perforated pipes				
length in mtrs	52	27	19	13
diameter in mm.	148	81	58	58
*perforations**				
diameter in mm.	0.9	0.9	0.9	0.9
average separation in mm.	13	13	13	13
no. of rows of perfs	5	3	2	1
no. of perfs per mtr	385	230	145	83

* first scheme

Table 8.2. Pipes and holes — pneumatic barriers in IJmuiden locks

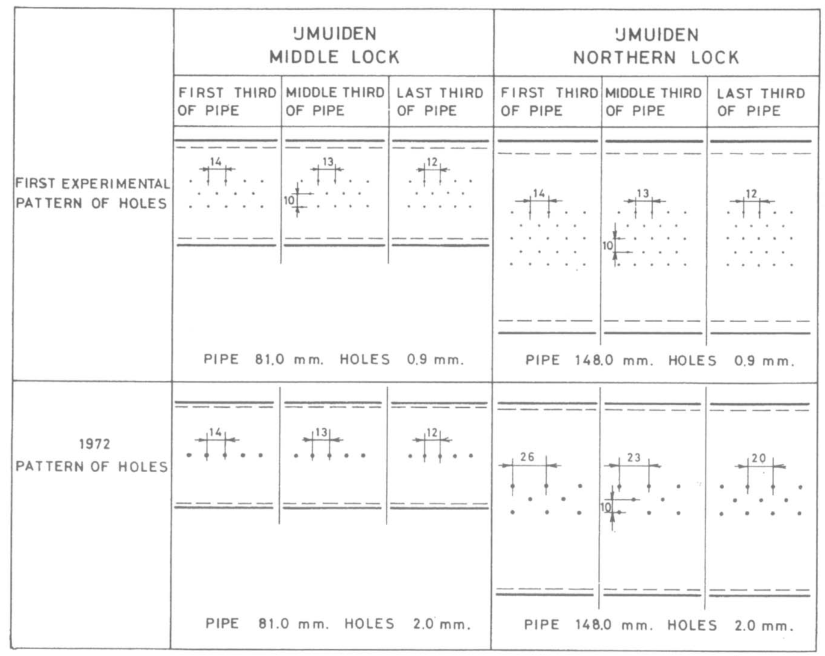
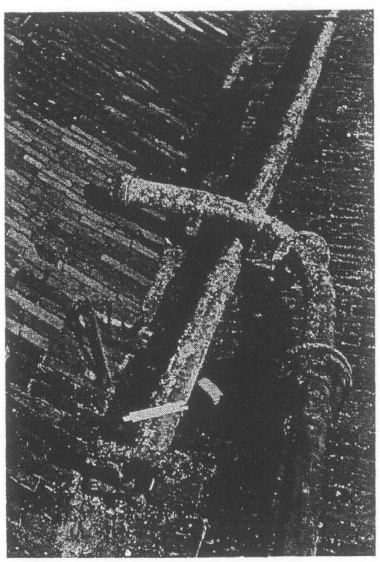


Figure 19. Pattern of holes in barrier pipes in IJmuiden locks

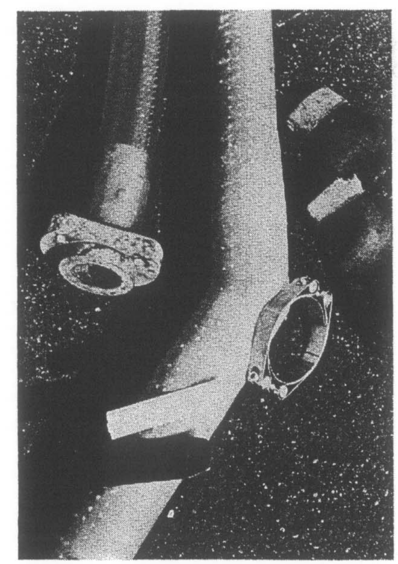
sure in the after-cooling unit when computing the operating pressures for the compressors.
The figures for the spacing of the holes are averages. Hole spacings of 14, 13 and 12 mm. were adopted for the first, second and third thirds of the width of the locks respectively in the three largest locks. The ends of the pipes are bent upwards at an angle. The number of holes in the ends is such that a slightly larger volume of air escapes than calculations demand.
Figure 19 shows the first pattern of holes adopted. It soon transpired that sediment, oil and organisms fouled the pipes and holes more or less permanently, despite regular cleaning. This resulted in less than the required volume of air escaping. Some considerable time was spent in efforts to discover the most suitable diameter of hole and the right number of holes. The distribution of the holes was often altered when maintenance work was being carried out. The ends of the pipes were also closely studied on such occasions. Holes 1 mm. in diameter have been almost universally adopted in the last few years.
A system employing pipes with three rows of 2 mm. dia. holes spaced an average of 23 mm. apart is to be installed in Northern Lock shortly (see figure 19). The escape coefficient η will then be 0.6. The turned-up ends of the pipes will have enough holes to allow 10% more air to escape than the straight portion to compensate for the drop in pressure outside the holes due to their higher average position.
The rows have always been 10 mm. apart.

8.3. Materials used for pipes

The air mains at IJmuiden have been placed underground wherever possible. Since the temperature of the air delivered by the compressors may occasionally be high, steel was used for the sections next to the compressors. Steel was also used for the sections running above ground. Polyvinylchloride piping was used for the underground sections.
Polythene piping was used provisionally for the perforated portion. Experience has shown that polythene piping tends to become brittle in time. Consequently, after from three to five years all the polythene sections were replaced by pipes made of epikote, a plastic reinforced with glass fibre. Air holes in epikote pipes can be closed if necessary by applying heat and redrilled. The outside of the pipes can be treated with an anti-fouling preparation to prevent acorn barnacles from attaching themselves to them.
Epikote piping has been in use for four years; it is more expensive but has proved satisfactory so far.



Photograph 14. Middle Lock, IJmuiden; two sections of old air pipes; the straight section is the perforated one



Photograph 15. Middle Lock, IJmuiden; new perforated sections; the white one is an 'EPIKOTE' synthetic pipe; the other is an experimental flexible plastic piece

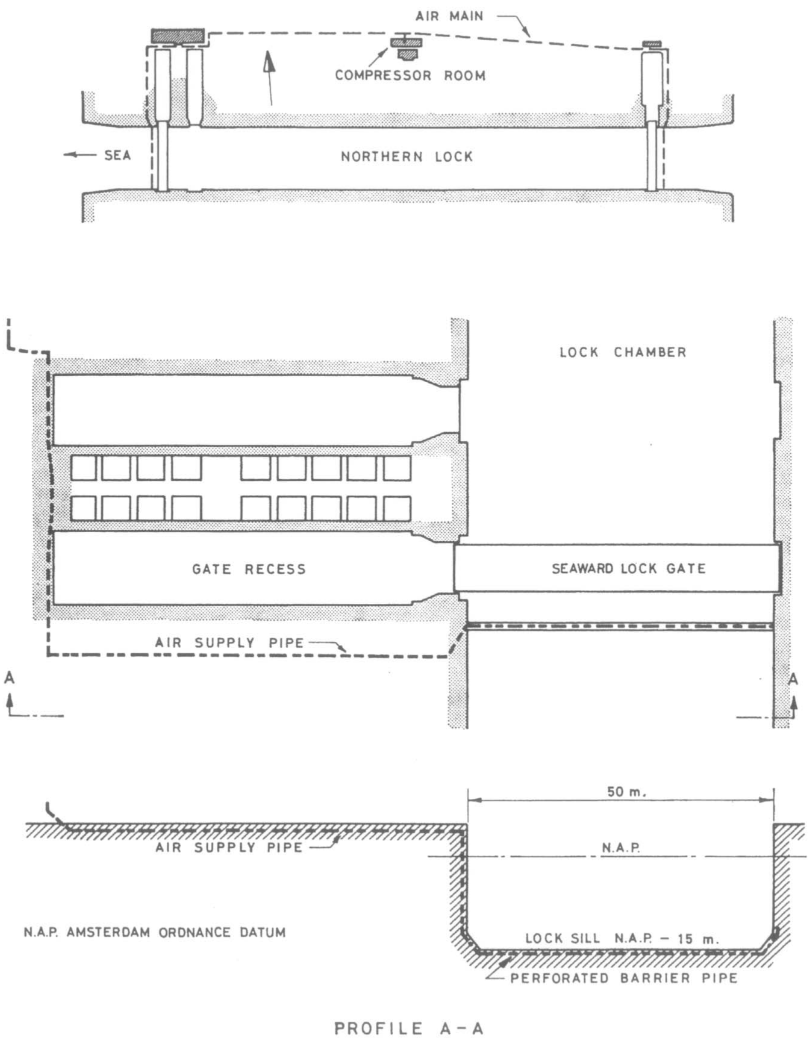
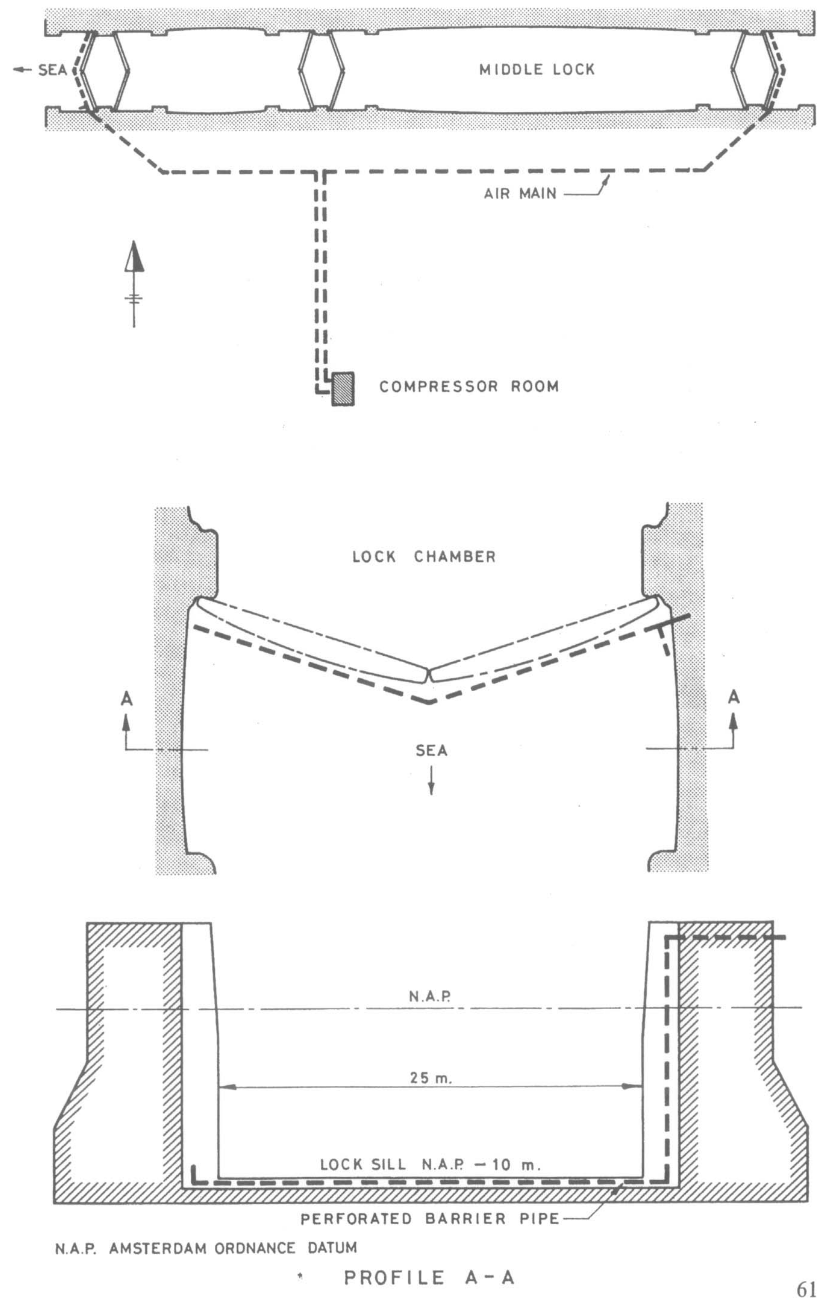


Figure 20. Pneumatic barriers in Northern Lock

Figure 21. Pneumatic barriers in Middle Lock ▶



8.4. Effects on lock-gate maintenance

8.4.1. *Northern Lock*

The Northern Lock gates move horizontally on rollers in recesses in the bottom of the lock chamber. The air main runs down a groove in the lock wall outside the lock chamber 5 mtrs from the gates (see figure 20). The perforated part of the pipe rests in a small recess in the bottom of the lock chamber parallel to the gate; this obviates any reduction in the effective depth of the lock due to the presence of the pipe. The grooves and recesses were prepared when Northern Lock was built; they were intended to receive a maintenance caisson, which was never used, however.

At first it was feared that the large quantity of air in the water would increase the corrosion of the steel gates but the fear proved unfounded.

Nor was there any material increase in sedimentation in the area around the pneumatic barriers and the roller gates, as the experts had feared there would be.

8.4.2. *Little Lock, Southern Lock and Middle Lock*

The three smaller locks have steel mitre gates. At first, the perforated pipes were placed on the bottom between the gate recesses perpendicular to the axis of the lock chamber and as far as possible from the swinging mitre gates. It was soon found that when a pneumatic barrier was put into operation any floating bits of wood that had collected in front of the gates were imprisoned and then caught between the walls and the gates in the recesses when the gates were opened, thus damaging the gates. Later, to prevent floating wood from being caught in this manner, the perforated pipes were laid parallel to the gate seatings in recesses in the floor of the lock chamber close to the outside bottom edges of the gates (see figure 21).

The circulating water now keeps any floating bits of wood away from the wall. A drawback of the new location of the perforated pipes is that they are more likely to be damaged by the dirt that is sometimes pushed along the bottom as the gates are opened. A solution to this problem is being sought.

9. Conclusions

Salt intrusion through locks on the coast is being increasingly regarded as a serious threat to the quality of the water in the 'collector' canals linked with the locks. There are several ways of countering salt intrusion.

The most effective and at the same time most expensive method is 'exchanging while gates are closed' (see 4.7.).

The expedient of equalizing levels by pumping instead of gravity (see 4.6), which only concerns the salt water required for equalization, is not very effective.

The selective withdrawal of salt water (see 4.4 and 4.5) usually calls for expensive alterations or additions to locks and generally requires fairly large quantities of fresh water.

The water barrier method (see 4.3) has not been tested exhaustively.

Pneumatic barriers (see 4.2) constitute a simple, convenient and cheap method of countering salt intrusion. This method will not keep all the salt out but will reduce intrusion quite considerably. Pneumatic barriers can be combined with the systems described in 4.1, 4.4 or 4.5.

Flushing the canal with fresh water (see 4.1) is nothing like as effective as the other methods and involve wasting large quantities of fresh water; it is, nevertheless, the oldest way of getting rid of intrusive salt. On the other hand, it can be retained as a useful supplement to one or more of the other methods, because the water in the 'collector' canals must always be renewed and because surplus rainwater has to be discharged into the sea. Flushing would also make the fresh water required for the other systems readily available.

PNEUMATIC BARRIERS IN EXISTING LOCKS

The pneumatic barrier method of preventing salt intrusion is suitable for practically all the locks adjoining the sea in the Netherlands. Pneumatic barriers are already operating in 13 locks. The largest are in Northern Lock at IJmuiden (2.65 cub. mtrs of air per sec.); the three smaller locks there are also fitted with pneumatic barriers. They have effectuated the anticipated reduction in the chloride content of the water in the North Sea Canal.

Satisfactory results have also been obtained in other places, in some cases by taking supplementary measures.

PNEUMATIC BARRIERS IN NEW LOCKS

The interests served by any measures taken to combat salt intrusion through new locks are considered for each case individually. Methods other than the pneumatic barrier system might be opted for on certain grounds; the locks are designed accordingly.

Notation

$\overline{A}$ = average area of circles produced where air bubbles are intersected by horizontal plane
A_s = area of lock chamber
B = length of perforated pipe
c = velocity of salt water front
C = coefficient of air delivery through main
$C = 2.9$ for plastic, 3.35 for steel pipes
C_e = integration constant
Cl = quantity of chloride in salt water of density $\rho + \Delta\rho$
C_1 = constant, velocity dimension as defined in equ^n (51)
d = diameter of main or perforation
dK = upward force exerted on air/water mixture per unit of volume; basic area = unit of area; height = distance dx
E_k = kinetic energy gained per unit of width
E_p = potential energy released per unit of width
g = acceleration due to gravity
h = depth
h_s = difference between water level on seaward side and that on canal side of lock
h_1 = depth of salt water (see fig. 5)
h_2 = depth of fresh water (see fig. 5)
Δh = term for $h_2 - h_1$ as defined by equ^n (45)
H_a = atmospheric pressure (water gauge)
I = volume of sphere of radius $r(= \frac{4}{3}\pi r^3)$
k = dimensionless coefficient denoting velocity distribution within air curtain [see equ^n (6)]
L = length of lock chamber
L_b = length of air main
ΔL_b = portion of air main
$L\Delta_t$ = distance covered by salt (fresh) water front in period Δt
n = number of bubbles in air/water mixture per unit of horizontal area
n_L = serial number of portion of air main ΔL_b
n_m = value of n when $y = 0$
N = salt intrusion with air curtain as percentage of intrusion without curtain
p_1 = pressure in salt water at level x far from air curtain
p_2 = pressure in fresh water at level x far from air curtain

p_3 = pressure at level x in upward current
P = $\frac{1}{2}(P_1 + P_2)$
P_1 = absolute pressure at air main inlet
P_2 = absolute pressure at air main outlet
P_i = absolute pressure inside perforation
P_u = absolute pressure outside perforation
ΔP = $P_1 - P_2$
q_a = volume of air per unit of pipe length measured at atmospheric pressure
q_h = volume of air escaping through one perforation measured at atmospheric pressure
q_{in} = quantity of salt water intruding through air curtain per unit of pipe length
$q_{in.\,o}$ = quantity of salt water penetrating fresh water per unit of width if there is no air curtain
q_L = volume of air per unit of pipe length at pressure obtaining at level involved
$q_{opw.}$ = quantity of water carried upwards in air/water mixture per unit of pipe length
$q_{opw.\,\frac{3}{4}}$ = value of $q_{opw.}$ at level $x = \frac{3}{4}h$
Q = air-volume factor pertaining to exchange process as defined in equ^n (64)
Q_D = air-volume factor pertaining to exchange process, taking $\Delta\rho'$ into account
r = radius of bubbles considered
Δt = period involved when determining E_p and E_k
u = upward velocity of water in air/water mixture
u_m = value of u when $y = 0$
$u_{rel.}$ = difference between velocity of ascent of air and that of water in air/water mixture
U = ratio of total quantity of salt (or fresh) water (taken as undiluted salt or fresh water) that has intruded into lock chamber to entire volume of water in chamber
T = time factor pertaining to exchange process as defined in equ^n (63)
T_D = time factor pertaining to exchange process, taking $\Delta\rho'$ into account
v_a and v_b = velocity of horizontal current flowing inwards and outwards respectively from upward current (terms used in fig. 5)
$v_{opp.}$ = velocity of horizontal current near surface (see fig. 3)
x = vertical distance from pipe emitting air
y = horizontal distance from pipe
Z = ratio of total quantity of salt water (taken as undiluted salt water) that has intruded into canal through twin air curtains in single locking cycle to entire volume of water in chamber
Z_o = as Z, but with air curtains out of action
μ = dimensionless coefficient denoting velocity distribution within air curtain [see equ^n (7)]
η = escape coefficient of perforation defined by equ^n (79)

ρ_w = density of water
ρ_L = density of air
$\Delta\rho$ = density difference between fresh and salt water
$\Delta\rho'$ = density difference between the water on the seaward side and that of the water on the landward side of the lock
φ = dimensionless value defined in equ^n (61); for relationship between φ and volume of air q_a see equ^{ns} (52), (53), (54) and (61)

Photographs:

Ing. M. v. d. Bijl, No's 5, 6, 11
Ing. J. v. d. Kuijp, No's 2, 12, 13
Rijkswaterstaat, No's 3, 4
Ir. P. de Vos, No's 1, 7, 8, 9, 10, 14, 15

Literature

[1] v. d. Burgh, P.: Zoutbestrijding door luchtschermen, Proeven in de grote sluis te Kornwerderzand, Rijkswaterstaat, Dienst voor de Waterhuishouding, januari 1962, 16 blz.

[2] v. d. Burgh, P. en de Vos, P.: Luchtschermen in schutsluizen, Rijkswaterstaat, Dienst voor de Waterhuishouding, Studiedienst IJmuiden, oktober 1962, 23 blz.

[3] de Vos, P.: Zoutbestrijding door luchtschermen in de sluizen te IJmuiden, een capaciteitsberekening luchtschermen, Rijkswaterstaat, Studiedienst IJmuiden, Rapport S.D.IJ. 62.03, 1962.

[4] Beperking van verzilting via schutsluizen in Deltagebied, Driemaandelijks bericht Deltawerken, februari 1964, nr. 27, blz. 354 ... 361.

[5] Abraham, G., v. d. Burgh, P. and de Vos, P.: Means to reduce salt intrusion through new and existing locks, 21st International Navigation Congress, Stockholm 1965, Section 1, Communication 1, pp. 1 ... 17.

[6] Bulson, P. S.: Currents produced by an aircurtain in deep water. The Dock and Harbour Authority, Vol. 42. May 1961, No. 487, pp. 15 ... 22.

[7] Waterloopkundig Laboratorium, Rapport model- en prototype-onderzoek, M 661, februari 1960.

[8] Taylor, G.: The action of a surface current used as a breakwater. Proceedings Royal Society of London, Series A, Vol. 231, September 1955, No. 1187, pp. 466 ... 478.

[9] Rouse, H., Yih, C. S. and Humphreys, H. W.: Gravitational convection from a boundary source. Tellus 4, (1952) No. 3, August, pp. 201 ... 210.

[10] Abraham, G.: Jet diffusion in stagnant ambient fluid, Delft Hydraulics Laboratory Publication No. 29, 1963.

[11] Hinze, J. O.: Turbulence McGraw-Hill, Series in Mechanical Engineering, 1959, section 6-2.

[12] Anwar, H. O.: Experiment on an effluent discharging from a slot into stationary or slow-moving fluid of greater density. Journal of Hydraulic Research, 7, (1969) No. 4, pp. 411 ... 431.

[13] Kobus, H.: Untersuchungen über die Verminderung der besonders sinkstoffreichen Dichteströmung in Brackwassergebieten durch Luftblasenschleier. Mitteilungen der Versuchsanstalt für Wasserbau und Schiffbau, Heft 50, Berlin, 1969.

[14] Abraham, G. and v. d. Burgh, P.: Pneumatic reduction of salt intrusion through locks. Proceedings American Society of Civil Engineers, Journal of Hydraulics Division, Vol. 90, No. HY 1, January 1964, pp. 83 ... 119. See also Delft Hydraulics Laboratory Publication No. 28, 1962.

[15] Rijkswaterstaat, Arrondissement Noordzeekanaal, Studiedienst IJmuiden.

[16] de Vos, P.: Rendement van doorspoelen van het Noordzeekanaal met IJsselmeerwater; onderzoek naar de verziltingstoestand van het Noordzeekanaal; Rijkswaterstaat, Studiedienst IJmuiden, Rapport S.D.IJ 61.05, 1961.

[17] Stehr, E.: Berechnungsgrundlagen für Preszluft-Ölsperren. Mitteilungen der Hannoversche Versuchsanstalt für Grundbau und Wasserbau, Heft 16, Hannover, 1959, p.p. 275-406.

[18] Stevin, H.: 'Wisconstich Filosofisch Bedrijf' 12e-boek, 25ste voorstel 'Hoe het gewelt en het vergif uyttet Verenigt Nederland te verdrijven sij, mits-gaders alle brac water uyt Hollant, Zeelant en West-Frieslant', 1667.

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Appendix C: Methods employed to limit salt water – fresh water exchange in locks

Methods employed to limit saltwater–freshwater exchange in locks

Lecture given at Karlsruhe University,
December 1980

P. A. Kolkman

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METHODS EMPLOYED TO LIMIT SALTWATER-FRESHWATER EXCHANGE IN LOCKS.(LECTURE GIVEN AT KARLSRUHE UNIVERSITY, DECEMBER 1980)

dr. P.A. Kolkman, Delft Hydraulics Laboratory

Various methods have been developed from hydraulic theory for limiting the saltwater-freshwater exchange in locks. These methods are considered in two articles.These articles were published (in Dutch language) in PT/Civiele techniek 37 (1982) 2 + 3. This publication contains both articles.
The methods include:

- return pumping the locking volume when lowering the water-level;
- keeping the lock gates open for a short period in combination with an air bubble screen;
- sucking off the saltwater tongue, directly or indirectly;
- exchanging the water in the lock chamber with the gates closed;
- using a freshwater outer chamber which contains a saltwater lift box.

The efficiency of the methods is compared and the relation with saltwater control is showed.

With normal locks it is a requirement that ship passages are made with the minimum loss of water. This loss is equivalent to the locking volume S (the chamber area multiplied by the difference between the upstream and downstream water-levels) and if necessary a similar volume of water can be pumped back to the uppper level. A serious problem occurs with locks leading directly into the sea: saltwater intrusion.Much thought has been given to this problem in the Netherlands. If, with a normal lock operating with a certain difference in water-level the loss of the locking volume is important and the solution using reservoirs expensive then for a lock lying between saltwater and fresh water which requires even more water, the solution can be much more expensive. Every time the lock is operated a quantity of saltwater which is considerably larger than the locking volume penetrates into the freshwater canal. If the saltwater flows out in a thin layer on to the bed of the canal there are many reasons for flushing it back. Figure 1 illustrates this situation. If the sluice is too high (figure 1c) hardly any saltwater is flushed back; if it is too low then the separation surface would have to have a sufficiently steep slope for the underlying salt to flow faster than the average water velocity back into the lock. This is not possible with a thin saltwater layer, the bed friction acting strongly against it when the layer is thin.

Eventually the saltwater layer is broken up by mixing, and is ultimately carried away with water flowing into the lock.
The action of winds and ship movements promote considerable mixing. On what does the volume of saltwater penetrating into the freshwater in fact depend?
As shown in figure 2 saltwater penetrates the canal with the locking volume (on the flood tide only) and with what is referred to as the exchange flow.
When the gates at the canal end of the lock chamber are opened the saline water volume of the chamber flows out forming an underflow with a velocity U_a.
A compensating upper flow with the same velocity, U_a, develops.
After a certain period of time the complete chamber volume, V_k (minus the submerged ship volume, V_s) is exchanged and, together with the locking volume, has entered the canal.

The maximum saltwater load = $V_k + S - V_s$ (1)

It should be noted that exchange flow sometimes produces large cross forces which hinder in coming/outgoing vessels.

Return pumping the locking volume and closing the gates quickly

Two methods for reducing saltwater intrusion come immediately to mind based on the description of how it takes place:

M_1 return pumping the locking volume during level lowering operations;

M_2 opening the lock gate over a short period

M_1 speaks for itself; some explanation is required, however, for M_2. In order to get an indicatation of the duration of the exchange process the situation shortly after the gates have been opened has been considered. This situation is shown in Figure 3.

For similar water-levels the pressure gradient in the saltwater is some what steeper than in the fresh and the resulting shaded pressure difference on the bed is $\Delta p = \Delta\rho gh$, where Δp is the density difference between salt and freshwater. In practice the pressure difference is symmetical and on both the bed and the surface is equal to $\frac{1}{2}\Delta\rho gh$. This situation (figure 3b) develops from the first situation because the excess pressure due to the saltwater causes an (external) translatory wave which has no further effect on the development of a two layer flow. The flow which develops can be caracterized by,what is referred to as, the internal Froude Number.

Using this number an expression can be obtained relating the flow pressure, $\frac{1}{2}\rho v^2$, a quantity which, for example, also occurs in the expression for the resistance of a body in a current, and the above represented pressure difference of $\frac{1}{2}\Delta\rho gh$. The Froude Number F_i, is defined as:

$$F_i = \sqrt{\frac{\text{current pressure}}{\text{pressure difference due to gravity}}}$$

$$= \sqrt{\frac{\frac{1}{2}\rho u^2}{\frac{1}{2}\Delta\rho gh}} = \frac{u}{\sqrt{\Delta gh}} \qquad (2)$$

According to Abraham [1 and 2] the value of F_i, can be calculated by relating the loss in potential energy per unit time (heavier water continually sinks to the bed) to the increase in kinetic energy.

In this situation $F_i = 0.5$ and, thus, $U_a = \frac{1}{2}\sqrt{\Delta gh}$ (3)

A value of F_i 10 % lower is found in practice because of friction on the saltwater/freshwater boundary.

From (3) it follows that the greater the water depth the larger the value of U_a. The exchange process continues as the freshwater tongue reaches the closed gate at the other end of the chamber and the complete saltwater volume is discharged out of the lock.

The exchange discharge per unit width is now:

$$q_a = (\tfrac{1}{2}h)(\tfrac{1}{2}\sqrt{\Delta gh}) \qquad (4)$$

The duration of the exchange process, for a lock chamber of length L is given by:

$$T_a = 2L/U_a = 2L/0.5\sqrt{\Delta gh} = 4L/\sqrt{\Delta gh} \qquad (5)$$

Figure 4 shows the varation in the quantity of saltwater exchanged with time, according to this theory. If we consider a situation which is not too extreme, we find T_a= 15 min, then in order to prevent complete exchange the gates must be opened even over a shorter period.

For ships entering/leaving the lock however this period of time is short, implying that exchange would be complete so that the M_2 approach barely has any effect.

The exchange proces must, therefore, be slowed down.

Application of an air bubble screen

If air is introduced into the chamber via a perforated tube set in the floor, under still water conditions, a zone of air/water develops. Above this zone the water density is less than that of the surroundings. An exchange flow, therefore, develops with a water discharge of q_w which flows sideways. If a simplified flow mechanism is considered in which it is assumed that this sideways flow curves upwards with a constant speed then the air-water mixture forms with a lower density, see Figure 5a. A more comprehensive description of this mechanism is given in [3]. The density difference, $\Delta\rho$, can be defined in this situation by:

$$\Delta = \Delta\rho/\rho_{water} = (q_1/q_w)\ [U_w/(U_w + U_{st})] \tag{6}$$

The second term, $[U_w/(U_w + U_{st})]$ arises because the time in wich the air is in the water is reduced by U_{st} where U_{st} is the rising velocity of the air bubbles relative to the water. If we now substitute in

$$q_w = \tfrac{1}{2}\ h.U_w = \tfrac{1}{2}h\ (\tfrac{1}{2}\sqrt{\Delta gh}), \tag{7}$$

in which water flows from both left and right sides it can be shown by calculation that, by approximation, the following relationship is valid

$$U_w \pm \sqrt[3]{q_\ell g} \tag{8}$$

The variation in the term $(\{U_w/(U_w + U_{st})\}^{1/3}$ can be neglected by approximation because it is only important for small air descharges. Although application of Equation(4) (found for a starting exchange flow), is a toss-up for a permanent steady flow, it appears that the relationship(8) can also be found in practice. The water discharge in fact only occurs in the upper ¼ of the depth.

It is possible to use the air bubble screen as a saltwater barrier: if there is freshwater on one side and saltwater on the other, see figure 5b, and air can be mixed with the saltwater giving a mixture (density $\rho_o - \Delta\rho$)

If the density of the mixture is similar to that of the freshwater no exchange flow takes place. There is, however then a density difference and, thus, an

$$\Delta = (q_\ell/q_w)\ (\frac{U_w}{U_w + U_{st}}) \qquad (9)$$

in which we find:

$$q_{\ell o} = \tfrac{1}{4}\ h \sqrt{\Delta gh} \sqrt{\Delta gh}\ (1 + 2\ U_{st}/\sqrt{\Delta gh}) \qquad (10)$$

The results from a series of full-size tests for different locks with various air discharges which has been adapted from [2] are shown in Figure 6.
The air discharges are expressed in the figure in terms of the water velocity produced by the bubble screen. The water velocities are then related to the velocities which must be formed to resist the salt.
This gives a parameter $\sqrt[3]{q_1/q_{1o}}$ which by approximation appears to be lineair with the extent to which the salt tongue is held back. For large values, of the order of 0.8 to 1, the effect of the bubble screen does not increase because there is so much mixing that this forms a new source of salt load.
The conclusion from Figure 6 is that the air bubble screen is effective for increasing the exchange period so that it becomes possible to close the gates before the complete chamber volume is exchanged. The following points should be taken into account when considering air bubble screen operation:

- an air bubble screen should be operated at both sets of gates, there is always mixed water in the chamber, so that $\Delta\rho$ across a screen is less than that wich occurs between fresh water and saltwater.
- gate closure, even with a screen, should be as rapid as possible.
- the locking volume, which is in effect unaltered by the screen(s) still increases the salt load.
- ships passing through the screen push the water aside, a process which is unaffected by the screen.

In practice, see Figure 7:

- hawser forces due to the exchange flow are strongly reduced,
- small ships have a problem with the disturbance in the water,
- air tends to enter the engine cooling system, and the ship's toilet, producing flow inwards.
- the combination of air and saltwater produces considerable corrosssion.
- the energy required for the air bubble system is expensive.

One adventage of the system is that it can be fitted into existing locks.

The Terneuzen System: sucking of the salt tongue, Method M_3

It is possible to flush or pump the penetrating saltflow on the bed directly back, see Figure 8a, or to use a receiving basin set in the canal bed, Figure 8b. With direct back pumping it is possible to prevent almost all the salt getting into the canal, provided that q_{sluice}=1.25...1.5q_a where q_a is defined by Equation (4) and there are no ships in the lock.
If ships are entering or leaving the chamber, however, the exchange flow varies considerably so that, in practice, $q_{pumping}$ must be 1.5..1.8 q_a. This discharge must be maintained for the whole exchange period (T_a) because this time is so short that the gates cannot be closed early. The factor 1.5...1.8 is, therefore also an indication of the relationship between the sluiced volume needed to hold back the salt and the volume of the chamber. From the numerical example given in Figure 8a, it appears that the exchange discharge is large implying that the pumping discharge to counter the salt tongue directly must be very large. By using a receiving basin set in the bed of the canal the return discharge can be spread over the entire emptying locking cycle. The basin can be located directly outside the lock gates or aside in order to reduce the mixing effect caused by ships. In order to prevent the salt tongue being diluted excessively the receiving basin should always be partly filled with saltwater.
In addition a full receiving basin promotes selective flushing of its contents. With this system it must be assumed that the volume to be back-flushed must be 1.5-1.8 times the volume of saltwater coming in. The amount of flow exchanged is unaffected by the system. Because of the large difference in velocity, $2U_a$, between flow at the surface and at the bed, however, the freshwater in the upper layers does become fairly polluted with salt. Since this water flows into the chamber the effect is not noticed in the freshwater canal until a ship enters the chamber forcing freshwater out, causing a salt load in the canal.
A plan view of the Terneuzen sea lock is shown in Figure 10. Here the intake for the return flushing system with its mouth immediately outside the lock gates is incorporated in the filling and emptying system. A description of the construction of the system is given in [4]. Experience with this lock has not been so good since during construction it was decided to deepen the canal but not the receiving basin or the mouth of the flushing system. As a result the volume of the basin is too small and the intake is too high relative to the

bed of the canal. In addition the amount of freshwater available is too small for back-flushing. Air bubble screens are also used in the Terneuzen lock in combination with the salt removal system. The screens are positioned at the gates at both ends of the lock. The air bubble screens certainly reduce the exchange flow but, at the same time, cause some mixing. This increases the volume of saltwater to be flushed back and also makes it difficult to remove out selectively the mixed zone which develops above the saltwater in the receiving basin. It appears that the air bubble screens are very effective for reducing hawser forces (because the depth is large, U_a is also large,and sea going vessels have, in comparision only small allowable hawser forces). Direct sucking of the salt tongue, using a large discharge, has not been applied at the Terneuzen lock because with inflow discharges larger than q_a, extra flows develop towards the lock and, ships entering the lock will experience loss of sterage. Investigations still have to be carried out into the allowable inflow discharge in relation to ship in manoeuvrability.

In the foregoing, measures used to prevent salt intrusion are treated in which, in principle, the exchange flow when the gates on the freshwater side are opened is stopped using an air bubble screen or is sucked off directly or indirectly (Terneuzen system). A combination of both methods can also be used. These methods have little effect on locking time, because vessels can enter or leave as soon as the gates are opened.

Air bubble screens can inprove locking operations since they tend to weaken the exchange flows which hinder ship manoeuvres. There is, however an increase in the volume of salt water to be flushed back.

The second part of this article discusses measures which are related to exchanging saltwater in the chamber for freshwater before the doors at the freshwater side are opened.

The Duinkerken / Kreekkrak / Philipsdam System

The article on measures limiting the salt-freshwater exchange at locks is continued here with a discussion of measures in which saltwater in the lock is exchanged more or less completely with freshwater before the gates on the freshwater canal side are opened. In the early sixties Sogréah developed a new system [5] known in the Netherlands as the Duinkerken system after the place where it was first applied. The principle of the system involves draining the chamber through its perforated floor, and filling with freshwater through wall apertures at about the water-level while the gates are still closed.
Since ships must not be allowed to stand dry and in order to save time and to obtain a lower discharge head for the pump, emptying and filling are carried out simultaneously and ships stay in their position. This process is referred to as saltwater-freshwater exchange.
The system can also be used in reverse, freshwater in the chamber being exchanged for salt, the freshwater draining back into the freshwater canal via the wall apertures. This process is referred to as freshwater recovery. It is very important that large scale mixing is not caused by the process. This can be prevented by correctly shaping the chamber and by using only small discharges at times which are critical for mixing. From the photograph of a laboraty test, reproduced in Figure 11, it appears that a layered situation develops in the process, in which there is, however, some mixing and , in which saltwater flows out at the bed as freshwater enters the lock chamber.
The advantage of the system is that saltwater is prevented from entering the canal with little loss of freshwater.
Disadvantages are that extra time is needed for locking, ships are affected by cross-flows, and a considerable volume of water has to be pumped. Some of the time lost is recovered because, with a bottom filling system, the levelling process can be speeded up without large cross-forces acting on vessels moored in the chamber.
With the Sogréah solution, Figure 12a, there is a freshwater system along each side of the chamber. When the saltwater in the chamber is higher than the freshwater outside it is pumped back into the saltwater approaches. When the level is down to that of the freshwater canal sluices are opened and the freshwater sewer system is linked up with the freshwater canal. In the Netherlands variant, Figure 12b, wall sluices are used along the whole length of the chamber on both sides, water from the freshwater canal surrounding the

chamber on both sides. This variant was applied for the first time in the Kreekrak lock in the Antwerp/Rhine link canal and is described further in [6] A saltwater-seal was introduced in the Sogréah solution to ensure that the freshwater sewer system remains fresh when the water in the chamber is salt.(see Figure 13)

This operates on the principle that the boundery layer between the saltwater and freshwater is only stable when there is horizontal stratification in which the heavier water is below.

To achieve this the saltwater in the chamber must first partly enter the sewer system to be pushed out again later on when the chamber content has to be exchanged to the fresh situation. Mixing occurs during this operation. Mixing also occurs when ships enter or leave the freshwater chamber and a presssure wave develops in front of the ship. Flow then takes place in the sewer system and salt is carried from the chamber into the sewers.

This is prevented in the Netherlands variant by using chamber wall apertures which can be closed. Another problem develops however. Level control sluices are used between the wall sluices and the chamber, see Figure 14a, to ensure that, with different water levels in the surrounding freshwater, freshwater can still be brought into the chamber at the level of the water surface. When the lock gates at the salt end of the chamber are open the chamber will be completely filled with saltwater. The freshwater pocket which develops immediately between the closed wall sluices and the levelling sluices then rises and the space is filled with saltwater.

The freshwater in the system is, as a result, lost. If freshwater subsequently flows again from the surrounding water then it must first displace the saltwater which then contaminates the freshwater. This saltwater volume is 2 to 3% of the volume of the chamber. An improvement is shown in Figure 15. This has been applied in the Krammer locks of the Philipsdam. In this case the levelling sluices also have a closure function so that virtually no water is lost near the wall sluices.

Causes of mixing

The M_4 system for preventing saltwater/freshwater intrusion through locks is based on the replacement of water in the chamber with freshwater and vice versa while maintaining statification. Mixing must, therefore, be prevented as much as possible. With saltwater-freshwater exchanges are carried out care must be taken to ensure that the speed of the incoming freshwater is as slow as possible, otherwise the freshwater jet through the wall apertures will suck a considerable amount of saltwater with it or a kind of internal hydraulic jump will develop, see Figure 16a. The speed, however, should not be so low that saltwater gets into the apertures, see also Figure 11. This requirement can be specified theoretically as $F_i = 1$, see Figure 16b, where F_i is as defined in Equation (2). It has also been shown to be this value in tests . If a ship is lying in front of the apertures there is much less mixing since the space between the ship and the wall quickly fills with freshwater and there is hardly any velocity difference between the upper and lower layers. If the ship lies asymmetrically across the chamber a problem arises because the space between the ship and the wall fills much more quickly with fresh water than that on the other side of the ship. This freshwater flows under the ship to rise to the surface on the other side, through the saltwater, see Figure 16c causing mixing. With rising level exchanges salt can penetrade into the wall apertures because a freshwater pocket persists for some time under the ship. This has to flow around the ship and a flow situation develops which is comparable to a free flow condition on a weir which restricts the discharge. Because the freshwater stays behind in the pocket under the ship the saltwater level alongside the ship rises sharply and thus care should be taken to ensure that not too much "fresh" water is recovered and this not too quickly, otherwise saltwater will be carried out into the canal, see Figure 17a. Mixing also occurs with a perforated floor and to prevent jet effects, see Figure 17b, the discharge through the floor must not be larger than that which can flow away sideways, Figure 17c. This requirement can also be expressed in terms of the internal Froude Number. When the freshwater/saltwater boundery is at the level of critical points in the chamber, which could cause mixing, the discharge should be reduced temporarily.

<u>A ship lying asymmetrically in the chamber</u>

The assymmetry of the boundery between freshwater and salt near to a ship lying across the chamber gives rise to problems during filling and emptying. The rate at which the boundery layer rises or falls should be fairly low, of the order of 1 cm/s, and the hydraulic resistance of the flow should be determined for the wall apertures where the velocity is considerably higher, Figure 18. Initially the flow out is symmetrical and

$$\Delta h = Sq^2 \qquad (11)$$

where S = the resistance per unit length of wall apertures,

q = the discharge per unit length of the apertures.

In this case the head drop across the right hand chamber wall equals that across the left, that is:

$$\Delta h_R = \Delta h_L \qquad (12)$$

and, therefore,

$$q_R = q_L \qquad (13)$$

When the boundary layer reaches the underside of the ship the rate of rise of the boundary layer becomes asymmetric, which can become an equilibrium situation in which the rate of rise to the left is similar to that to the right. This does not occur, however, in all situations.

Because of the difference in level of the boundery layer of z and because the saltwater pressure is the same on both sides there is a difference in freshwater level given by, see Figure 19:

$$z = \Delta h_R - \Delta h_L = \Delta Z \qquad (14)$$

since for a simular rate of rise on both sides

$$q_L = q \frac{a}{a+b}, \qquad (15a)$$

and therefore

$$q_R = q \frac{b}{a+b} \qquad (15b)$$

Δh_L can be calculated from:

$$\Delta h_L = Sq^2 \frac{a^2}{(a+b)^2} \quad \text{and } \Delta h_R = Sq^2 \frac{b^2}{(a+b)^2} \qquad (16)$$

thus

$$z = \frac{Sq^2}{\Delta} \frac{b^2-a^2}{(a+b)} = \frac{Sq^2}{\Delta} \frac{b-a}{b+a} \qquad (17)$$

From this appears that the effect of asymmetry can be by reducing the discharge q, through the floor, by aligning the ship more symmetrically and what is also important, by lowering the resistance of the wall apertures (although it should be remembered that this resistance naturally helps to distribute the flow uniformly over the length of the basin). The value $\Delta h_R - \Delta h_L$ should ideally be small in view of the transverse forces which can develop on the ship. In the Netherlands variant saltwater should not be allowed to penetrate the wall apertures since it would ultimately be able to get from there into the freshwater canal. Normaly, therefore, freshwater recovery is stopped when the boundery layer approaches the underside of the ship with the largest draught. This means that there is a loss of freshwater equivalent to 0.3 to 0.4 times the chamber volume. It is possible to recover further on at extra low speed.
With the Sogréah solution somewhat higher boundary layer positions are accepted because salt, in the first instance, enters the freshwater sewer, from which it is pushed out without too much mixing during the emptying phase, see Figure 20.
Large pump discharges are needed with large push-tow locks in order to be able to exchange water in a reasonable locking time. Sometimes it is recommended that this discharge is spread out over the whole locking cycle by using auxilliary reservoires. Two auxilliary saltwater reservoirs are needed for the Philipsdam locks because the salt seawater is sometimes higher and sometimes lower than the level in the freshwater canal, see Figure 21a. The result is a complex sewer system, Figure 21b.
A pump station is located in the connection between the low and high level reservoirs; Figure 22 shows an oblique view of the lock complex. The floor construction of such a lock, in this case the Kreekrak locks in the Scheldt-Rhine link canal, is shown in Figure 23.
The lock at Duinkerken, the Sogréah solution, funtions as designed[7]. The Netherlands variants, however, have not yet been put into operation because the saltwater-freshwater delta compartimentation works are not ready yet. (Are planned to be put in operation in 1987)

Salt lift lock system

When a somewhat small lock, the Bergsche Dieplock near Bergen op Zoom, had to be built near to oyster breeding beds it was necessery to provide an installation in which the freshwater load in the saltwater area seaward of the lock was kept to a minimum. The various lock systems were re-evaluated and a number of new ideas were proposed. The idea of pumping the chamber completely dry was also considered afresh. In the system selected the ships are not allowed to set dry; a saltwater box is provided in what would be the normal floor of the chamber. Saltwater and freshwater are pumped in and out of the chamber via apertures located low down in the chamber walls at the level of the lock gate tresholds. Discussions were held with nautical engineers and experts to determine whether or not smaller ships and pleasure craft could be allowed to set dry. The following idea was developed from these discussions. (It concerns a meeting with mr. R.E.P Vallenduuk of the ANWB (Organisation of Dutch Tourists)) see Figure 24. The lock chamber is constructed to double its normal height and with a permanent low level dividing wall across the middle. When freshwater is pumped into the lock the ship is lifted above the saltwater, the saltwater behind the dividing wall remaining relatively undiluted.

When the ship is moved over the dividing wall it can be lowered by draining out the freshwater back into the freshwater canal.

Some alternatives considered for improving the basic design are shown in Figure 25. The first alternative, Figure 25a, involved extending the sidewalls over which the freshwater flows into the chamber. One of the disadvantages of this alternative was that the large volume of freshwater had to be pumped while the head could be some metres. The next alternative to be considered involved a low level saltwater basin provided with a lift system, reffered to as a lift box. Such a system conserves energy and the ship need not be moved during the operation, Figure 25b. It is possible to use this system when water levels at the ends of the lock are different, Figure 25c. In this situation, however there is a complication since the saltwater basin box and the lift system must be able to take fairly large water pressure differences. These results from the differences in level between the freshwater and saltwater approaches to the lock.

The system ultimately selected has a fixed concrete outer chamber in which the freshwater outside of the box can be filled up to the level of the freshwater canal (this is in fact the levelling process) so that large pressures cannot develop across the lift box.

Figure 26 shows how a concrete lock, with a large additional depth, remains filled up with fresh water, levels are equalized by pumping water from the freshwater approaches or by gravity. Inside the permament concrete lock there is a steel box, filled with saltwater which can be sunk from under the ship. Ultimately the choice was for a lift box with open sides which slides along the end walls of the outer chamber. The rubber sealing strips are provided with pressure relief systems. Figure 27 shows the sequence of locking operations. In the figure the ship is sailing from the saltwater approaches into the basin which contains saltwater because the lift box is raised. The lock gates are then closed and the lift box containing saltwater is lowered. At the same time the freshwater content of the chamber is adapted to the level of the freshwater approaches. The gates are opened and the ship then sails into the canal. This system causes little mixing because freshwater is introduced effectively along the full length of both sides of the chamber. Only a small difference, z, in the boundery layer develops across a ship lying asymmetrically because the resistance S, caused, by the wall sluices is now low, see Figure 19 and relationship 17, and is similar on each side of the chamber.

With a lift lock very low saltwater loads, of the order of 5% maximum of the volume of the lift box, are expected. The freshwater loss will be about 10% of the volume of the lift box. Two aspects have to be taken into consideration.

- The volume of saltwater required in the box varies with the water displaced by ships in the box and this must be adjusted for using saltwater from the saltwater approaches using a flexible pipework system such as those used by the dredging industry.
- mixing and internal waves develop because ships above the boundery layer sail into and out off the freshwater approach. Internal wave crests should be below the level of the sides of the lift box.

These aspects have been tested in a scale model. Figure 28 shows two cross-sections of the lock chamber, one filling and one emptying.

Figure 29 shows plan, side and end views of such a lock.

Method effectivity analysis

A comparison of the various systems for minimising salt and freshwater exchange, discussed in these articles is given in Figure 30. If the effect of the locking volume is neglected (or if method M_1 is applied) and also if the underwater volume of the ship is ignored, the whole chamber volume ($\approx M_0$) will be exchanged unless special measures are taken. If such an exchange occurs the volume of water in the freshwater canal, will remain unchanged but the quality will be reduced. If the freshwater is now used to flush clean the freshwater canal, many times the volume, M_0, will be required. M_0, is somewhat less than 100 % of the chamber volume, because the gates are never allowed to remain open infinitely long and the rate at which the exchange takes place is a little less than the theoretical value, see Figure 6. With the air bubble system (M_2) the situation is the same but the exchange volume rate is limited, depending on the air discharge. When the salt tongue is sucked off, directly or indirectly, (M_3), about 1.5 to 1.8 times more freshwater is used than the reduction in the saltwater load on the canal. At the same time freshwater in the canal is contaminated when ships enter and leave the lock. M_2 and M_3 can be apllied in combination. In the Sogréah solution, M_4, the amount of freshwater used is greatly reduced but mixing occurs when freshwater is pumped into the chamber and when saltwater is forced in and out of the freshwater sewers. This effect is reduced in the Netherlands version of M_4 but less freshwater can be recovered (in case less freshwater is used the salt load on the freshwater component is increased). This problem can be reduced a little, if filling exchanges are carried out more slowly when there are fewer ships in the lock . It appears that generally M_4 works more effectively if a lower discharge is used during exchanges. As stated above very low salt loading can be expected with solution M_5, the lift box, even with a small loss of freshwater.This is also shown in Figure 30. The amount of freshwater used in system M_4 depends on whether freshwater recovering is chosen or not and if so, to what extent. In M_5, freshwater is lost if the saltwater volume in the lift box is adjusted to the ship's volume. The choice of a particular system depend on freshwater availability, while the way of operation can depend on the season.

Is the effect worthwhile?

In general it is difficult to say which particular system should be applied to combat salt intrusion in a particular situation. What is certain is that the quality of agriculture, drinking water, industrial water, the environment, and living conditions are all strongly related the amount of salt in the freshwater system. In the densely populated Netherlands a considerable effort has to be made in this respect. In order to illustrate how the results of figure 30 can be applied a situation with a canal, at the end of which there is a lock and a water intake requiring a certain water quality, see Figure 31, is considered. The lock, filled with a salt combating system, uses a freshwater discharge of Q and, at the same time depending on how good the salt combating system is, also uses saltwater discharge, averaged over the locking period, Q_a (the resulting exchange flow). The freshwater discharge of the lock, Q is equivalent to the flushing discharge of the canal. The larger the value of the canal discharge (larger Q available) the larger Q_a can be, while maintaining the required quality of the canal water at the inlet of the flushing discharge. This process is repesented graphically in Figure 31 by the "freshwater needed" line. The lock characteristics given in Figure 30 are superimposed on Figure 31, the point of intersection giving the discharge quantity of freshwater needed to flush the canal.

It is obvious that a small improvement in the "lock characteristic" will have an important effect on the quantity of freshwater needed. Since the freshwater availability varies over the year the position of the lock characteristic curve greatly influence the duration of the period in the year when the intake quality requirement can be satisfied. In addition the results of Figure 30 should be especially assessed for the quantity of freshwater used in relation to the volume of water exchanged (Volume A)

Closing remarks

From this review it can be concluded that in the last 20 years important developments have been made in the Netherlands in combating salt intrusion at locks located on the fresh/saltwater boundary. The results of efforts to reduce the loss of freshwater are even more obvious. If no salt/freshwater intrusion prevention measures are taken there will be exchange of almost 100% of the chamber volume with every locking operation. These losses can be halved using an air bubble screen. The application of reservoirs in the freshwater area, in which saltwater is stored initially to be returned to the saltwater area, is an important step in the prevention of saltwater intrusion. Because of the mixing which takes place during locking in fact about two times the chambers volume must be return pumped. This system, therefore, requires a considerable amount of freshwater. Systems have been developed recently in an attempt to reduce both salt and freshwater losses. These can be important in two situations: when freshwater is required (for other purposes) and when freshwater cannot be allowed in a seawater area.

Of the developments outlined in the article the lift lock seems to be the most succesful (appears to be the most promising)

The Netherlands Ministry of Public Works and Transport is now seeking the maximum possible reduction in freshwater/saltwater losses with lift locks.*

In 1 This is because positive decisions have to be taken about the application of these locks in the Oesterdam at Bergen op Zoom in connection with the oyster beds in the area.

Since Duinkerken no developments have been published by foreign organizations related to systems used for preventing salt/freshwater intrusion at locks. The developments outlined above are very Dutch and can be seen as a very important contribution by the Netherlands hydraulic engineering sector in this field. It will be obvious to the reader that the more effective a system is in reducing salt/freshwater intrusion the greater will be investments in the system. Given allowable fresh/saltwater losses for a particular project it is now possible for the designer to choose from various systms. It appears also that the "internal Froude number" plays an important role. From this it follows that the speed at which water flows into or out of the chamber is also important. Efficient lock mangement is, therefore, essential, for the succesful operation of a salt/freshwater separation systèm and for this reason the relationship between salt/freshwater losses, schematized in Figure 30, should only be seen as indicative of the efficiency of particular systems.

Remark: In 1982 the decision was taken to build a very small lock instead of the lift lock.

References

1 Abraham, G., v.d. Burgh, P.:
"Reduction of Saltwater Intrusion through Locks by Pneumatic Barriers"
Publ.28. Delft Hydraulics Laboratory, 1962.
shorted also in Proc. ASCE(90) 1964, HYI paper 3759.

2 Abraham, G.,van der Brugh, P. de Vos, P.:
"Pneumatic Barriers to Reduce Salt Intrusion through Locks".
Rijkswaterstaat Communications 1973 nr.17.
Also W.L. Publ. 126.

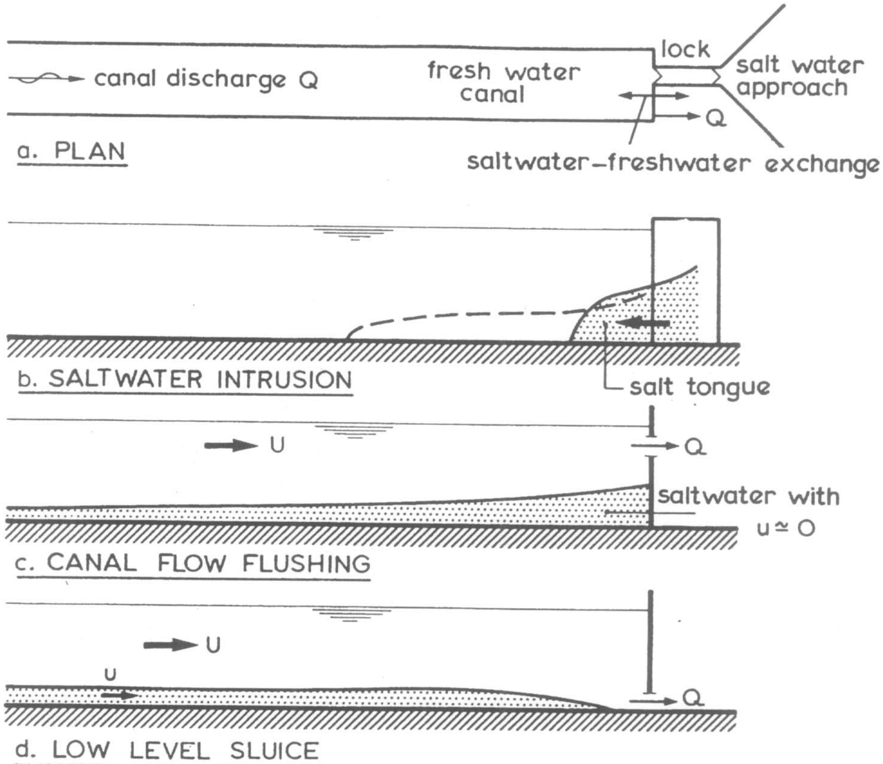
3 Abraham, G.:"Theoretische beschouwingen over zoutbestrijding bij schutsluizen door luchtbellengordijnen.
De Ingenieur (84) maart 1972, no.2, Also W.L. Publ.nr.138N.

4 Jonker, L.A. and Barentsen, W.H.: "De nieuwe zeevaartsluis te Terneuzen"
5th Internat. Haven Congres. Antwerpen juni 1968, paper 2.12

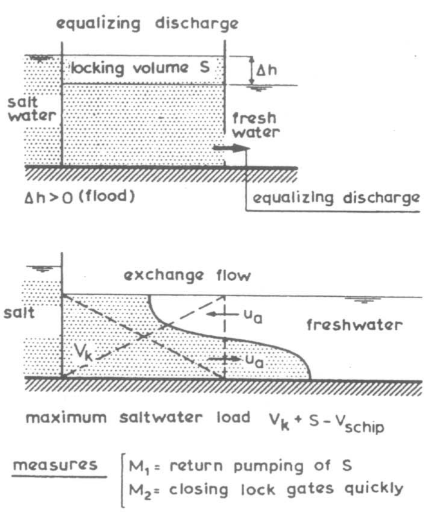
5 Ribes, G. and Blanchet, CH.: "Les courants de densité et le projet de l'écluse de Mardyck á Dunkerque' La Houille Blanche 1965 no.1.

6 Kolkman, P.A. and Slagter, J.C.: "The Kreekrak Locks on the Scheldt-Rhine Connection". Rijkswaterstaat Communications nr.24, 1976.

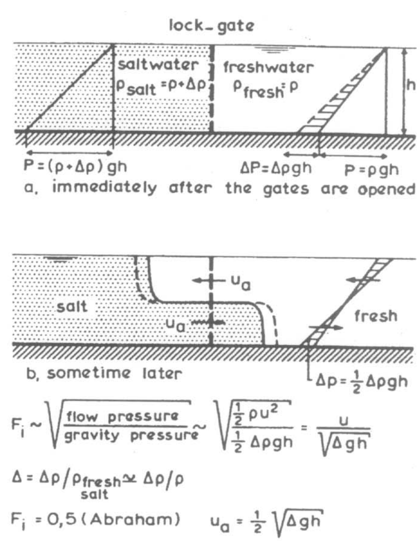
7 Quetin, B.: "l'écluse de Mardyck (près de Dunkerque) limite la pénétration d'eau de mer dans le canal à grand Gabarit".
La Houille Blanche, (27) 1972 no.2/3.



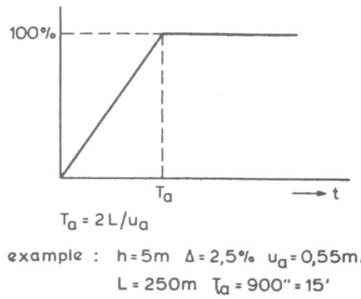
1. Situation with a normal salt intrusion



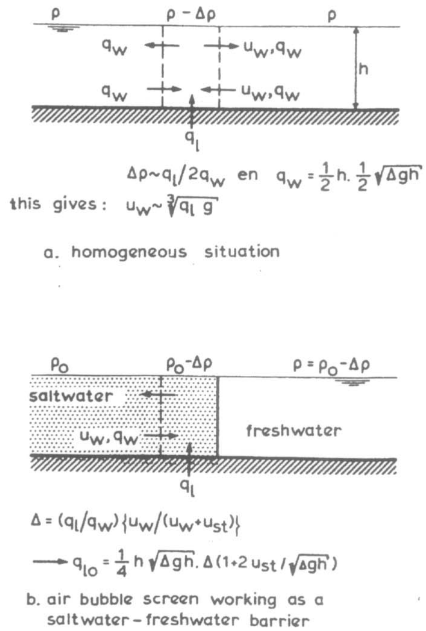
2. Factors which determine the salt load



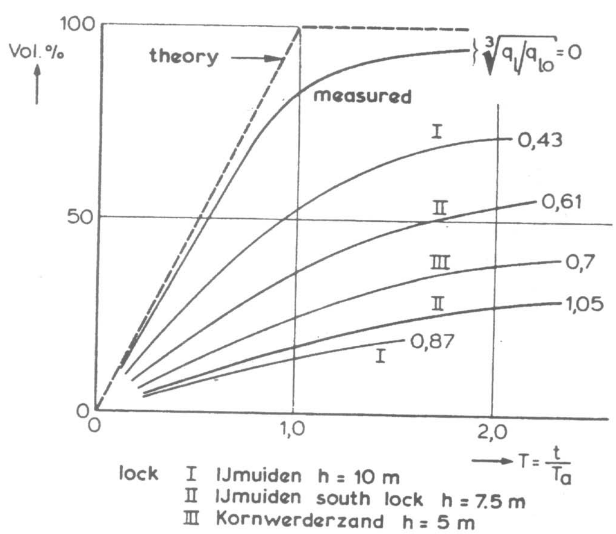
3. Saltwater-freshwater exchange shortly after the gates have been opened



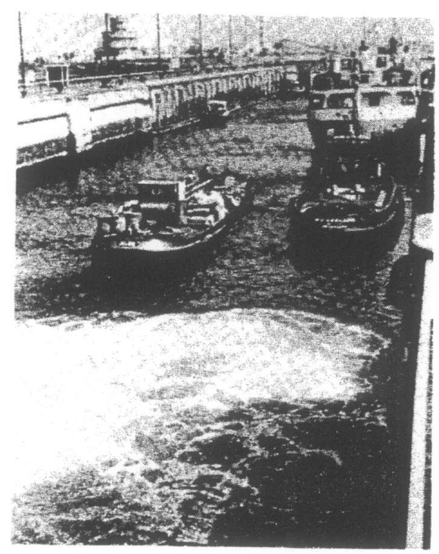
4. Volume exchanged related to time



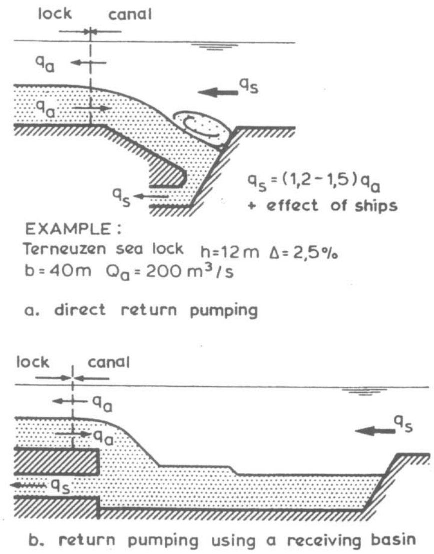
5. How an air bubble screen works



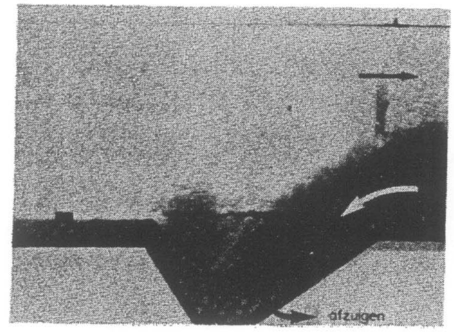
6. Reduction in exchange using an air bubble screen



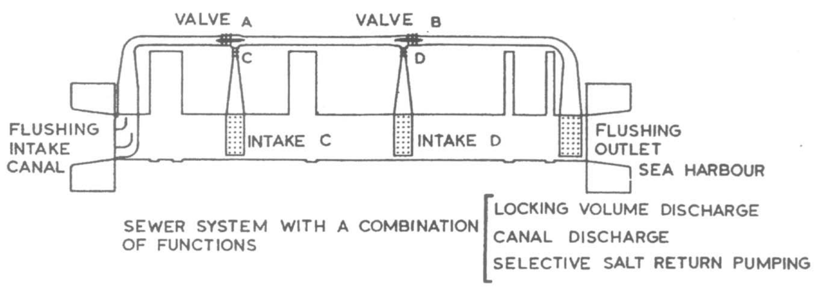
7. Airbubble screen in Ijmuiden South Lock.



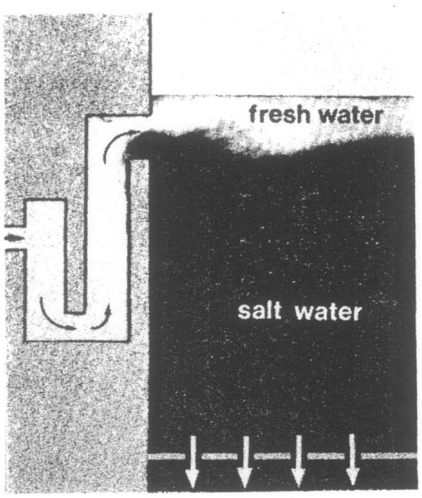
8. Method M3: pumping back (return pumping) the salt tongue



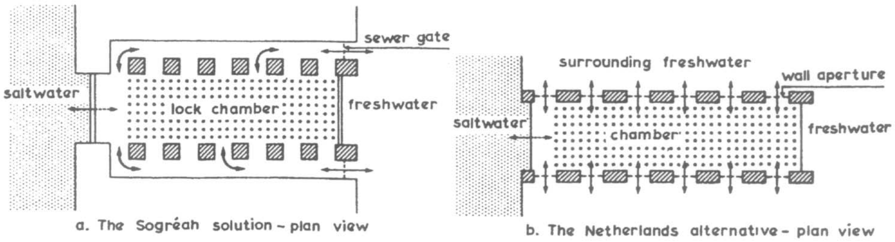
9. The salt (coloured) underflow being return pumped directly.



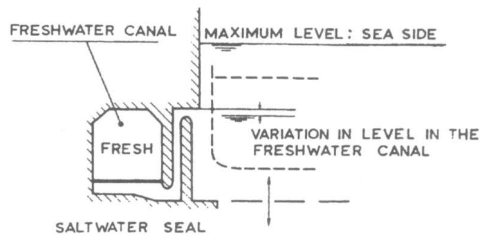
10 Plan view of the Terneuzen sea lock



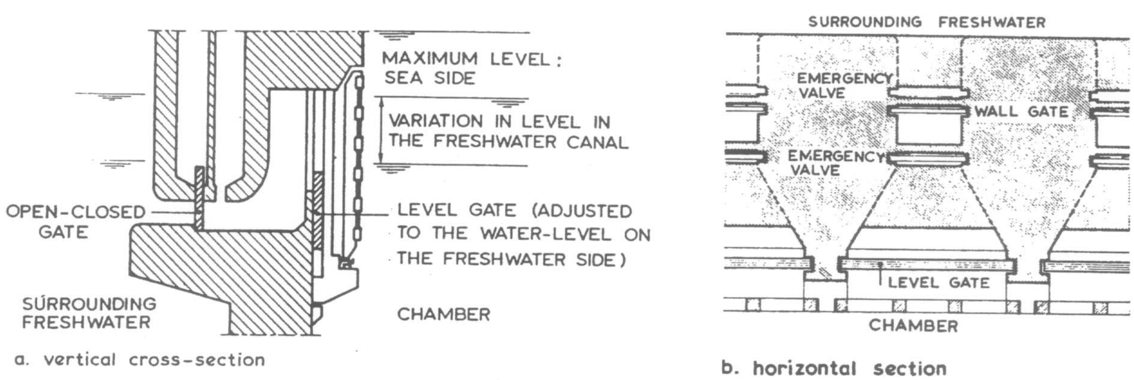
11.Test introducing freshwater into the lock chamber which is full of saltwater.



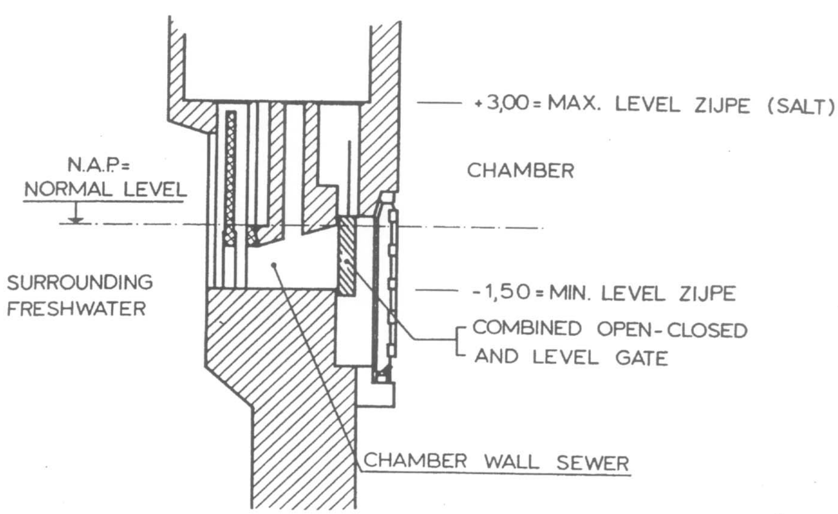
12. Preventing salt intrusion by exchanging the chamber contents with the lock



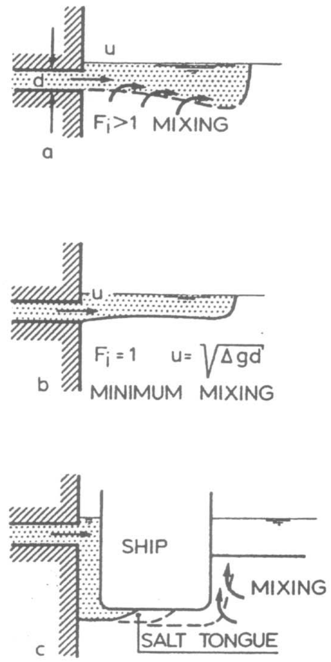
13. The lock system used at Duinkerken - cross section



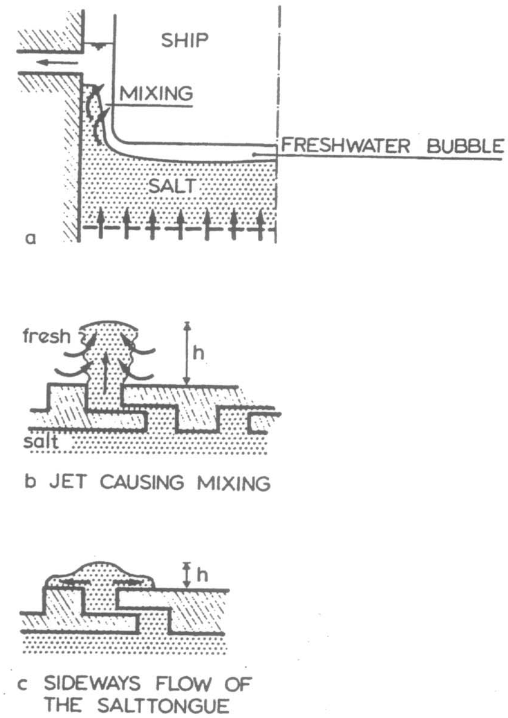
14. The Kreekrak chamber wall



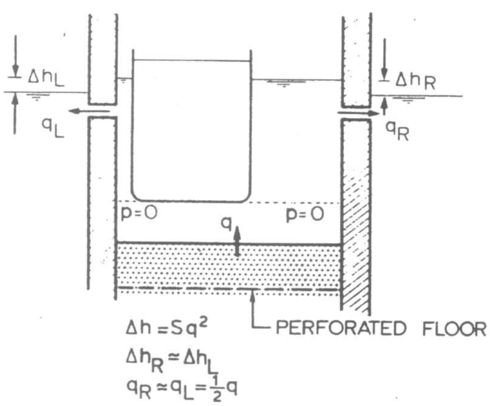
15. The Philipsdam lock chamber wall sewer system, cross section



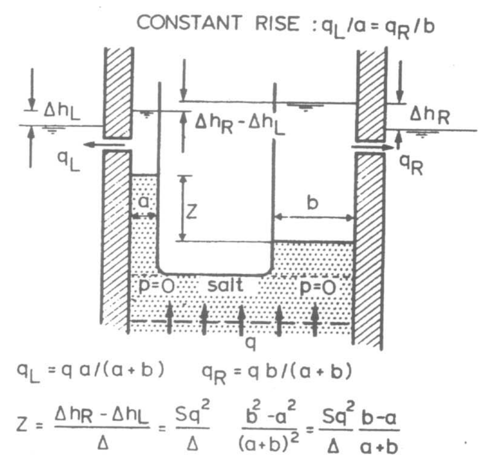
16. The causes of mixing during saltwater-freshwater exchange



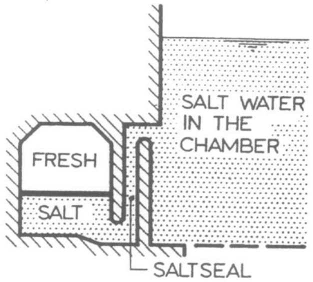
17. The causes of mixing and saltwater loss during freshwater recovery



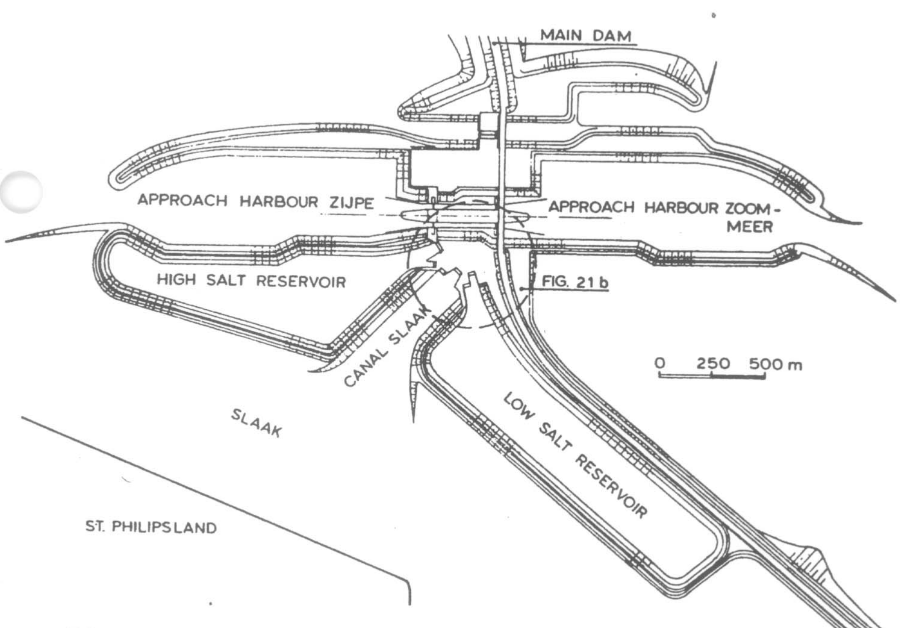
18. The effect of wall aperture resistance when the chamber still contains freshwater



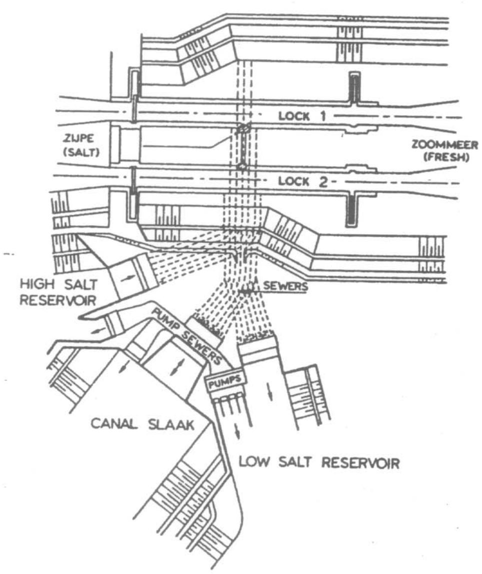
19. The situation when the rate of rise of the boundery layer is the same on both sides of the ship.



20. Salt penetrating the freshwater sewer

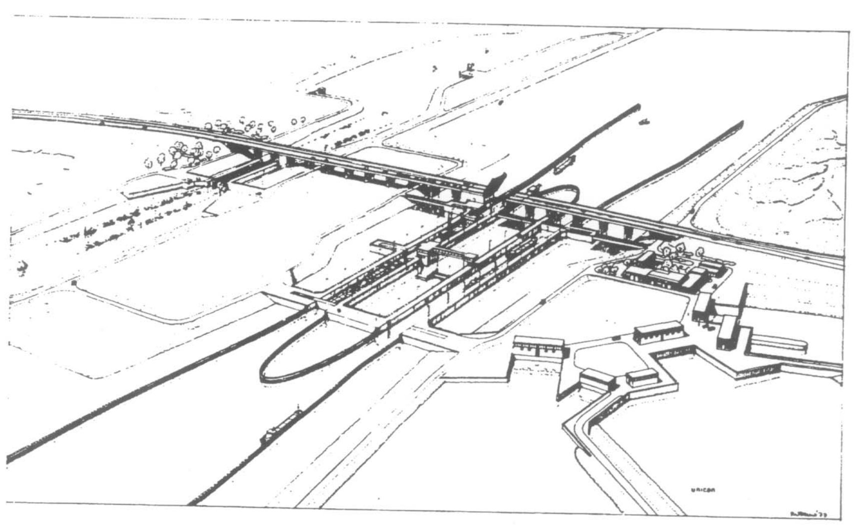


a. Plan view of the two push-tow locks with auxiliary reservoirs

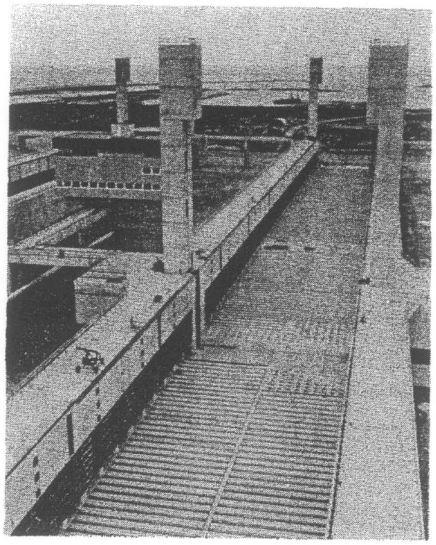


b The sewer system

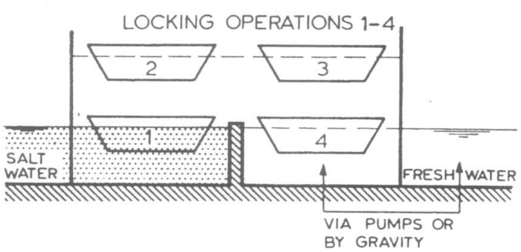
21. The philipsdam lock complex - plan view



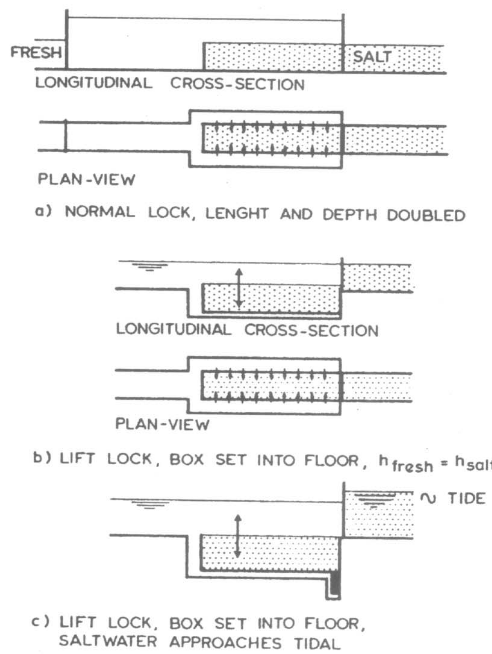
22. Push - tow locks at Philipsdam with freshwater in the foreground which runs alongside the locks.



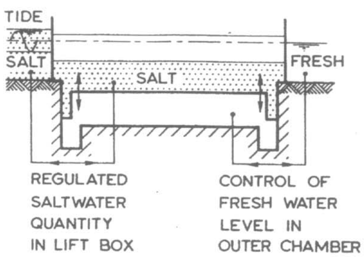
23. The Kreekrak locks in the Scheldt-Rhine Link Canal constructed with a perforated floor for distributing the saltwater inflow and outflow.



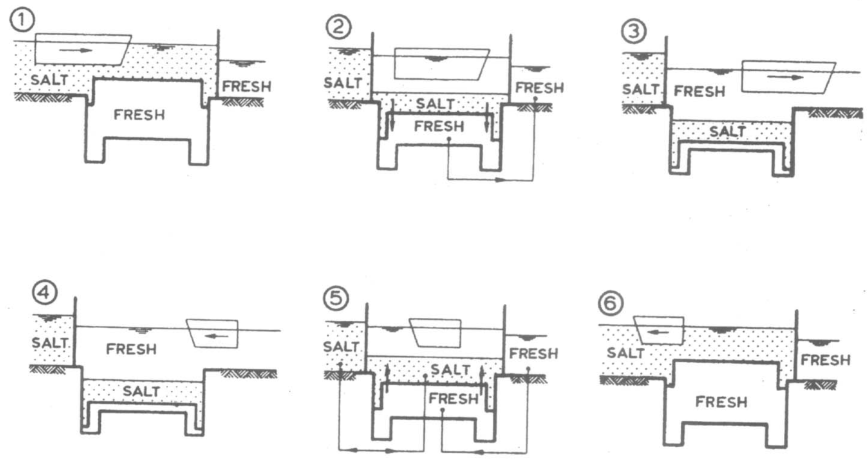
24. Lock with high dividing wall



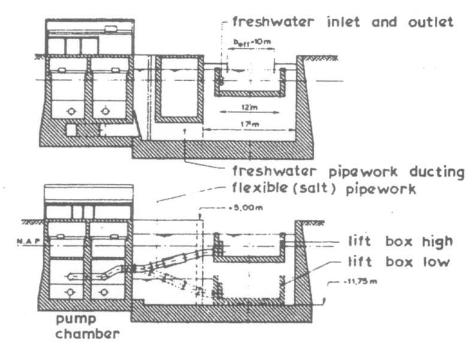
25. Development stages in lift lock design, longitudinal cross-section, plan view



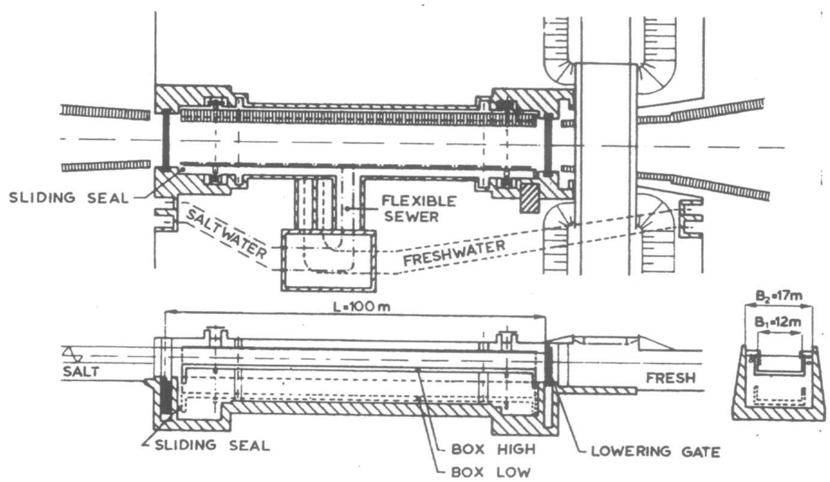
26.The lift lock principle



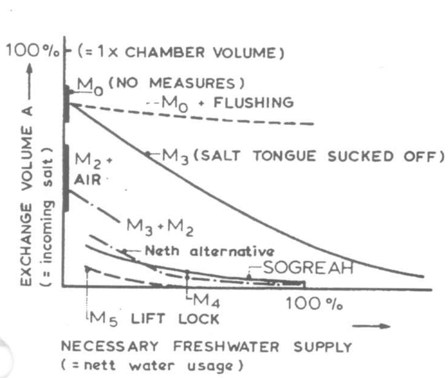
27.Locking operations with a lift lock



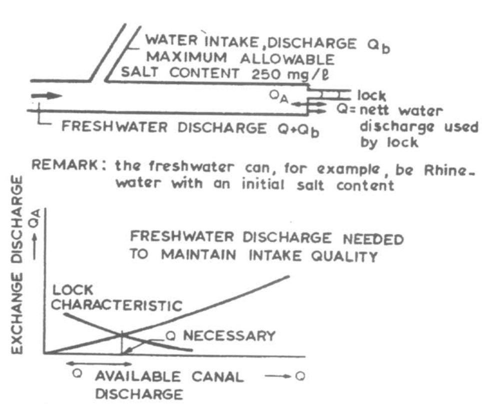
28.Cross-section showing pumping systems for adjusting salt and freshwater levels.



29.Lift lock - plan view and cross - section



30.Exchange volume A(= incoming salt)



31.The situation of a lock with a freshwater intake in the canal.

Appendix D: Water quality control at ship locks

Book by Kerstma et al (separate)

Water Quality Control at Ship Locks

Prevention of Salt- and Fresh Water Exchange

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